Screening-level microbial risk assessment of acute gastrointestinal illness attributable to wastewater treatment systems in Nunavut, Canada

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4 **Title**

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14 **Authorship**

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5 Abstract

6 Most arctic communities use primary wastewater treatment systems that are capable of only low levels
7 of pathogen removal. Effluent that potentially contains fecally-derived microorganisms is released into
8 wetlands and marine waters that may simultaneously serve as recreation or food harvesting locations
9 for local populations. The purpose of this study is to provide the first estimates of acute gastrointestinal
10 illness (AGI) attributable to wastewater treatment systems in Arctic Canada. A screening-level, point
11 estimate quantitative microbial risk assessment (QMRA) model was developed to evaluate worst-case
12 scenarios across an array of exposure pathways in five case study locations. A high annual AGI
13 incidence rate of 5.01 cases per person is estimated in Pangnirtung, where a mechanical treatment plant
14 discharges directly to marine waters, with all cases occurring during low tide conditions. The
15 probability of AGI per person per single exposure event during this period ranges between 0.10 (shore
16 recreation) and 0.63 (shellfish consumption). A moderate incidence rate of 1.16 episodes of AGI per
17 person is estimated in Nauyasat, where a treatment system consisting of a stabilization pond and tundra
18 wetland is used, with the majority of cases (87%) occurring during spring. The pathway with the
19 highest individual probability of AGI per single exposure event is wetland travel at 0.60. All of the
20 remaining risk probabilities per single exposure are less than 0.01. The AGI incidence rates estimated
21 for the other three case study location are low (≤ 0.13). These findings suggest that wastewater
22 treatment sites may be contributing to elevated rates of AGI in some arctic Canadian communities. The
23 absolute risk values, however, should be weighed with caution based on the exploratory nature of this

study design. These results can be used to inform future risk assessment and epidemiological research as well as support public health and sanitation infrastructure decisions in the region.

Keywords

Indigenous health; Arctic; Rural and remote health; Quantitative Microbial Risk Assessment (QMRA); Water, Sanitation, and Hygiene (WASH)

1. Introduction

Communities in the Arctic employ basic wastewater (sewage) treatment systems, which may be contributing to elevated rate of infectious disease in the region (Harper et al., 2015; Hayward et al., 2014; Ragush et al., 2015; Yates et al., 2012). In many ways these economical treatment systems, which make use of natural environmental processes, are effective and well-suited for the small population sizes and extreme climate of the Arctic (Heinke et al. 1991; ITK and Johnson 2008). A limitation, however, is that they are capable of only primary treatment and low levels of pathogen removal (Hayward et al., 2014; Huang et al., 2017; Ragush et al., 2015; Yates et al., 2012). As a result, partially treated effluent potentially containing fecally derived microorganisms is released into wetlands and marine waters near communities (Huang et al., 2017; Krumhansl et al., 2015). The predominantly Indigenous populations in Arctic Canada have strong connections to their immediate physical environment; as such, the natural areas that are being used for passive wastewater treatment may simultaneously serve as recreation or food harvesting locations (Nilsson et al., 2013). Within these mixed ecological systems, people may unknowingly be exposed to wastewater pathogens, either by

direct contact or indirectly through handling of contaminated wild food (Dorevitch et al., 2012; Holeton et al., 2011).

There are several microbial pathogens of human health concern which may be present in domestic wastewater (Bitton, 2005). Some of these have a very low infectious dose, meaning that they can lead to acute gastrointestinal illness (AGI) and other human diseases even after exposure to low concentrations (Leclerc et al., 2002). Within Inuit Nunangat, the distinct Inuit region of Arctic Canada, the enteric illness burden is believed to be significantly higher than in southern parts of the country (Parkinson et al., 2014). A study of self-reported AGI in Inuit communities estimated a range of 2.9 to 3.9 annual cases per person; a stark contrast to a national estimate of 0.6 annual cases per person (Harper et al., 2015; Thomas et al., 2013) and higher than average estimates from developing countries (0.8-1.3) as well (Mathers et al., 2002; WHO, 2006). Furthermore, socioeconomic challenges in some remote Arctic communities, such as suboptimal housing, nutrition, and health care access may exacerbate the seriousness and longer term implications of AGI (Hennessy and Bressler, 2016; Yansouni et al., 2016). The degree of enteric illness attributable to wastewater contamination in the Arctic is currently unknown. Studies of pathogens present in fecal samples collected from cases of AGI have yet to be linked with wastewater exposure (Goldfarb et al., 2013; Iqbal et al., 2015; McKeown et al., 1999; Messier et al., 2012; Pardhan-Ali et al., 2012a, 2012b; Thivierge et al., 2016). However, environmental contamination from wastewater treatment sites remains a potential risk factor and ongoing concern among communities and public health officials in the region (Daley et al., 2015; Goldfarb et al., 2013; Hastings et al., 2014; Pardhan-Ali et al., 2013).

The limited knowledge of possible human health impacts attributable to wastewater treatment operations in the Arctic is partially due to the complexity of the setting. Defining the exposure

71 pathways and characterizing health risk in a natural system is difficult due to the conflux of human and
72 environment interactions, none of which are likely to follow a linear relationship or have been
73 elucidated with full field data sets (Haas et al., 2014). Resource-intensive epidemiological studies of
74 multiple exposure pathways, without clear associations between microbial hazard sources and health
75 outcomes are not well-suited for this type of problem. A broader assessment, which considers the
76 whole ecological system and is flexible enough to include an array of microorganisms and exposures, is
77 better suited to model conditions and estimate the level of risk (Boehm et al., 2009; Dunn et al., 2014;
78 Waltner-Toews et al., 2003).

79

80 Quantitative microbial risk assessment (QMRA) has emerged as a practical approach for evaluating
81 health risks in complex ecological systems (Haas et al., 2014). The disease burden attributable to
82 microbial pathogens in the environment can be estimated based on information about their
83 concentration and distribution or that of suitable surrogates, i.e., usually indicator organisms (Haas et
84 al., 2014; USEPA, 2012). It is particularly useful for assessing risk at low levels of exposure (Haas et
85 al., 2014). Through four stages (hazard identification, exposure assessment, dose-response analysis,
86 risk characterization), data from a variety of sources, including field studies, models, and literature, are
87 integrated to quantify the microbial risks attributed with defined exposure scenarios. A range of
88 computationally-demanding and detailed analysis is possible – from point estimate risk
89 characterizations to stochastic models incorporating Monte Carlo simulation – depending on
90 availability of data and scope of the problem. This design flexibility makes QMRA a useful tool to
91 estimate effects where direct measurements of microbial pathogens at the point of exposure are not
92 available or feasible (Haas et al., 2014; Howard et al., 2006). Simplified QMRA approaches have been
93 adapted for use in some developing regions with limited data (Ferrer et al., 2012; Howard et al., 2006;
94 Hunter et al., 2009; Yapo et al., 2014). QMRA has also been used in other contexts where populations

95 may be unknowingly exposed to wastewater effluent through food harvesting or recreational activities
96 (Fuhrmann et al., 2017; 2016). These applications are promising for the use of QMRA in addressing
97 similar public health challenges in remote, arctic communities.

98

99 Considering the basic treatment systems and high rates of AGI in the Arctic, the objective of this study
100 is to provide the first estimates of microbial health risks attributable to wastewater-borne pathogens in
101 Inuit Nunangat and other Arctic Canadian communities. A conceptual model, supported by a literature
102 review, was first developed to serve as a directional guide for the risk assessment (Daley et al., 2017).
103 A simplified, point estimate QMRA model was then designed to allow a broad range of potential
104 exposure pathways to be evaluated and to discern those that pose high levels of risk and warrant further
105 attention.

