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Title

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

Authorship

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Abstract

Most arctic communities use primary wastewater treatment systems that are capable of only low levels of pathogen removal. Effluent that potentially contains fecally-derived microorganisms is released into wetlands and marine waters that may simultaneously serve as recreation or food harvesting locations for local populations. The purpose of this study is to provide the first estimates of acute gastrointestinal illness (AGI) attributable to wastewater treatment systems in Arctic Canada. A screening-level, point estimate quantitative microbial risk assessment (QMRA) model was developed to evaluate worst-case scenarios across an array of exposure pathways in five case study locations. A high annual AGI incidence rate of 5.01 cases per person is estimated in Pangnirtung, where a mechanical treatment plant discharges directly to marine waters, with all cases occurring during low tide conditions. The 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 person is estimated in Naujaat, where a treatment system consisting of a stabilization pond and tundra wetland is used, with the majority of cases (87%) occurring during spring. The pathway with the 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 for the other three case study location are low (≤ 0.13). These findings suggest that wastewater treatment sites may be contributing to elevated rates of AGI in some arctic Canadian communities. The 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 pathways and characterizing health risk in a natural system is difficult due to the conflux of human and 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 multiple exposure pathways, without clear associations between microbial hazard sources and health outcomes are not well-suited for this type of problem. A broader assessment, which considers the whole ecological system and is flexible enough to include an array of microorganisms and exposures, is better suited to model conditions and estimate the level of risk (Boehm et al., 2009; Dunn et al., 2014; Waltner-Toews et al., 2003).

Quantitative microbial risk assessment (QMRA) has emerged as a practical approach for evaluating health risks in complex ecological systems (Haas et al., 2014). The disease burden attributable to microbial pathogens in the environment can be estimated based on information about their concentration and distribution or that of suitable surrogates, i.e., usually indicator organisms (Haas et al., 2014; USEPA, 2012). It is particularly useful for assessing risk at low levels of exposure (Haas et al., 2014). Through four stages (hazard identification, exposure assessment, dose-response analysis, risk characterization), data from a variety of sources, including field studies, models, and literature, are 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 characterizations to stochastic models incorporating Monte Carlo simulation – depending on availability of data and scope of the problem. This design flexibility makes QMRA a useful tool to estimate effects where direct measurements of microbial pathogens at the point of exposure are not available or feasible (Haas et al., 2014; Howard et al., 2006). Simplified QMRA approaches have been adapted for use in some developing regions with limited data (Ferrer et al., 2012; Howard et al., 2006; Hunter et al., 2009; Yapo et al., 2014). QMRA has also been used in other contexts where populations may be unknowingly exposed to wastewater effluent through food harvesting or recreational activities (Fuhrimann et al., 2017; 2016). These applications are promising for the use of QMRA in addressing similar public health challenges in remote, arctic communities.

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

2. Methods

2.1 Ethical considerations

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

2.2 QMRA scope and design

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

2.3 Hazard identification

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

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 *Cryptosporidium parvum*). All six agents are commonly present in partially-treated wastewater effluent and transmissible via faecal-oral routes (i.e., direct accidental ingestion of water, hand-to-mouth exchange following contact with contaminated water, or ingestion of contaminated food). The prevalence and emergence of pathogenic infections in Arctic Canadian populations were considered during the selection of microorganisms (Goldfarb et al., 2013; Iqbal et al., 2015; Pardhan-Ali et al., 2012b; Thivierge et al., 2016; Yansouni et al., 2016). As a simplification within the entire assessment, we refer to the pathogenic strains known to be associated with AGI.

2.4 Exposure assessment

2.4.1 Case study locations

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

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.

