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Title

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

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5 Abstract

Most arctic communities use primary wastewater treatment systems that are capable of only low levels 6 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 estimate quantitative microbial risk assessment (OMRA) model was developed to evaluate worst-case 11 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 recreation) and 0.63 (shellfish consumption). A moderate incidence rate of 1.16 episodes of AGI per 16 17 person is estimated in Naujaat, 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 remaining risk probabilities per single exposure are less than 0.01. The AGI incidence rates estimated 20 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.

26

27 Keywords

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

- 30
- 31
- 32

33 1. Introduction

34 Communities in the Arctic employ basic wastewater (sewage) treatment systems, which may be 35 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, 36 37 which make use of natural environmental processes, are effective and well-suited for the small 38 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 39 removal (Hayward et al., 2014; Huang et al., 2017; Ragush et al., 2015; Yates et al., 2012). As a result, 40 41 partially treated effluent potentially containing fecally derived microorganisms is released into 42 wetlands and marine waters near communities (Huang et al., 2017; Krumhansl et al., 2015). The 43 predominantly Indigenous populations in Arctic Canada have strong connections to their immediate 44 physical environment; as such, the natural areas that are being used for passive wastewater treatment 45 may simultaneously serve as recreation or food harvesting locations (Nilsson et al., 2013). Within these 46 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).

49

There are several microbial pathogens of human health concern which may be present in domestic 50 51 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 52 53 concentrations (Leclerc et al., 2002). Within Inuit Nunangat, the distinct Inuit region of Arctic Canada, 54 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 55 56 3.9 annual cases per person; a stark contrast to a national estimate of 0.6 annual cases per person 57 (Harper et al., 2015; Thomas et al., 2013) and higher than average estimates from developing countries 58 (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 59 exacerbate the seriousness and longer term implications of AGI (Hennessy and Bressler, 2016; 60 Yansouni et al., 2016). The degree of enteric illness attributable to wastewater contamination in the 61 62 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; Igbal et al., 2015; McKeown et 63 al., 1999; Messier et al., 2012; Pardhan-Ali et al., 2012a, 2012b; Thivierge et al., 2016). However, 64 65 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; 66 67 Goldfarb et al., 2013; Hastings et al., 2014; Pardhan-Ali et al., 2013). 68

69 The limited knowledge of possible human health impacts attributable to wastewater treatment 70 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 elucidated with full field data sets (Haas et al., 2014). Resource-intensive epidemiological studies of 73 multiple exposure pathways, without clear associations between microbial hazard sources and health 74 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 computationally-demanding and detailed analysis is possible – from point estimate risk 88 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). OMRA has also been used in other contexts where populations

95	may be unknowingly exposed to wastewater effluent through food harvesting or recreational activities
96	(Fuhrimann 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.

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

Six pathogenic agents were included in the assessment: three bacteria (*Escherichia coli*, *Salmonella*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 Naujaat (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, Naujaat, Pangnirtung, Pond Inlet*, and *Sanikiluq*).

159

- 160 Community locations, populations, annual volume of wastewater, treatment system, effluent discharge
- 161 schedule, annual volume of wastewater (m⁻³), effluent *E. coli* concentrations at discharge reported as
- 162 most probable number (MPN) of coliform per 100 ml of water, and receiving environment
- 163 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 (m³/year)	<i>E. coli</i> concentration at initial discharge (MPN/100 mL)	Receiving environment and maximum tidal range (m)
lqaluit 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 × 10⁵	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; Fuhrimann 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 (Fuhrimann 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 used to store boats, vehicles, and equipment. It also serves as a public walking trail and children's play 223 224 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

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

237

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

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

Furthermore, the nets remain suspended within the marine water for several hours or days, increasing the potential for contamination. Our model assumed recreational, as opposed to commercial, netfishing