106

107 **2. Methods**

108 ***2.1 Ethical considerations***

109 The study protocol was reviewed and approved by the Dalhousie University Research Ethics Board
110 (reference number 2013-3021). This study is registered with the Nunavut Research Institute.

111

112 ***2.2 QMRA scope and design***

113 Given the exploratory nature of this research and limited local data, the risk assessment was designed
114 as a screening level, point estimate model. This type of QMRA is very useful in comparing and ranking
115 scenarios prior to proceeding with a more complex stochastic assessment of those presenting the
116 highest risk (Sales-Ortells and Medema, 2014; USEPA, 2012; WHO, 2016). All model inputs were
117 based on site-specific data, where available, or existing literature. Conservative, but plausible, values
118 were used in order to represent point estimates of maximum reasonable exposure.

119

120 **2.3 Hazard identification**

121 The microbial hazard source was associated with partially-treated wastewater effluent being released
122 from treatment sites. Most communities in Arctic Canada use passive treatment systems comprised of
123 wastewater stabilization ponds (WSPs) that are referred to locally as lagoons and wetlands. The
124 wastewater treatment site is typically located on the perimeter of the main habitation area. Effluent is
125 discharged into the WSP where it is stored and remains frozen for the seven to eight month duration of
126 the arctic winter. WSPs across the region vary in terms of initial design – from unaltered existing
127 shallow depressions to engineered ponds with polyethylene liners and granular berms to prevent
128 unplanned seepage (Ragush et al., 2015; Schmidt et al., 2016). The WSPs also differ regarding state of
129 repair and operational procedures. During the spring and summer in some communities, the effluent
130 either seeps or is manually decanted into natural tundra wetlands, where further passive treatment
131 occurs (Hayward et al., 2014; Yates et al., 2012). The effluent ultimately enters a marine receiving
132 water body within or near community boundaries. In a few communities, wastewater is treated using
133 primary mechanical plants, rather than WSPs, and is discharged directly to a marine receiving
134 environment (Krumhansl et al., 2015). These mechanical systems can be prone to malfunction, often
135 relating to cold temperatures, and can be offline for extended time periods as the remote locations make
136 access to replacement parts and repair challenging (Johnson et al., 2014). At present, most systems in
137 Arctic Canada are classified as primary treatment with no effluent disinfection, meaning low levels of
138 pathogen removal (Huang et al., 2017).

139

140 Six pathogenic agents were included in the assessment: three bacteria (*Escherichia coli*, *Salmonella*
141 spp., and *Campylobacter jejuni*); one virus (rotavirus); and two protozoa (*Giardia lamblia*, and
142 *Cryptosporidium parvum*). All six agents are commonly present in partially-treated wastewater effluent

143 and transmissible via faecal-oral routes (i.e., direct accidental ingestion of water, hand-to-mouth
144 exchange following contact with contaminated water, or ingestion of contaminated food). The
145 prevalence and emergence of pathogenic infections in Arctic Canadian populations were considered
146 during the selection of microorganisms (Goldfarb et al., 2013; Iqbal et al., 2015; Pardhan-Ali et al.,
147 2012b; Thivierge et al., 2016; Yansouni et al., 2016). As a simplification within the entire assessment,
148 we refer to the pathogenic strains known to be associated with AGI.

149

150 ***2.4 Exposure assessment***

151 *2.4.1 Case study locations*

152 Based on sufficient water quality data having been collected in their receiving environments, five
153 Nunavut communities were selected as QMRA case study locations: Iqaluit, Pangnirtung, Pond Inlet,
154 Sanikiluaq, and Nauyasat (Figure 1). These sites represent examples of all the major treatment type and
155 receiving environment combinations found in the Territory of Nunavut.

Figure 1. Map of five case study locations in the territory of Nunavut, Canada (*Iqaluit, Nauyasat, Pangnirtung, Pond Inlet, and Sanikiluaq*).

Community locations, populations, annual volume of wastewater, treatment system, effluent discharge schedule, annual volume of wastewater (m^3), effluent *E. coli* concentrations at discharge reported as most probable number (MPN) of coliform per 100 ml of water, and receiving environment characteristics including maximum tidal range (m) are presented in Table 1.

165 **Table 1** Characteristics of the five case study locations included in the quantitative microbial risk
 166 assessment (QMRA) to estimate the burden of acute gastrointestinal illness (AGI) attributable
 167 to wastewater treatment in Arctic Canada.

Community and location	Population size	Treatment type	Discharge method and timing	Wastewater volume (m ³ /year)	<i>E. coli</i> concentration at initial discharge (MPN/100 mL)	Receiving environment and maximum tidal range (m)
Iqaluit 63°44'40"N, 68°31'01"W	7740	Mechanical treatment (bulk solids removal)	Continuous, year round	867,167	1.12×10^7	Inlet/small bay, 11.0
Pangnirtung 66°08'47"N, 65°42'04"W	1481	Mechanical treatment (activated sludge)	Continuous, year round	49,751	1.23×10^5	Narrow fiord, 6.9
Pond Inlet 72°42'00"N, 77°57'30"W	1617	Stabilization pond with no wetland	Controlled decant, 2-3 weeks in late summer	41,046	4.40×10^5	Open marine, 2.5
Sanikiluaq 56°32'34"N, 79°13'30"W	882	Stabilization pond and wetland	Continuous uncontrolled seepage, 12-15 weeks (from spring freshet until winter freeze)	32,120	6.00×10^4 (spring), 2.30×10^4 (summer)	Wetland into open marine, 1.2
Naujaat 66° 31'19"N, 86°14'16"W	1082	Stabilization pond and wetland	Continuous uncontrolled seepage, 12-15 weeks (from spring freshet until winter freeze)	35,430	1.73×10^6 (spring), 1.10×10^6 (summer)	Wetland into open marine, 3.9

168 References: Fisheries and Oceans Canada (2016); Nunavut Water Board (2015); Statistics Canada (2016).

169

170 2.4.2 Exposure scenario development

171 Aside from the physical and natural characteristics of the wastewater treatment areas, the case study
172 locations also vary regarding the types of interactions taking place at the human-environment interface.
173 Understanding these interactions and carefully delineating the exposure pathways in this previously
174 uninvestigated setting was an important step in the assessment. Emphasis was placed on incorporating
175 community-grounded information into the model in order to accurately depict potential exposure
176 scenarios (Barber and Jackson, 2015), using participatory epidemiology techniques. Between 2013 and
177 2016, a total of 11 data collection visits were made to the case study locations by members of the
178 research team. Each community was visited at least twice, with each trip lasting one to three weeks.
179 Key informant meetings were held, which included questionnaires and site-mapping in order to gather
180 activity pattern data about the local population's interactions with the land and water surrounding
181 wastewater treatment sites and their awareness of potential hazards. The key informants included
182 public health officials, municipal wastewater operators, wildlife and environmental conservation
183 officers, and subsistence hunters and fishers. A total of 42 meetings with key informants were
184 conducted, with each meeting lasting from 30 to 60 minutes. Key informant data were used to identify
185 the most likely wastewater-associated exposure pathways in each case study location and to set model
186 parameters for event locations, timing, durations, frequency, and exposure group sizes. Community
187 presentations and displays were also organized, where approximately 100 additional members of the
188 public provided general comments regarding human activity surrounding the treatment areas. Site
189 assessments of each treatment area were conducted alongside engineers and local partners to situate
190 human-environment interaction data. Ingestion rates for each exposure were sourced from literature.
191 Corrective factors were used to adjust standard literature-based exposure factors to the local context.
192 The corroboration of exposure factors from literature-to-local has been demonstrated in previous
193 QMRA applications (Barker et al., 2014; Fuhrmann et al., 2016).