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

Community and location	**Population size**	**Treatment type**	**Discharge method and timing**	**Wastewater volume (m^3/year)**	***E. coli* 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

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

2.4.2 Exposure scenario development

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

Six activities were selected as the most likely pathways of human exposure to wastewater hazards: shoreline recreation; small craft boating; netfishing; shellfish harvesting; shellfish consumption; and wetland travel. Descriptions of each pathway are provided below and a full summary of the human activity parameters used in the QMRA model are presented in Table 2. The parameters include: distance (location where the human exposure event occurs as measured in metres from the effluent release point); frequency (number of exposure events per year); exposure group (number of individual people exposed per event); and ingestion (amount of media ingested per individual per exposure event). In all but the shellfish consumption scenario, the modelled transmission route is accidental ingestion of contaminated water. In the shellfish consumption scenario, the transmission route is ingestion of contaminated tissue. Community data showed that people do not source drinking water downstream from any of the wastewater treatment sites. Consumption of contaminated finfish (non-shellfish), marine mammals, and wild game were also excluded as transmission routes in this screening-level assessment as dose-response data for these mediums as a secondary source of microbial contamination is limited (CAMRA, 2015). The accidental ingestion rates for shoreline recreation, small craft boating, and netfishing were adapted from values characterizing three classes of water recreation exposure (Dorevitch et al., 2011; McBride et al., 2013). The low contact accidental ingestion rate is an average of 3.8 mL/hour and is applicable to activities such as fishing and wading. A middle contact average rate of 5.8 mL/hour is recommended for canoeing or kayaking with occasional capsizing and the high contact average rate of 10.0 mL/hour pertains to swimming. Three times the average value is recommended for use as a conservative estimate (Dorevitch et al., 2011; McBride et al., 2013). Accidental ingestion rates for the wetland travel and shellfish harvesting exposure pathways were drawn from assessments of agricultural and aquacultural harvest work in areas where wastewater irrigation is practiced (Fuhrimann et al., 2016, 2017; WHO, 2006). These studies included assessment of harvesting crops such as rice grown in marshy areas – similar to the tundra wetland sites – and suggest 50.0 mL/day as a conservative accidental ingestion rate.

Shoreline recreation: All five case study locations are coastal communities and as such the shoreline is 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 area. It is plausible that children may splash and wade into the edge of the water, though swimming or full submersion would be rare. Community shorelines are also common areas for rod fishing, which could include shallow wading and handling of wet fish and fishing equipment. Shoreline recreation was classified with a conservative, low-exposure contact rate and estimated event duration of two hours resulting in an accidental ingestion of 22.8 mL per event (Dorevitch et al., 2011; McBride et al., 2013).

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).

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.

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).

Shellfish consumption: Exposure via consumption of contaminated shellfish was evaluated independently of accidental water ingestion depicted during the harvesting scenario. Pathogens can become concentrated within the digestive tissue of shellfish that obtain their nutrients by filtering large quantities of seawater (Bitton, 2005; Ford, 2005). The infectious agents are then potentially transmissible to humans who consume the shellfish raw or partially cooked. Most organisms that lead to infectious illness can be killed or inactivated through thorough cooking (Butt et al., 2004). The 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 tissue to account for the range of preparation methods. Another longstanding custom within Inuit communities is the sharing of harvested food, referred to as country food, with family and community 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 (Fuhrimann 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										
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 (persons)	100	100	50	50	50	50	50	50	40	50
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
Frequency (per year)	85	85	85	85	10	10	35	50	35	50
Exposure group (persons)	100	100	50	50	50	50	50	50	50	50
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	-	-	-	-	-	-
Frequency (per year)	-	40	-	40	-	-	-	-	-	-
Exposure group (persons)	-	100	-	50	-	-	-	-	-	-
Ingestion (millilitres)	-	50.0	-	50.0	-	-	-	-	-	-
Shellfish consumption										
Distance (metres)	-	2000	-	1000	-	-	-	-	-	-
Frequency (per year)	-	40	-	40	-	-	-	-	-	-
Exposure group (persons)	-	400	-	200	-	-	-	-	-	-
Ingestion (grams)	-	75.0	-	75.0	-	-	-	-	-	-
Wetland travel										
Distance (metres)	-	-	-	-	-	-	500	500	250	250
Frequency (per year)	-	-	-	-	-	-	50	50	35	45
Exposure group (persons)	-	-	-	-	-	-	50	50	50	50
Ingestion (millilitres)	-	-	-	-	-	-	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 begins. Then, during the 12 to 15 weeks where temperatures remain above freezing, wastewater effluent of varying volume and microbial concentration seeps intermittently into the adjacent wetland and marine waters; this creates a window of time when human exposures may occur. In Pond Inlet, wastewater is also treated using a stabilization pond, which thaws in the spring and freezes in the early fall. It differs from Sanikiluaq and Naujaat, however, in that the pond has been partially engineered to prevent seepage. The wastewater is contained within the cell throughout and summer and then manually decanted into the marine receiving environment using a pump over a two to three week period just prior to winter freeze-up. Based on the community data regarding awareness of hazards, it was assumed that there is no human contact with wastewater directly in the stabilization ponds. Therefore, the only time period that exposures can occur in Pond Inlet is during the short period when this controlled decanting is taking place.