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

246

Shellfish harvesting: The shellfish scenarios are applicable only to Iqaluit and Pangnirtung, and only
during low tide conditions, when several kilometres of fine grained sea bed are exposed. During this
time, people walk on the tidal flats and dig shellfish (mostly clams) from the sea bed using their hands
or a small trowel. Evidence has shown that fecal coliforms can become concentrated in mud and sand,
with the bottom sediment acting as a reservoir, and increase the risk of enteric illness (Ford, 2005;
Heaney et al., 2012). The accidental water ingestion rate for shellfish harvesting is 50.0 mL per day
(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 residents. A reduction factor of 0.5 was assumed and applied to the concentration within the shellfish 262 263 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

268	event of 75 grams was based on a standard seafood portion per serving with consideration given to
269	North American Indigenous populations (Health Canada, 2007; Moya, 2004).
270	
271	Wetland travel: This scenario is only applicable to Sanikiluaq and Naujaat; the two case study locations
272	that incorporate tundra wetlands into the wastewater treatment system. Wetland travel includes
273	traversing the area by foot, all-terrain vehicle, or snowmobile (during the spring when there is still
274	snow within the wetland). Although it is well-known within communities that the stabilization pond is
275	a hazard, it may not be apparent that the wetland is also part of the wastewater treatment train as there
276	is typically little or no signage or fencing. People may enter or pass thru the wetland while small game
277	hunting, berry picking, or collecting geese eggs. The accidental ingestion rate for wetland travel is 50.0
278	mL per day (Fuhrimann et al., 2017; WHO, 2006).

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

279

266

267

280Table 2Summary of human activity parameters per case study location, receiving environment281conditions, and exposure pathway included in the quantitative microbial risk assessment282(QMRA) model to estimate acute gastrointestinal illness (AGI) attributable to wastewater283treatment systems in Arctic Canada.

Case study location	lqa	luit	Pangn	irtung	Pond	Inlet	Sani	kiluaq	Nau	ujaat
Receiving environment	High	Low	High	Low	High	Low	Spring	Summer	Spring	Summer
conditions	tide	tide	tide	Tide	tide	tide				
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	100	100	50	50	50	50	50	50	50	50
(persons)										
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										
Distance (metres)	1000	3000	1000	2000	250	250	1500	1500	1550	1550
Frequency (per year)	105	105	105	105	10	10	40	65	25	50
Exposure group	100	100	50	50	50	50	50	50	40	50
(persons)										
Ingestion (millilitres)	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Netfishing										
Distance (metres)	1500	3000	2000	2000	1000	1000	1500	1500	1550	1550
Erequency (ner year)	2000	85	85	2000	10	10	25	50	255	50
Exposure group	100	100	50	50	50	50	50	50	50	50
(persons)	100	100	50	50	50	50	30	50	50	30
Ingestion (millilitres)	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Shellfish harvesting										
Distance (metres)	-	2000	-	1000	-	-	-	_	-	-
Erequency (ner year)	-	40	-	40	-	-	_	_	_	_
Exposure group	_	100	_	50	_	_				
(persons)	-	100	-	50	-	_	-	-	-	-
Ingestion (millilitres)	-	50.0	-	50.0	-	-	-	-	-	-
Shellfish consumption										
Distance (metres)	-	2000	-	1000	-	-	-	-	-	-
Frequency (per year)	-	40	-	40	-	-	-	-	-	-
Exposure group	-	400	-	200	-	-	-	-	-	-
(persons)										
Ingestion (grams)	-	75.0	-	75.0	-	-	-	-	-	-
Wetland travel										
Distance (metres)	-	_			_	-	500	500	250	250
Frequency (per year)	-	_			_	-	50	50	35	45
Exposure group	-	_			_	-	50	50	50	50
(persons)							-		-	
Ingestion (millilitres)	-	-			-	-	50.0	50.0	50.0	50.0

²⁸⁴

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

and/or set of receiving environment conditions.