194

195 Six activities were selected as the most likely pathways of human exposure to wastewater hazards:
196 shoreline recreation; small craft boating; netfishing; shellfish harvesting; shellfish consumption; and
197 wetland travel. Descriptions of each pathway are provided below and a full summary of the human
198 activity parameters used in the QMRA model are presented in Table 2. The parameters include:
199 distance (location where the human exposure event occurs as measured in metres from the effluent
200 release point); frequency (number of exposure events per year); exposure group (number of individual
201 people exposed per event); and ingestion (amount of media ingested per individual per exposure event).
202 In all but the shellfish consumption scenario, the modelled transmission route is accidental ingestion of
203 contaminated water. In the shellfish consumption scenario, the transmission route is ingestion of
204 contaminated tissue. Community data showed that people do not source drinking water downstream
205 from any of the wastewater treatment sites. Consumption of contaminated finfish (non-shellfish),
206 marine mammals, and wild game were also excluded as transmission routes in this screening-level
207 assessment as dose-response data for these mediums as a secondary source of microbial contamination
208 is limited (CAMRA, 2015). The accidental ingestion rates for shoreline recreation, small craft boating,
209 and netfishing were adapted from values characterizing three classes of water recreation exposure
210 (Dorevitch et al., 2011; McBride et al., 2013). The low contact accidental ingestion rate is an average
211 of 3.8 mL/hour and is applicable to activities such as fishing and wading. A middle contact average rate
212 of 5.8 mL/hour is recommended for canoeing or kayaking with occasional capsizing and the high
213 contact average rate of 10.0 mL/hour pertains to swimming. Three times the average value is
214 recommended for use as a conservative estimate (Dorevitch et al., 2011; McBride et al., 2013).
215 Accidental ingestion rates for the wetland travel and shellfish harvesting exposure pathways were
216 drawn from assessments of agricultural and aquacultural harvest work in areas where wastewater
217 irrigation is practiced (Fuhrmann et al., 2016, 2017; WHO, 2006). These studies included assessment

218 of harvesting crops such as rice grown in marshy areas – similar to the tundra wetland sites – and
219 suggest 50.0 mL/day as a conservative accidental ingestion rate.

220

221 *Shoreline recreation:* All five case study locations are coastal communities and as such the shoreline is
222 a focal point of human activity. Houses are often situated close to the water and the nearby shore is
223 used to store boats, vehicles, and equipment. It also serves as a public walking trail and children’s play
224 area. It is plausible that children may splash and wade into the edge of the water, though swimming or
225 full submersion would be rare. Community shorelines are also common areas for rod fishing, which
226 could include shallow wading and handling of wet fish and fishing equipment. Shoreline recreation was
227 classified with a conservative, low-exposure contact rate and estimated event duration of two hours
228 resulting in an accidental ingestion of 22.8 mL per event (Dorevitch et al., 2011; McBride et al., 2013).

229

230 *Small craft boating:* The use of small watercraft near the community and wastewater marine receiving
231 environments is common in all case study locations. Most popular are small, open-top boats fitted with
232 outboard motors. Larger boats as well as kayaks are also seen. Accidental ingestion may occur through
233 fishing, spray created by motors or paddles, wading into the water from shore to launch the boat, or an
234 occasional capsized. An ingestion rate of 34.8 mL per event was assumed based on the conservative,
235 mid-exposure contact rate classification and estimated event duration of two hours (Dorevitch et al.,
236 2011; McBride et al., 2013).

237

238 *Netfishing:* Similar in many ways to the small craft boating scenario, netfishing was also designated a
239 mid-exposure contact rate (Dorevitch et al., 2011; McBride et al., 2013). A corrective factor of five
240 times the average rate was applied, however, leading to an accidental ingestion per exposure event of
241 58.0 mL. Reasoning for the corrective exposure factor is that netfishing entails reaching over the edge

242 of the boat and into the water to set or retrieve equipment such as large nets, ropes, and buoys.

243 Furthermore, the nets remain suspended within the marine water for several hours or days, increasing

244 the potential for contamination. Our model assumed recreational, as opposed to commercial, netfishing

245 and therefore no use of specialized protective clothing or decontamination procedures.

246

247 *Shellfish harvesting:* The shellfish scenarios are applicable only to Iqaluit and Pangnirtung, and only

248 during low tide conditions, when several kilometres of fine grained sea bed are exposed. During this

249 time, people walk on the tidal flats and dig shellfish (mostly clams) from the sea bed using their hands

250 or a small trowel. Evidence has shown that fecal coliforms can become concentrated in mud and sand,

251 with the bottom sediment acting as a reservoir, and increase the risk of enteric illness (Ford, 2005;

252 Heaney et al., 2012). The accidental water ingestion rate for shellfish harvesting is 50.0 mL per day

253 (Fuhrimann et al., 2017; WHO, 2006).

254

255 *Shellfish consumption:* Exposure via consumption of contaminated shellfish was evaluated

256 independently of accidental water ingestion depicted during the harvesting scenario. Pathogens can

257 become concentrated within the digestive tissue of shellfish that obtain their nutrients by filtering large

258 quantities of seawater (Bitton, 2005; Ford, 2005). The infectious agents are then potentially

259 transmissible to humans who consume the shellfish raw or partially cooked. Most organisms that lead

260 to infectious illness can be killed or inactivated through thorough cooking (Butt et al., 2004). The

261 community data did, however, indicate a preference for raw or lightly cooked shellfish among some

262 residents. A reduction factor of 0.5 was assumed and applied to the concentration within the shellfish

263 tissue to account for the range of preparation methods. Another longstanding custom within Inuit

264 communities is the sharing of harvested food, referred to as country food, with family and community

265 members (Collings et al., 1998). To reflect this practice, it was assumed that each harvester shared

collected shellfish with three other people. Thus, the exposure group size parameter used in the shellfish harvesting scenario was multiplied by four. The shellfish consumption value per exposure event of 75 grams was based on a standard seafood portion per serving with consideration given to North American Indigenous populations (Health Canada, 2007; Moya, 2004).

Wetland travel: This scenario is only applicable to Sanikiluaq and Naujaat; the two case study locations that incorporate tundra wetlands into the wastewater treatment system. Wetland travel includes traversing the area by foot, all-terrain vehicle, or snowmobile (during the spring when there is still snow within the wetland). Although it is well-known within communities that the stabilization pond is a hazard, it may not be apparent that the wetland is also part of the wastewater treatment train as there is typically little or no signage or fencing. People may enter or pass thru the wetland while small game hunting, berry picking, or collecting geese eggs. The accidental ingestion rate for wetland travel is 50.0 mL per day (Fuhrmann et al., 2017; WHO, 2006).

Table 2 Summary of human activity parameters per case study location, receiving environment conditions, and exposure pathway included in the quantitative microbial risk assessment (QMRA) model to estimate acute gastrointestinal illness (AGI) attributable to wastewater treatment systems in Arctic Canada.