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.

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;

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

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 model is widely used to characterize microbial decay or inactivation within environmental systems (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 quality monitoring of recreational waters in many public health jurisdictions (Ashbolt et al., 2010; Ferguson et al., 2007; McBride et al., 2012; Sokolova et al., 2015; WHO, 2016). First, the natural logarithms of observed *E. coli* concentrations in the receiving environments at each treatment site were 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 study locations under varying conditions.

Cut-points were set at distances where it appeared that concentrations detected had reached background 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 reference sites. In instances where multiple samples had been collected at the same distance, the highest concentration was chosen. For censored data (greater or less than method detection limit), we 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 modelling coefficients used for predicting *E. coli* concentration in effluent-impacted receiving environments is available in the supplementary material. The calculated reduction constants (k) from 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 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 environments and tidal conditions.

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

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

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

Pathogen	**Ratio (*E. coli: Path*)**	**References**
Pathogenic *E. coli*	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)

In the shellfish consumption exposure scenario, it was also necessary to estimate the concentration of contaminants within the bivalve tissue based on the indicator *E. coli* concentration in the overlying 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).

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

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.

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

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).

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

Pathogen	Model	Parameters	References
Pathogenic *E. coli* (EIEC)	Beta-Poisson	$\alpha = 0.16$ $N_{50} = 2.11 \times 10^6$	CAMRA (2015); Dupont et al. (1971)
Salmonella spp.	Beta-Poisson	$\alpha = 0.389$ $N_{50} = 1.68 \times 10^4$	CAMRA (2015); McCullough and Eisele (1951)
Campylobacter 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)
Giardia spp.	Exponential	$k = 0.020$	CAMRA (2015); Rendtorff (1954)
Cryptosporidium spp.	Exponential	$k = 0.057$	CAMRA (2015); Messner et al. (2001)

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

Pathogen	Probability ($P_{ill \mid inf}$)	References
Pathogenic *E. coli*	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)

2.6 Risk characterization

The health outcome measures included in the model are expected annual cases of AGI, expected annual incidence of AGI per total population and 1000 persons, and estimated probability of AGI per person per year for a single exposure event. Although some of these endpoints may not be as common across global literature as disability-adjusted life years, they were chosen for their direct comparability to the limited epidemiological studies of AGI in Arctic Canada (Harper et al., 2015), while still being relatable to disease burden measures used in some QMRA studies of wastewater exposures in other regions (Fuhrimann et al., 2017, 2016).

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

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

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

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

$$D_{path} = D_{E.\ coli} \ * (E.\ coli\colon Path) \qquad [5]$$

$D_{E.\ coli}$ was then multiplied by *E. coli:Path*, an indicator *E. coli*-to-pathogen inference ratio from Table 3, to produce the corresponding pathogen-specific dose at exposure, D_{path} (MPN). The obtained doses of each pathogen, D_{path}, were then entered into corresponding dose-response models (Equations 3 and 4), described in section 2.5, with parameters from Table 4 to obtain individual probability of infection per pathogen per single exposure event, $P_{inf, path}$. The morbidity ratios from Table 5, $P_{ill \mid inf}$, were then applied to determine the probability of illness per pathogen, per exposure pathway, $P_{ill,path}$ (Equation 6).

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

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, ($P_{ill,path}$).

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

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.

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

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

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

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

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

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

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

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

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

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

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.

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.