287

288 The discharge method and timing at each wastewater treatment site are important considerations in

289 defining the human activity parameters of the model as these operational procedures impact the

290 frequency of potential exposure events. The mechanical plants in Iqaluit and Pangnirtung discharge

291 effluent into the receiving environment continuously, year-round. In Sanikluaq and Naujaat,

292 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 Sanikiluag and Naujaat, 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

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

311

312 2.4.3 Pathogen concentration modelling within receiving environment

An indirect exposure assessment method was used to estimate pathogen concentrations at human exposure points within the effluent receiving environment. A dataset of indicator *E. coli* concentrations in effluent-impacted wetlands and marine waters that had been collected as part of a previous research 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 discharged effluent. Sampling cycles were conducted during spring freshet and late summer as 326 327 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 Sanikiluag were analyzed according to standard methods at the 332 commercial laboratory Maxam 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

Given that most of the human interactions with the receiving environment occur beyond the distance ranges that were sampled in the original dataset, it was necessary to infer representative concentration values at the theorized exposure points. To do so, a first-order kinetic model was applied to estimate 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 contamination events in combination with QMRA is steadily gaining merit over traditional water 343 quality monitoring of recreational waters in many public health jurisdictions (Ashbolt et al., 2010; 344 345 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 concentration reduction constants (m⁻¹) were derived from the slope of the line for each of the case 348 349 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 set at <10 MPN/100 mL based on concentration measurements taken at non-effluent impacted 353 354 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. Graphing and statistical analyses were conducted using SigmaPlot (2014). A summary table of the 357 358 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 points of human exposure (C_d) as a function of initial concentrations at effluent release points (C_0) and 361 362 distance (d), under similar conditions. The model constants represented varying levels of concentration reduction due to dilution, inactivation, and sedimentation associated with the different receiving 363 364 environments and tidal conditions.

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

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)
Salmonella spp.	1:0.01	Fuhrimann et al. (2016); Hynds et al. (2014); Shere et al.
		(2002); Soller et al. (2010)
Campylobacter spp.	1:10 ⁻⁵	WHO (2006)
Rotavirus	1:10 ⁻⁵	Fuhrimann et al. (2017); Katukiza et al. (2013)
Giardia spp.	1:10 ⁻⁵	Machdar et al. (2013) (general protozoa ratio)
Cryptosporidium spp.	1:10 ⁻⁶	Fuhrimann et al. (2017)

380

In the shellfish consumption exposure scenario, it was also necessary to estimate the concentration of 381

contaminants within the bivalve tissue based on the indicator E. coli concentration in the overlying 382

383 marine water at the harvest locations. There is great variation in accumulation factors presented within

[1]

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).

386

387 2.5 Dose-Response Models

388 Dose-response models are mathematical functions that are used to predict the relationship between

389 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).

392

393
$$P(d) = 1 - e^{-kd}$$
 [2]

394

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.

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

398

400

With the beta-Poisson function shown in Equation 3, P(d) represents the probability of infection and da 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).

409Table 4Dose-response models and parameters for use in the quantitative microbial risk assessment410(QMRA) estimating acute gastrointestinal illness (AGI) attributable to wastewater treatment

411 systems in Arctic Canada.

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

412

415

413 **Table 5** Morbidity ratios estimating probability of illness condition upon infection for selected

414 pathogens (P_{ill | inf}) for use in the quantitative microbial risk assessment (QMRA) of acute

gastrointestinal illness (AGI) attributable to wastewater treatment systems in Arctic Canada.

Pathogen	Probability (P _{ill inf})	References
Pathogenic <i>E. coli</i>	0.35	Fuhrimann et al. (2017); Machdar et al. (2013); Westrell
		(2004)
Salmonella spp.	0.80	Westrell (2004); WHO (2006)
Campylobacter spp.	0.30	Fuhrimann et al. (2017); Machdar et al. (2013); Westrell
		(2004)
Rotavirus	0.50	Barker et al. 2014; Westrell (2004); WHO (2006)
Giardia spp.	0.90	Schoen and Ashbolt (2010)
Cryptosporidium spp.	0.79	Fuhrimann 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	$D_{E.\ coli} = C \ *V $ [4]
435	
436	$D_{E. coli}$, the dose of E. coli at exposure (MPN) was calculated by multiplying, C, the concentration of E.
437	<i>coli</i> at the exposure distance (MPN/mL) by <i>V</i> , the volume of water or tissue (mL or g) ingested per
438	exposure event.
439	
440	$D_{path} = D_{E. \ coli} \ * (E. \ coli: Path) $ [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

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

450

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

457

$$P_{ill,path,total} = \sum P_{ill,path}$$

458 The total probability of illness caused by any pathogen per person per single exposure event

(*P_{ill,path,total}*) was obtained by summing the probabilities of illness (*P_{ill,path}*) of every pathogen for a given
exposure pathway.