Case study location	Iqaluit		Pangnirtung		Pond Inlet		Sanikiluaq		Naujaat	
Receiving environment conditions	High tide	Low tide	High tide	Low Tide	High tide	Low tide	Spring	Summer	Spring	Summer
Exposure pathway										
Parameter (unit)										
Shoreline recreation										
Distance (metres)	1000	1000	1000	1000	500	500	1500	1500	1550	1550
Frequency (per year)	105	105	105	105	10	10	55	65	25	40
Exposure group (persons)	100	100	50	50	50	50	50	50	50	50
Ingestion (millilitres)	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8

Small craft boating										
<i>Distance (metres)</i>	1000	3000	1000	2000	250	250	1500	1500	1550	1550
<i>Frequency (per year)</i>	105	105	105	105	10	10	40	65	25	50
<i>Exposure group (persons)</i>	100	100	50	50	50	50	50	50	40	50
<i>Ingestion (millilitres)</i>	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Netfishing										
<i>Distance (metres)</i>	1500	3000	2000	2000	1000	1000	1500	1500	1550	1550
<i>Frequency (per year)</i>	85	85	85	85	10	10	35	50	35	50
<i>Exposure group (persons)</i>	100	100	50	50	50	50	50	50	50	50
<i>Ingestion (millilitres)</i>	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Shellfish harvesting										
<i>Distance (metres)</i>	-	2000	-	1000	-	-	-	-	-	-
<i>Frequency (per year)</i>	-	40	-	40	-	-	-	-	-	-
<i>Exposure group (persons)</i>	-	100	-	50	-	-	-	-	-	-
<i>Ingestion (millilitres)</i>	-	50.0	-	50.0	-	-	-	-	-	-
Shellfish consumption										
<i>Distance (metres)</i>	-	2000	-	1000	-	-	-	-	-	-
<i>Frequency (per year)</i>	-	40	-	40	-	-	-	-	-	-
<i>Exposure group (persons)</i>	-	400	-	200	-	-	-	-	-	-
<i>Ingestion (grams)</i>	-	75.0	-	75.0	-	-	-	-	-	-
Wetland travel										
<i>Distance (metres)</i>	-	-	-	-	-	-	500	500	250	250
<i>Frequency (per year)</i>	-	-	-	-	-	-	50	50	35	45
<i>Exposure group (persons)</i>	-	-	-	-	-	-	50	50	50	50
<i>Ingestion (millilitres)</i>	-	-	-	-	-	-	50.0	50.0	50.0	50.0

Table cells denoted with “-” indicate that the exposure pathway is not applicable to that case study location and/or set of receiving environment conditions.

The discharge method and timing at each wastewater treatment site are important considerations in defining the human activity parameters of the model as these operational procedures impact the frequency of potential exposure events. The mechanical plants in Iqaluit and Pangnirtung discharge effluent into the receiving environment continuously, year-round. In Sanikluaq and Naujaat, wastewater is contained frozen in stabilization ponds throughout the winter until the spring thaw

293 begins. Then, during the 12 to 15 weeks where temperatures remain above freezing, wastewater
294 effluent of varying volume and microbial concentration seeps intermittently into the adjacent wetland
295 and marine waters; this creates a window of time when human exposures may occur. In Pond Inlet,
296 wastewater is also treated using a stabilization pond, which thaws in the spring and freezes in the early
297 fall. It differs from Sanikiluaq and Nauyasat, however, in that the pond has been partially engineered to
298 prevent seepage. The wastewater is contained within the cell throughout and summer and then
299 manually decanted into the marine receiving environment using a pump over a two to three week
300 period just prior to winter freeze-up. Based on the community data regarding awareness of hazards, it
301 was assumed that there is no human contact with wastewater directly in the stabilization ponds.
302 Therefore, the only time period that exposures can occur in Pond Inlet is during the short period when
303 this controlled decanting is taking place.

304

305 Another important consideration when determining parameters is the extended periods of daylight –
306 nearly 24-hour in some locations – in the Arctic during the summer months. This is a lively season in
307 Arctic communities during which people spend a lot of time outdoors engaged in recreational and food
308 harvesting activities. This, in turn, creates potential for high exposure event frequencies and large
309 exposed groups. The total population of each community also invariably factors into the assumed
310 exposed population group.

311

312 *2.4.3 Pathogen concentration modelling within receiving environment*

313 An indirect exposure assessment method was used to estimate pathogen concentrations at human
314 exposure points within the effluent receiving environment. A dataset of indicator *E. coli* concentrations
315 in effluent-impacted wetlands and marine waters that had been collected as part of a previous research
316 program was sourced and repurposed (Greenwood, 2016; Hayward et al., 2018; Huang et al., 2017;

317 Neudorf et al., 2017; Ragush et al., 2015). The sampling method involved collecting water samples
318 from treatment system outfalls and at several points within the receiving environments. In communities
319 discharging directly to marine waters (Iqaluit, Pangnirtung, and Pond Inlet), sampling occurred during
320 both high and low tidal conditions, when safely possible, as water exchange within the receiving
321 environment greatly influences contaminant concentration (Gunnarsdóttir et al., 2013). When possible,
322 a dye tracer was used to provide a visual indication of wastewater discharge plumes within marine
323 water environments and sampling sites were chosen in locations where the dye concentrations were
324 highest, as well as at the visual boundaries of the plumes. In wetland receiving environments
325 (Sanikiluaq and Naujaat), samples were collected at various points along the predominant stream of
326 discharged effluent. Sampling cycles were conducted during spring freshet and late summer as
327 conditions in wetland receiving environments are highly variable over the treatment season (Hayward
328 et al., 2014; Yates et al., 2012). To analyze for indicator *E. coli* in the collected wastewater samples
329 from Iqaluit, Pangnirtung, and Pond Inlet, the Colilert-18 method was followed using the Quanti-
330 Tray/2000 system, in accordance with manufacturer's instructions (IDEXX Laboratories Inc., 2013).
331 The water samples from Naujaat and Sanikiluaq were analyzed according to standard methods at the
332 commercial laboratory Maxxam Analytics in Montréal, Quebec, Canada (APHA, 2012). Neudorf et al.
333 (2017), Greenwood (2016), and Hayward et al. (2018) provide full descriptions of the wastewater
334 sampling methods and the indicator *E. coli* analysis. Concentrations were provided as the most
335 probable number of *E. coli* in 100 mL (MPN/100 mL).

336

337 Given that most of the human interactions with the receiving environment occur beyond the distance
338 ranges that were sampled in the original dataset, it was necessary to infer representative concentration
339 values at the theorized exposure points. To do so, a first-order kinetic model was applied to estimate
340 reductions in microorganism concentrations at varying distances from the release point. This type of

341 model is widely used to characterize microbial decay or inactivation within environmental systems
342 (Haas et al., 2014; Stetler et al., 1992). In fact, the use of such hydrodynamic modelling of
343 contamination events in combination with QMRA is steadily gaining merit over traditional water
344 quality monitoring of recreational waters in many public health jurisdictions (Ashbolt et al., 2010;
345 Ferguson et al., 2007; McBride et al., 2012; Sokolova et al., 2015; WHO, 2016). First, the natural
346 logarithms of observed *E. coli* concentrations in the receiving environments at each treatment site were
347 plotted and linearly regressed against distance from the effluent release points. From this, first order
348 concentration reduction constants (m^{-1}) were derived from the slope of the line for each of the case
349 study locations under varying conditions.

350

351 Cut-points were set at distances where it appeared that concentrations detected had reached background
352 levels in the receiving waters and were not directly related to effluent releases. Background levels were
353 set at <10 MPN/100 mL based on concentration measurements taken at non-effluent impacted
354 reference sites. In instances where multiple samples had been collected at the same distance, the
355 highest concentration was chosen. For censored data (greater or less than method detection limit), we
356 used the detection limit (minimum detection limit was 1 MPN/100 mL) as the measured value.