3.1 Expected total annual cases of AGI

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

Table 6 Expected annual cases of acute gastrointestinal illness (AGI) attributable to wastewater treatment systems in five arctic case study locations, per receiving environment conditions and 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	≤ 1.00 × 10^{-16}	507.81	3.03	≤ 1.00 × 10^{-16}	0.0003	2.63 × 10^{-9}	6.42	8.01 × 10^{-6}
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}
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}
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 activity occurs. Also effluent is discharged into open marine waters, where the sea bed is not exposed, 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 into more shallow, enclosed waters between tapering shores (Greenwood, 2016; Neudorf et al., 2017). At the Pond Inlet site it was observed, however, that high winds combined with a strong ambient current cause the discharged effluent plume to attach to the shoreline and drift toward the central area of the community (Greenwood, 2016; Krumhansl et al., 2015). This phenomenon is reflected in the model output with the resulting 36.73 estimated cases of AGI.

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

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

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).

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

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

Comparison of the two pond-and-wetland sites, Naujaat and Sanikiluaq, highlights the variation of potential human health risks even amongst seemingly alike passive systems. Both communities are similar in terms of total population, discharge method, annual volume of wastewater, and the types of exposure pathways, as presented in Tables 1 and 2. However, the annual incidence per person rate in Naujaat (1.16) is more than two orders of magnitude greater than that in Sanikiluaq (0.004). One reason for this difference is the design and condition of the WSPs and their effectiveness in reducing pathogen loads within effluent prior to seepage into the wetland (Hayward et al., 2018). In Naujaat, for instance, 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.

3.3 Estimated probability of AGI per single exposure event

This study placed emphasis on soliciting community input and feedback during the development and 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 attributable to any of the modelled pathogens. Many of the risk probabilities are very low ($\leq 2.50 \times 10^{-6}$) including all exposures occurring during high tide conditions in Iqaluit and Pangirtung, all exposures occurring during low tide conditions in Pond Inlet, all exposures occurring during late summer conditions in Naujaat with the exception of wetland travel (0.0722), and all exposures entirely in Sanikiluaq with the exception of wetland travel during spring (0.002).

Table 8 Estimated probability of acute gastrointestinal illness (AGI), per person per single exposure event, attributable to wastewater treatment systems in five arctic case study locations as 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

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

High risk probabilities per single exposure are estimated for shellfishing harvesting (0.178) and 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 greatly reduced in comparison to Pangnirtung. Studies of microbial contamination within shellfish tissue in the Arctic, for comparative purposes, are limited. Those that have been undertaken found shellfish to be of generally good microbiological quality; however *Giardia* spp. and *Cryptosporidium* spp. were present in some samples (Lévesque et al., 2010; Manore et al., 2017). In agreeance with recommendations from these studies, the range of estimates from this QMRA model suggests a need for continued research on shellfish in Arctic communities. As a more immediate application, these results may be useful in informing economical risk management strategies in Nunavut. In the remote, resource-limited region, risk alleviation via infrastructure upgrades is extremely costly and difficult (Suk et al., 2004). In Pond Inlet for example, wastewater operations staff had previously established a precautionary risk mitigation practice of delaying the annual decant of the WSP into the marine receiving environment until after the migratory passage of Arctic char (*Salvelinus alpinus*), a fish of 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 schedules at the mechanical treatment plants to discharge primarily during high and outgoing tide cycles, when the greatest water exchange is ensuing (Nevers and Boehm, 2011), may be an effective mitigation effort; particularly during periods of maximum tidal range when most shellfish harvesting takes place.

Broad community involvement during model development allowed for differing perspectives to be 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; Knibbs and Sly, 2014). For example, in some case study locations the more established food harvesters stated that they never travel nor hunt near wastewater treatment areas; implying that these exposure pathways could be dismissed. Younger residents or those with fewer of the resources necessary to reach prime locations beyond the community boundaries (e.g. all-terrain vehicle, money for fuel and supplies), however, mentioned that they had harvested food in close proximity to the wastewater treatment site. In terms of risk management and communication, this type of community-based information is very important to accurately capture within the QMRA model. For example, in Naujaat, where an unmarked and unfenced wetland that is used as a travel route is also part of the treatment train, the estimated probability of risk per single wetland travel exposure during spring is 0.60.

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.

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.

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 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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Supplementary Material

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

Appendix B. Full QMRA Model (Microsoft Excel)

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