461

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

$$Cases_{all\,path} = \sum Cases_{pathi...j}$$
[9]

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

$$Cases_{all\,path,location} = \sum Cases_{all\,path}$$
[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).

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

Annual individual incidence rate of AGI per location is denoted by *Inclocation*. Location population sizes, *Poplocation*, were presented in Table 1.

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

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

486

487 **3.** Results and discussion

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

494

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).

501

502**Table 6**Expected annual cases of acute gastrointestinal illness (AGI) attributable to wastewater503treatment systems in five arctic case study locations, per receiving environment conditions and504exposure pathway, as estimated using a quantitative microbial risk assessment (QMRA).

Case study location	Iqal	uit	Pangn	irtung	Pond	Inlet	San	ikiluaq	Na	ujaat
Receiving environment	High tide	Low tide	High tide	Low tide	High tide	Low tide	Spring	Summer	Spring	Summer

Total 354.45 7410.10 30.75 5.05 1251.44										
Total	994.	45	7416	6.16	36	5.73	3.	65	125	1.44
travel									2	
Wetland	-	-	-	-	-	-	3.64	0.0063	1050.4	162.44
consumption		0		5						
Shellfish	-	191.2	-	5000.5	-	-	-	-	-	-
Shellfish harvesting	-	6.54	-	355.62	-	-	-	-	-	-
Netfishing	≤ 1.00 × 10 ⁻¹⁶	0.13	≤ 1.00 × 10 ⁻¹⁶	841.09	0.11	≤ 1.00 × 10 ⁻¹⁶	0.0005	5.14 × 10 ⁻⁹	22.43	2.55 × 10 ⁻⁵
Small craft boating	3.85 × 10 ⁻¹¹	0.10	≤ 1.00 × 10 ⁻¹⁶	711.09	33.59	≤ 1.00 × 10 ⁻¹⁶	0.0003	4.01 × 10 ⁻⁹	9.73	1.22 × 10 ⁻⁵
Exposure pathway Shore recreation	2.45 × 10 ⁻¹¹	796.4 8	≤ 1.00 × 10 ⁻¹⁶	507.81	3.03	≤ 1.00 × 10 ⁻¹⁶	0.0003	2.63 × 10 ⁻⁹	6.42	8.01 × 10 ⁻⁶

conditions

506

505

507 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 508 509 discharge of effluent during this period, when the sea bed is exposed and only minimal dilution can 510 occur, creates a period of potentially elevated human health risk. Studies of the marine environmental 511 impact associated with this effluent discharge practice also detected negative effects (Greenwood, 512 2016; Krumhansel et al., 2015). In Pond Inlet, however, all 36.73 of the estimated annual cases in that 513 location occur during higher tide conditions. This low case total is partially explained by the short, 514 scheduled window during which effluent is discharged from the WSP (two to three weeks in later 515 summer) and because there are fewer exposure pathways in Pond Inlet. The explanation for the cases 516 occurring at high tide – contrary to low tide as seen in Iqaluit and Pangnirtung – may be due to 517 differences in system siting and receiving environments. At the Pond Inlet site, the treatment system is 518 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 Pangnirtung, the treatment plants are directly within the main settlements and effluent is discharged 521 522 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 quickly and a high volume of minimally-treated effluent is flowing rapidly through the wetland and 531 532 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

Among the suite of pathogens modelled, rotavirus (46%) and Salmonella spp. (32%) contribute the 543 544 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, 2010), which may prove of importance as high rates of rotavirus infection in the Arctic have been 556 557 documented (Desai et al., 2017; Goldfarb et al., 2013; Gurwith et al., 1983).