357 Graphing and statistical analyses were conducted using SigmaPlot (2014). A summary table of the
358 modelling coefficients used for predicting *E. coli* concentration in effluent-impacted receiving
359 environments is available in the supplementary material. The calculated reduction constants (k) from
360 the regressions were then used in a first-order model (Equation 1) to predict *E. coli* concentrations at
361 points of human exposure (C_d) as a function of initial concentrations at effluent release points (C_0) and
362 distance (d), under similar conditions. The model constants represented varying levels of concentration
363 reduction due to dilution, inactivation, and sedimentation associated with the different receiving
364 environments and tidal conditions.

365

365 $C_d = C_0 * e^{-k(d)}$ [1]

366

367 Concentration of *E. coli* within receiving environments was the only available indicator organism
368 dataset. It was assumed that, in the absence of other indicators, the inactivation or dilution of *E. coli*
369 within these conditions can be used to conservatively predict the reduction of specific pathogens
370 (Nevers and Boehm, 2011; Schoen and Ashbolt, 2010). Published ratios were used to infer levels of
371 other enteric pathogens from the indicator *E. coli* results (Table 3). When a ratio from wastewater was
372 not available, information sourced from surface water or drinking water was used. An inference ratio of
373 indicator *E. coli* to pathogenic *Salmonella* was not available. In lieu, the ratio between non-pathogenic
374 and pathogenic strains of *Salmonella* was used in the model (Fuhrimann et al., 2016; Hynds et al.,
375 2014; Shere et al., 2002; Soller et al., 2010).

376

377 **Table 3** Referenced indicator *E. coli*-to-pathogen inference ratios (*E. coli: Path*) for use in the
378 quantitative microbial risk assessment (QMRA) model estimating acute gastrointestinal illness
379 (AGI) attributable to wastewater treatment systems in Arctic Canada.

Pathogen	Ratio (<i>E. coli: Path</i>)	References
Pathogenic <i>E. coli</i>	1 : 0.08	Haas et al. (1999); Howard et al. (2006)
<i>Salmonella</i> spp.	1 : 0.01	Fuhrimann et al. (2016); Hynds et al. (2014); Shere et al. (2002); Soller et al. (2010)
<i>Campylobacter</i> spp.	1 : 10 ⁻⁵	WHO (2006)
Rotavirus	1 : 10 ⁻⁵	Fuhrimann et al. (2017); Katukiza et al. (2013)
<i>Giardia</i> spp.	1 : 10 ⁻⁵	Machdar et al. (2013) (<i>general protozoa ratio</i>)
<i>Cryptosporidium</i> spp.	1 : 10 ⁻⁶	Fuhrimann et al. (2017)

380

381 In the shellfish consumption exposure scenario, it was also necessary to estimate the concentration of
382 contaminants within the bivalve tissue based on the indicator *E. coli* concentration in the overlying
383 marine water at the harvest locations. There is great variation in accumulation factors presented within

the literature due to differences in water columns, sewage content, and species between studies. An accumulation factor of 10 was chosen based on a critical review of available data (CEFAS, 2014).

2.5 Dose-Response Models

Dose-response models are mathematical functions that are used to predict the relationship between level of microbial exposure and probability of adverse health outcomes. Two dose-response models, the single-parameter exponential function (Equation 2) or the two-parameter beta-Poisson (Equation 3), have proven widely applicable to most microorganisms and exposure routes (Haas et al., 2014).

$$P(d) = 1 - e^{-kd} \quad [2]$$

When using the exponential function (Equation 2), $P(d)$ represents the probability of infection and d is a single dose at exposure. The base of the natural logarithm (e) and the probability that one organism survives to initiate the health outcome (k) are pathogen infectivity constants.

$$P(d) = 1 - \left[1 + \left(\frac{d}{N_{50}} \right) \cdot \left(2^{1/\alpha} - 1 \right) \right]^{-\alpha} \quad [3]$$

With the beta-Poisson function shown in Equation 3, $P(d)$ represents the probability of infection and d a single dose at exposure, with model slope parameter α and median effective dose N_{50} . The data analyses used to develop the functions originates primarily from clinical trials (Haas et al., 2014). The dose-response model and parameters recommended for most circumstances were used and are presented in Table 4 (CAMRA, 2015). To determine the proportion of infections that result in symptomatic cases, morbidity ratios (i.e. probability of illness conditional upon infection) were then applied (Table 5).

408

409 **Table 4** Dose-response models and parameters for use in the quantitative microbial risk assessment
 410 (QMRA) estimating acute gastrointestinal illness (AGI) attributable to wastewater treatment
 411 systems in Arctic Canada.

Pathogen	Model	Parameters	References
Pathogenic <i>E. coli</i> (EIEC)	Beta-Poisson	$\alpha = 0.16$ $N_{50} = 2.11 \times 10^6$	CAMRA (2015); Dupont et al. (1971)
<i>Salmonella</i> spp.	Beta-Poisson	$\alpha = 0.389$ $N_{50} = 1.68 \times 10^4$	CAMRA (2015); McCullough and Eisele (1951)
<i>Campylobacter</i> spp.	Beta-Poisson	$\alpha = 0.14$ $N_{50} = 890.38$	Black et al. (1988); CAMRA (2015)
Rotavirus	Beta-Poisson	$\alpha = 0.253$ $N_{50} = 6.17$	CAMRA (2015); Ward (1986)
<i>Giardia</i> spp.	Exponential	$k = 0.020$	CAMRA (2015); Rendtorff (1954)
<i>Cryptosporidium</i> spp.	Exponential	$k = 0.057$	CAMRA (2015); Messner et al. (2001)

412

413 **Table 5** Morbidity ratios estimating probability of illness condition upon infection for selected
 414 pathogens ($P_{\text{ill} | \text{inf}}$) for use in the quantitative microbial risk assessment (QMRA) of acute
 415 gastrointestinal illness (AGI) attributable to wastewater treatment systems in Arctic Canada.

Pathogen	Probability ($P_{\text{ill} \text{inf}}$)	References
Pathogenic <i>E. coli</i>	0.35	Fuhrmann et al. (2017); Machdar et al. (2013); Westrell (2004)
<i>Salmonella</i> spp.	0.80	Westrell (2004); WHO (2006)
<i>Campylobacter</i> spp.	0.30	Fuhrmann et al. (2017); Machdar et al. (2013); Westrell (2004)
Rotavirus	0.50	Barker et al. 2014; Westrell (2004); WHO (2006)
<i>Giardia</i> spp.	0.90	Schoen and Ashbolt (2010)
<i>Cryptosporidium</i> spp.	0.79	Fuhrmann et al. (2017)

416

417 2.6 Risk characterization

418 The health outcome measures included in the model are expected annual cases of AGI, expected annual
 419 incidence of AGI per total population and 1000 persons, and estimated probability of AGI per person
 420 per year for a single exposure event. Although some of these endpoints may not be as common across
 421 global literature as disability-adjusted life years, they were chosen for their direct comparability to the
 422 limited epidemiological studies of AGI in Arctic Canada (Harper et al., 2015), while still being

423 relatable to disease burden measures used in some QMRA studies of wastewater exposures in other
424 regions (Fuhrimann et al., 2017, 2016).

425

426 The risk characterization equations used to estimate these outcomes are based on adapted versions from
427 Haas et al. (2014), Howard et al. (2006), WHO (2016), Sales-Ortells and Medema (2014), and
428 Fuhrimann et al. (2017, 2016). The model was developed using Microsoft Excel (2010) and is available
429 in the supplementary material.

430

431 Using the data described in the methods section, individual probabilities of infection and illness were
432 calculated with equations 4 thru 6:

433

$$434 \quad D_{E. coli} = C * V \quad [4]$$

435

436 $D_{E. coli}$, the dose of *E. coli* at exposure (MPN) was calculated by multiplying, C , the concentration of *E.*
437 *coli* at the exposure distance (MPN/mL) by V , the volume of water or tissue (mL or g) ingested per
438 exposure event.

439

$$440 \quad D_{path} = D_{E. coli} * (E. coli: Path) \quad [5]$$

441

442 $D_{E. coli}$ was then multiplied by $E. coli: Path$, an indicator *E. coli*-to-pathogen inference ratio from Table
443 3, to produce the corresponding pathogen-specific dose at exposure, D_{path} (MPN). The obtained doses
444 of each pathogen, D_{path} , were then entered into corresponding dose-response models (Equations 3 and
445 4), described in section 2.5, with parameters from Table 4 to obtain individual probability of infection

446 per pathogen per single exposure event, $P_{inf, path}$. The morbidity ratios from Table 5, $P_{ill | inf}$, were then
 447 applied to determine the probability of illness per pathogen, per exposure pathway, $P_{ill, path}$ (Equation 6).

448

$$449 \quad P_{ill, path} = P_{inf, path} * P_{ill | inf} \quad [6]$$

450

451 Within the model, it was assumed that each exposure event was independent, that people can become
 452 ill from more than one hazard at the same time, and there was no acquired immunity after a previous
 453 infection (Haas et al., 2014). It was also assumed that a person could belong to any, or all, of the
 454 exposed groups within the community that they reside (e.g. a resident of Iqaluit could be a shellfish
 455 harvester as well as participate in netfishing). These assumptions allowed for summations to be
 456 performed (Equations 7, 8, 9, and 10), based on the probability of illness, ($P_{ill, path}$).

457

$$P_{ill, path, total} = \sum P_{ill, path} \quad [7]$$

458 The total probability of illness caused by any pathogen per person per single exposure event
 459 ($P_{ill, path, total}$) was obtained by summing the probabilities of illness ($P_{ill, path}$) of every pathogen for a given
 460 exposure pathway.

461

$$Cases_{path} = \sum_{i=1}^{(Freq)(ExpGroup)} P_{ill, path} \quad [8]$$

462

463 $Cases_{path}$ represents the annual number of expected AGI cases per pathogen per exposure scenario,
 464 incorporating frequency of exposure events per year, $Freq$, and exposure group per single event,
 465 $ExpGroup$, from the human activity data (Table 2).

466

$$Cases_{all\ path} = \sum Cases_{path\ i...j} \quad [9]$$

467

468 Summing all of the individual pathogen-specific cases, $Cases_{path}$, provided the annual number of
 469 expected AGI cases per exposure scenario, $Cases_{all\ path}$.

470

$$Cases_{all\ path, location} = \sum Cases_{all\ path} \quad [10]$$

471 Finally, summing all of the cases attributable to each exposure scenario, $Cases_{all\ path}$, provided the total
 472 expected annual AGI cases attributable to wastewater exposure, per case study location, $Cases_{all}$
 473 $path, location$.

474

475 Based on these results, annual individual incidence rates per community population and per 1000
 476 persons were calculated (Equations 11 and 12).

477

$$Inc_{location} = \frac{Cases_{all\ path, location}}{Pop_{location}} \quad [11]$$

478

479 Annual individual incidence rate of AGI per location is denoted by $Inc_{location}$. Location population sizes,
 480 $Pop_{location}$, were presented in Table 1.

481

$$Inc_{location, 1000} = Inc_{location} * 1000 \quad [12]$$

482

483 In turn, $Inc_{location}$, was multiplied by 1000 to provide comparable annual rates of individual incidence
 484 rates per 1000 persons, per location ($Inc_{location, 1000}$). Secondary transmissions and sensitives
 485 subpopulations were not included in the model.

487 **3. Results and discussion**

488 Model results should be evaluated in the context of a screening-level point estimate assessment based
 489 on worst case conditions aiming to provide the first assessments of AGI attributable specifically to
 490 wastewater exposures in Arctic Canada. Given the uncertainty and variability inherent in the data, the
 491 relative risk between scenarios is of greater importance than absolute risk values. In exploring relative
 492 risk, elements of the system that warrant further assessment are discussed and risk management ideas
 493 are presented.

495 **3.1 Expected total annual cases of AGI**

496 The expected annual AGI cases attributable to wastewater exposures, by case study location, are
 497 presented in Table 6. The highest estimate of AGI cases per location occurs in Pangnirtung at 7416.16
 498 episodes of AGI per year. Naujaat and Iqaluit follow with 1251.44 and 994.45 respective annual
 499 estimated cases. Considerably fewer cases are estimated in Pond Inlet and Sanikiluaq (36.73 and 3.65
 500 episodes per year, respectively).

502 **Table 6** Expected annual cases of acute gastrointestinal illness (AGI) attributable to wastewater
 503 treatment systems in five arctic case study locations, per receiving environment conditions and
 504 exposure pathway, as estimated using a quantitative microbial risk assessment (QMRA).

Case study location	Iqaluit		Pangnirtung		Pond Inlet		Sanikiluaq		Naujaat	
Receiving environment	High tide	Low tide	High tide	Low tide	High tide	Low tide	Spring	Summer	Spring	Summer

conditions

Exposure pathway

Shore recreation	2.45×10^{-11}	796.48	$\leq 1.00 \times 10^{-16}$	507.81	3.03	$\leq 1.00 \times 10^{-16}$	0.0003	2.63×10^{-9}	6.42	8.01×10^{-6}
Small craft boating	3.85×10^{-11}	0.10	$\leq 1.00 \times 10^{-16}$	711.09	33.59	$\leq 1.00 \times 10^{-16}$	0.0003	4.01×10^{-9}	9.73	1.22×10^{-5}
Netfishing	$\leq 1.00 \times 10^{-16}$	0.13	$\leq 1.00 \times 10^{-16}$	841.09	0.11	$\leq 1.00 \times 10^{-16}$	0.0005	5.14×10^{-9}	22.43	2.55×10^{-5}
Shellfish harvesting	-	6.54	-	355.62	-	-	-	-	-	-
Shellfish consumption	-	191.20	-	5000.55	-	-	-	-	-	-
Wetland travel	-	-	-	-	-	-	3.64	0.0063	1050.42	162.44
Total	994.45	7416.16	36.73	3.65	1251.44					

Table cells denoted with “-” indicate that the exposure pathway is not applicable to that case study location.

In both of the locations operating mechanical wastewater treatment plants, Iqaluit and Pangnirtung, all of the estimated cases occur during low tide conditions. This finding suggests that the continuous discharge of effluent during this period, when the sea bed is exposed and only minimal dilution can occur, creates a period of potentially elevated human health risk. Studies of the marine environmental impact associated with this effluent discharge practice also detected negative effects (Greenwood, 2016; Krumhansel et al., 2015). In Pond Inlet, however, all 36.73 of the estimated annual cases in that location occur during higher tide conditions. This low case total is partially explained by the short, scheduled window during which effluent is discharged from the WSP (two to three weeks in later summer) and because there are fewer exposure pathways in Pond Inlet. The explanation for the cases occurring at high tide – contrary to low tide as seen in Iqaluit and Pangnirtung – may be due to differences in system siting and receiving environments. At the Pond Inlet site, the treatment system is located approximately two kilometres away from the central area of the community, where most human

519 activity occurs. Also effluent is discharged into open marine waters, where the sea bed is not exposed,
520 and effluent quickly mixes with seawater (Greenwood, 2016; Ragush et al., 2015). In Iqaluit and
521 Pangnirtung, the treatment plants are directly within the main settlements and effluent is discharged
522 into more shallow, enclosed waters between tapering shores (Greenwood, 2016; Neudorf et al., 2017).
523 At the Pond Inlet site it was observed, however, that high winds combined with a strong ambient
524 current cause the discharged effluent plume to attach to the shoreline and drift toward the central area
525 of the community (Greenwood, 2016; Krumhansl et al., 2015). This phenomenon is reflected in the
526 model output with the resulting 36.73 estimated cases of AGI.