558

559 3.2 Expected annual incidence rates of AGI

The expected annual incidence rates per person, corresponding to the total population, and per 1000 persons in each case study location are shown in Table 7. For comparison, the incidence rate results table also includes an estimate of all food- and waterborne AGI in Arctic communities that is based 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 to566wastewater 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

study locations, with comparison to all food- and waterborne AGI arctic estimate (Harper et al.,

568

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 (Fuhrimann
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

Comparison of the two pond-and-wetland sites, Naujaat and Sanikiluaq, highlights the variation of 588 589 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 Sanikiluag (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 freshet is 1.73×10^6 , compared to only 6.04×10^4 in Sanikiluaq. 596

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 exposure event for each scenario are presented in Table 8. The probabilities correspond to AGI 601 602 attributable to any of the modelled pathogens. Many of the risk probabilities are very low ($\leq 2.50 \times 10^{-10}$ ⁶) including all exposures occurring during high tide conditions in Iqaluit and Pangirtung, all exposures 603 604 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

calculated using a quantitative microbial risk assessment (QMRA) model.

Case study location	Iqal	uit	Pangni	rtung	Pond	Inlet	Sanik	kiluaq	Na	ujaat
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	0.076	≤ 1.00 × 10 ⁻¹⁶	0.097	0.006	≤ 1.00 × 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	≤ 1.00 × 10 ⁻¹⁶	0.135	0.067	≤ 1.00 × 10 ⁻¹⁶	1.61 × 10 ⁻⁷	1.23 × 10 ⁻¹²	0.008	6.11 × 10 ⁻⁹
Netfishing	≤ 1.00 × 10 ⁻¹⁶	1.57 × 10 ⁻⁵	≤ 1.00 × 10 ⁻¹⁶	0.198	0.0002	≤ 1.00 × 10 ⁻¹⁶	2.68 × 10 ⁻⁷	2.06 × 10 ⁻¹²	0.013	1.02 × 10 ⁻⁸
Shellfish harvesting	≤ 1.00 × 10 ⁻¹⁶	0.002	≤ 1.00 × 10 ⁻¹⁶	0.178	-	-	-	-	-	-
Shellfish consumption	≤ 1.00 × 10 ⁻¹⁶	0.012	≤ 1.00 × 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

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 OMRA 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 Iqaluit and Pangnirtung, a similar control measure could be employed. Adjusting the effluent release 629 630 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

Broad community involvement during model development allowed for differing perspectives to be 635 636 incorporated into the research and exhibits how primary environmental risk factors are influenced by social, cultural, and behavioural determinants in Indigenous communities (Barber and Jackson, 2015; 637 638 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 Naujaat,

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

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

656

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

664

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

669 in this study, indicator E. coli analysis may arguably be the best practical indicator of pathogenic 670 organisms in Arctic communities, given the relative ease and low-cost of analysis. The suite of 671 pathogens included in the model were chosen as a representative group of the major microbial hazards 672 present in wastewater effluent, with consideration given to infections in arctic populations. AGI is also 673 attributable to several other waterborne pathogens not included in the suite of six microbial infectious 674 agents. Additional types of waterborne infections, such as eye and skin infections, were not included. 675 Similarly, the occupational risk to wastewater operators was not targeted, as the aim was to assess 676 community risk in the effluent receiving environment.

677

678 4. Conclusion

679 A point estimate QMRA was used to provide the first estimates of AGI attributable to wastewater 680 treatment systems in the arctic territory of Nunavut, Canada. A number of exposure pathways and 681 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 682 683 where mechanical treatment systems are releasing effluent directly into marine waters at low tide 684 conditions. Moderate risks are also seen in some stabilization pond and treatment wetland sites during 685 seasonal events such as spring freshet. Based on these findings, human exposure to partially treated 686 wastewater effluent may be contributing to high AGI rates in some communities. These results can be 687 used to provide evidence to support public health initiatives as well as decisions regarding water and 688 sanitation infrastructure investment in the region. Follow-up research will involve more complex 689 modelling of the higher risk pathways that have been identified as well as risk mitigation options. 690

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696

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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)

714

715 Appendix B. Full QMRA Model (Microsoft Excel)

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