527

528 Of the two locations relying on WSP treatment systems with an adjoining wetland, only the estimated
529 1251.44 annual cases of AGI in Naujaat suggest potential cause for immediate concern. The majority
530 of the cases (87%) in Naujaat are estimated to occur during spring. At this time, the WSP is melting
531 quickly and a high volume of minimally-treated effluent is flowing rapidly through the wetland and
532 into the ocean (Hayward et al., 2018). Key informants from the community also noted that this period
533 coincides with a time of increased human activity near the treatment wetland. People travelling by all-
534 terrain vehicles or snowmobile reroute inland as travel over the melting sea ice near shore is no longer
535 safe. In combination, these results and factors suggest that low frequency, short term events may dictate
536 conditions of higher risk in pond and wetland systems. These events include foreseeable occurrences
537 such as scheduled decants or annual spring freshets as well as less predictable episodes such as high-
538 precipitation levels or failed treatment due to unmaintained or undersized WSPs. Even if risks appear
539 low the majority of the time, understanding these drivers may help effectively control exposures –
540 through public health advisories or changes to operational procedures, for instance – when those
541 conditions periodically occur.

542

543 Among the suite of pathogens modelled, rotavirus (46%) and *Salmonella* spp. (32%) contribute the
544 highest percentages of cases to the combined total AGI burden for all five locations. The remaining
545 percent allocations are *Giardia* spp. at 10%, pathogenic *E. coli* at 6%, and *Campylobacter* spp. and
546 *Cryptosporidium* spp. at 3% each (full results of AGI cases by pathogen, per exposure pathway not
547 shown, but available with the risk model in supplementary material). Attributing AGI cases to specific
548 pathogens based on these QMRA results, however, must be done with caution. The model used to
549 predict pathogen concentrations within the receiving environment is based solely on *E. coli* as an
550 indicator organism and then uses inference ratios. Minimal account was given to the difference in
551 environmental persistence between pathogens. *Salmonella* spp. along with *Campylobacter* spp. and
552 *Giardia* spp. are believed to die-off in seawater exposed to sunlight in less than 24 hours, which may
553 reduce the number of infections; however, microbial inactivation is highly variable (Bitton, 2005;
554 Johnson et al., 1997; Schoen and Ashbolt, 2010). Viruses and *Cryptosporidium* spp. do have potential
555 to persist in seawater for several days (Johnson et al., 1997; Noble et al., 2004; Schoen and Ashbolt,
556 2010), which may prove of importance as high rates of rotavirus infection in the Arctic have been
557 documented (Desai et al., 2017; Goldfarb et al., 2013; Gurwith et al., 1983).

558

559 **3.2 Expected annual incidence rates of AGI**

560 The expected annual incidence rates per person, corresponding to the total population, and per 1000
561 persons in each case study location are shown in Table 7. For comparison, the incidence rate results
562 table also includes an estimate of all food- and waterborne AGI in Arctic communities that is based
563 upon a cross-sectional retrospective epidemiological survey (Harper et al., 2015).

564

565 **Table 7** Expected annual incidence rates of acute gastrointestinal illness (AGI) attributable to
566 wastewater treatment systems per person, corresponding to total population, and per 1000

567 persons as estimated using a quantitative microbial risk assessment (QMRA) in five arctic case
 568 study locations, with comparison to all food- and waterborne AGI arctic estimate (Harper et al.,
 569 2015).

Case study location	Iqaluit	Pangnirtung	Pond Inlet	Sanikiluaq	Naujaat	All food- and waterborne AGI Arctic estimate (Harper et al., 2015)
Population	7740	1481	1671	882	1082	Not applicable
Incidence rate per person	0.13	5.01	0.02	0.004	1.16	2.9-3.9
Incidence rate per 1000 persons	128.48	5007.53	21.98	4.13	1156.59	2900-3900

570

571 In four of the five case study locations, estimates of AGI incidence attributed to wastewater exposure
 572 are below the minimum range of Harper et al.'s (2015) estimate of 2.9-3.9 cases per person per year for
 573 all food- and waterborne exposures. The study by Harper et al. (2015) included an assortment of
 574 potential risk factors in Arctic communities such as diet, drinking water source, exposure to pets, and
 575 in-home conditions. It follows then that the annual incidence rates per person from Iqaluit (0.13), Pond
 576 Inlet (0.02), and Sanikiluaq (0.004) seem reasonable estimates of the proportion of AGI attributable to
 577 wastewater exposure, with Naujaat (1.16) being moderately high but plausible. The per person
 578 incidence rate estimate for Pangnirtung (5.01) is very high. In comparison to some other environments
 579 where populations may be indirectly exposed to wastewater pathogens, the Pangnirtung AGI incidence
 580 rate per person is in between that of urban farmers in Hanoi, Vietnam (1.98) and Kampala, Uganda
 581 (10.92); both locations where agricultural fields are flooded with partially treated effluent (Fuhrmann
 582 et al., 2017, 2016). On one hand, it is prudent to recall that the result is a modelled projection of
 583 maximum exposure in an arctic community, including a period of low tide conditions, with effluent
 584 being discharged undiluted, and individuals harvesting and consuming shellfish in near proximity. On

585 the other hand, the model is demonstrating that, in the worst case scenario, potential does exist for an
586 outbreak of waterborne disease.

587
588 Comparison of the two pond-and-wetland sites, Naujaat and Sanikiluaq, highlights the variation of
589 potential human health risks even amongst seemingly alike passive systems. Both communities are
590 similar in terms of total population, discharge method, annual volume of wastewater, and the types of
591 exposure pathways, as presented in Tables 1 and 2. However, the annual incidence per person rate in
592 Naujaat (1.16) is more than two orders of magnitude greater than that in Sanikiluaq (0.004). One reason
593 for this difference is the design and condition of the WSPs and their effectiveness in reducing pathogen
594 loads within effluent prior to seepage into the wetland (Hayward et al., 2018). In Naujaat, for instance,
595 the initial indicator *E. coli* concentration (MPN/100 mL) observed at the pond outlet during spring
596 freshet is 1.73×10^6 , compared to only 6.04×10^4 in Sanikiluaq.

597
598 **3.3 Estimated probability of AGI per single exposure event**

599 This study placed emphasis on soliciting community input and feedback during the development and
600 parameterization of the exposure scenarios. The estimated probabilities of AGI per person per a single
601 exposure event for each scenario are presented in Table 8. The probabilities correspond to AGI
602 attributable to any of the modelled pathogens. Many of the risk probabilities are very low ($\leq 2.50 \times 10^{-6}$)
603 including all exposures occurring during high tide conditions in Iqaluit and Pangirtung, all exposures
604 occurring during low tide conditions in Pond Inlet, all exposures occurring during late summer
605 conditions in Naujaat with the exception of wetland travel (0.0722), and all exposures entirely in
606 Sanikiluaq with the exception of wetland travel during spring (0.002).

607
608 **Table 8** Estimated probability of acute gastrointestinal illness (AGI), per person per single exposure

609 event, attributable to wastewater treatment systems in five arctic case study locations as
 610 calculated using a quantitative microbial risk assessment (QMRA) model.

Case study location	Iqaluit		Pangnirtung		Pond Inlet		Sanikiluaq		Naujaat	
Receiving environment conditions	High tide	Low tide	High tide	Low tide	High tide	Low tide	Spring	Summer	Spring	Summer
Exposure pathway										
Shore recreation	2.33×10^{-15}	0.076	$\leq 1.00 \times 10^{-16}$	0.097	0.006	$\leq 1.00 \times 10^{-16}$	1.05×10^{-7}	8.08×10^{-13}	0.005	4.0×10^{-9}
Small craft boating	3.66×10^{-15}	9.40×10^{-6}	$\leq 1.00 \times 10^{-16}$	0.135	0.067	$\leq 1.00 \times 10^{-16}$	1.61×10^{-7}	1.23×10^{-12}	0.008	6.11×10^{-9}
Netfishing	$\leq 1.00 \times 10^{-16}$	1.57×10^{-5}	$\leq 1.00 \times 10^{-16}$	0.198	0.0002	$\leq 1.00 \times 10^{-16}$	2.68×10^{-7}	2.06×10^{-12}	0.013	1.02×10^{-8}
Shellfish harvesting	$\leq 1.00 \times 10^{-16}$	0.002	$\leq 1.00 \times 10^{-16}$	0.178	-	-	-	-	-	-
Shellfish consumption	$\leq 1.00 \times 10^{-16}$	0.012	$\leq 1.00 \times 10^{-16}$	0.625	-	-	-	-	-	-
Wetland travel	-	-	-	-	-	-	0.002	2.50×10^{-6}	0.600	0.072

611 Table cells denoted with “-” indicate that the exposure pathway is not applicable to that case study location
 612 and/or set of receiving environment conditions.

613
 614 High risk probabilities per single exposure are estimated for shellfishing harvesting (0.178) and
 615 consumption (0.625) in Pangnirtung. Lower estimates are seen for these pathways in Iqaluit (harvesting
 616 at 0.002 and consumption at 0.012) where pathogen concentrations in shellfish harvesting waters were
 617 greatly reduced in comparison to Pangnirtung. Studies of microbial contamination within shellfish
 618 tissue in the Arctic, for comparative purposes, are limited. Those that have been undertaken found
 619 shellfish to be of generally good microbiological quality; however *Giardia* spp. and *Cryptosporidium*
 620 spp. were present in some samples (Lévesque et al., 2010; Manore et al., 2017). In agreeance with

621 recommendations from these studies, the range of estimates from this QMRA model suggests a need
622 for continued research on shellfish in Arctic communities. As a more immediate application, these
623 results may be useful in informing economical risk management strategies in Nunavut. In the remote,
624 resource-limited region, risk alleviation via infrastructure upgrades is extremely costly and difficult
625 (Suk et al., 2004). In Pond Inlet for example, wastewater operations staff had previously established a
626 precautionary risk mitigation practice of delaying the annual decant of the WSP into the marine
627 receiving environment until after the migratory passage of Arctic char (*Salvelinus alpinus*), a fish of
628 great local importance. Given the estimated reduction in risk between low and high tide cycles in
629 Iqaluit and Pangnirtung, a similar control measure could be employed. Adjusting the effluent release
630 schedules at the mechanical treatment plants to discharge primarily during high and outgoing tide
631 cycles, when the greatest water exchange is ensuing (Nevers and Boehm, 2011), may be an effective
632 mitigation effort; particularly during periods of maximum tidal range when most shellfish harvesting
633 takes place.

634
635 Broad community involvement during model development allowed for differing perspectives to be
636 incorporated into the research and exhibits how primary environmental risk factors are influenced by
637 social, cultural, and behavioural determinants in Indigenous communities (Barber and Jackson, 2015;
638 Knibbs and Sly, 2014). For example, in some case study locations the more established food harvesters
639 stated that they never travel nor hunt near wastewater treatment areas; implying that these exposure
640 pathways could be dismissed. Younger residents or those with fewer of the resources necessary to
641 reach prime locations beyond the community boundaries (e.g. all-terrain vehicle, money for fuel and
642 supplies), however, mentioned that they had harvested food in close proximity to the wastewater
643 treatment site. In terms of risk management and communication, this type of community-based
644 information is very important to accurately capture within the QMRA model. For example, in Nauyasat,

645 where an unmarked and unfenced wetland that is used as a travel route is also part of the treatment
646 train, the estimated probability of risk per single wetland travel exposure during spring is 0.60.

647

648 **3.4 Limitations**

649 This initial assessment of a complex socioecological system was conducted using a point estimate,
650 “worst-case” scenario model. A point estimate QMRA follows a transparent process making it an
651 effective tool for communicating with multiple stakeholder groups, whom may be unfamiliar with risk
652 assessment concepts (Howard et al., 2006). However, a single number describing risk can lead to a
653 false sense of safety or unnecessary alarm. This QMRA should be considered a first tier, useful for
654 identifying scenarios where a stochastic assessment, including sensitivity analysis of the uncertainty
655 associated with each input, should be conducted.

656

657 The specific exposure pathways modelled and parameter values used may or may not be directly
658 transferable to sites outside of the five case study locations as food harvesting practices and
659 recreational activities vary by community. Notwithstanding, this information will serve as a starting
660 point for applying the model in other arctic and northern regions. The treatment type and receiving
661 environment characterizations do broadly categorize most wastewater sites in Arctic Canada.
662 Furthermore, as treatment systems are revamped or operational procedures are adjusted, the model can
663 be used to estimate the change in risk attributable to the improvements.

664

665 Indicator *E. coli* concentrations were the only available indexer of pathogen occurrence within the
666 effluent receiving environments. Reliance on one type of indicator organism inevitably requires many
667 assumptions and introduces additional uncertainty, but many initial QMRAs must be conducted using
668 fecal indicator bacteria due to lack of data (Haas et al., 2014). Fecal coliform analysis, or as was done

in this study, indicator *E. coli* analysis may arguably be the best practical indicator of pathogenic organisms in Arctic communities, given the relative ease and low-cost of analysis. The suite of pathogens included in the model were chosen as a representative group of the major microbial hazards present in wastewater effluent, with consideration given to infections in arctic populations. AGI is also attributable to several other waterborne pathogens not included in the suite of six microbial infectious agents. Additional types of waterborne infections, such as eye and skin infections, were not included. Similarly, the occupational risk to wastewater operators was not targeted, as the aim was to assess community risk in the effluent receiving environment.

4. Conclusion

A point estimate QMRA was used to provide the first estimates of AGI attributable to wastewater treatment systems in the arctic territory of Nunavut, Canada. A number of exposure pathways and microbial pathogens were assessed using worst case scenario models based on the types of human activity occurring near effluent receiving environments. High incidence rates are estimated in scenarios where mechanical treatment systems are releasing effluent directly into marine waters at low tide conditions. Moderate risks are also seen in some stabilization pond and treatment wetland sites during seasonal events such as spring freshet. Based on these findings, human exposure to partially treated wastewater effluent may be contributing to high AGI rates in some communities. These results can be used to provide evidence to support public health initiatives as well as decisions regarding water and sanitation infrastructure investment in the region. Follow-up research will involve more complex modelling of the higher risk pathways that have been identified as well as risk mitigation options.

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704

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710

711 **Supplementary Material**

712 Appendix A. Summary table of Modelling Coefficients for Predicting Indicator *E. coli* Concentrations
713 in Effluent-Impacted Receiving Environments (Microsoft Word)

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715 Appendix B. Full QMRA Model (Microsoft Excel)

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