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Wastewater treatment and public health in Nunavut: a microbial risk assessment framework for the Canadian Arctic

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Abstract Wastewater management in Canadian Arctic communities is influenced by several geographical factors including climate, remoteness, population size, and local food-harvesting practices. Most communities use trucked collection services and basic treatment systems, which are capable of only low-level pathogen removal. These systems are typically reliant solely on natural environmental processes for treatment and make use of existing lagoons, wetlands, and bays. They are operated in a manner such that partially treated wastewater still containing potentially hazardous microorganisms is released into the terrestrial and aquatic environment at random times. Northern communities rely heavily on their local surroundings as a source of food, drinking water, and recreation, thus creating the possibility of human exposure to wastewater effluent. Human exposure to microbial hazards present in municipal wastewater can lead to acute gastrointestinal illness or more severe disease. Although estimating the actual disease burdens associated with wastewater exposures in Arctic communities is challenging, waterborne- and sanitation-related illness is believed to be comparatively higher than in other parts of Canada. This review offers a conceptual framework and evaluation of current knowledge to enable the first microbial risk assessment of exposure scenarios associated with food-harvesting and recreational activities in Arctic communities, where simplified wastewater systems are being operated.

Keywords Conceptual model · Environmental exposures · Indigenous health · Inuit · Quantitative microbial risk assessment (QMRA) · Rural health · Water, Sanitation, and Hygiene (WASH) · Wastewater

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Introduction

Communities in the Canadian Arctic territory of Nunavut face unique wastewater treatment challenges due to climate, remoteness, small populations, and local food-harvesting practices (Bjerregaard et al. 2008; Johnson et al. 2014; Lam and Livingston 2011; Martin et al. 2007). The territory has a total population of 34,000 spread across 25 remote communities, varying in population from 150 to 7000 (Nunavut Bureau of Statistics 2014). No roads connect the 25 isolated communities to one another or to other communities in Southern Canada. Thus, each community requires its own municipal public work infrastructure including wastewater treatment facilities. All but three have trucked drinking water distribution and wastewater collection services, as opposed to piped conveyance or individual on-site systems. Communities use basic wastewater treatment systems that are capable of only low levels of pathogen removal (Huang et al. 2014). These systems typically rely exclusively on natural environmental processes for treatment, making use of existing lagoons, wetlands, and ocean bays. They are operated in a manner such that effluent—partially treated wastewater still containing potentially hazardous microorganisms—is released into the terrestrial and aquatic environment at random times.

Inuit, the indigenous inhabitants of the region whom comprise 84% of the territory's population, as well as other residents rely significantly on their local surroundings for food, drinking water, and recreation. Inuit were semi-nomadic hunters and gatherers until settlement increased in the 1950s and traditional fishing, hunting, and foraging activities are still ingrained in daily life (Fleming et al. 2006; Suk et al. 2004). These traditional activities increase the risk of human exposure to effluent both directly as people move through wastewater treatment areas and indirectly via the food web. Human exposure to microbial hazards present in municipal wastewater can lead to acute gastrointestinal illness, more severe infectious enteric disease, and longer-term chronic illness (Ashbolt 2004; Prüss et al. 2002). Although estimating the actual disease burden associated with wastewater exposures in the remote arctic territories is difficult, waterborne- and sanitation-related illness in northern communities is believed to be comparatively higher than in other parts of Canada (Harper et al. 2011a, 2015b; Thomas et al. 2013).

Exposure pathways and public health risks associated with sustenance and recreational activities in Nunavut communities, where simplified wastewater systems are concurrently being operated, have never been systematically assessed. There is limited site-specific data available to evaluate the potential risks associated with the basic wastewater treatment systems used in Canadian Arctic communities and, in particular, among Inuit populations who access their immediate natural environment to harvest food and drinking water. The objective of this paper is to propose a conceptual model of the ecological system, thus providing a foundation for a microbial risk assessment of potential exposure scenarios related to current wastewater treatment practices. A topical review of literature relevant to the hazard identification and exposure assessment steps involved in the risk assessment is also included. The intent is to diagram the complexities involved in the ecological system being studied, evaluate the current level of scientific evidence available, and to identify the critical knowledge gaps and research needed to complete a comprehensive microbial health risk assessment.

Background and context

In 2009, the majority of the Canadian Council of Ministers of the Environment endorsed a strategy for a harmonized, Canada-wide management framework of municipal wastewater effluent standards (Canadian Council of Ministers of the Environment 2009). This strategy was developed in preparation for the country's first national regulations for wastewater treatment, which were commissioned in 2012 (Environment Canada 2015). However, Nunavut did not endorse the strategy given the stark differences between conditions in the territory and most of the rest of Canada (Inuit Tapiriit Kanatami and Johnson 2008). There was also a very limited base of information regarding the potential environmental and human health risks associated with wastewater systems currently in use in that territory (Canadian Council of Ministers of the Environment 2009). A grace period was thus allotted to Nunavut, as well as to some other northern and remote regions experiencing similar circumstances, prior to their having to comply with the regulations (Canadian Council of Ministers of the Environment 2014). During this grace period, the territorial government of Nunavut launched a multi-year research program to evaluate their wastewater systems and management practices in an effort to develop adapted performance standards and risk assessment procedures more suitable for northern regions (Lam and Livingston 2011).

Engineering assessments show that passive wastewater treatment systems are capable of reducing the level of *Escherichia coli* (used as a regulatory indicator of the presence of pathogenic organisms) in an arctic climate but generally not to levels typically achieved with conventional wastewater disinfection systems (Hayward et al. 2014; Krkosek et al. 2012; Krumhansl et al. 2015; Ragush et al. 2015; Yates et al. 2012). However, these assessments do not explicitly consider possible human exposures and potential risks to public health. Many northern wastewater effluent management policies, although thorough in their definition of receiving environment quality standards, are not designed with specific consideration of how human populations interact with receiving environments or how they may be exposed to health hazards. Public health risks associated with exposure to wastewater systems have become a higher priority at the community level. For example, in February 2015, the hamlet of Pond Inlet declared a state of emergency following a chain of mechanical and operational failures with the sanitation system that resulted in lengthy service disruptions and raw sewage spills near homes (Canadian Broadcast Corporation 2015). Therefore, an assessment specifically focused on human health risks is a necessary and timely next step towards a comprehensive municipal wastewater treatment strategy for northern and remote regions.

Model development and literature review sources

The microbial risk assessment framework proposed in this paper includes a conceptual model of exposure pathways and a literature review of public health risks associated with wastewater treatment in the Canadian Arctic. The model is an initial visualization of exposure pathways between hazards present in wastewater effluent and human receptors. The literature review is a guide to support the progression of the unparameterized model into a quantitative risk assessment tool.

The conceptual model is informed by prior research of the authors (Daley et al. 2015) as well as more recent stakeholder meetings with municipal administrators, wastewater treatment employees, engineers, health professionals, environmental conservation officers, and hunter and trapper organizations in Iqaluit, Pangnirtung, and Pond Inlet, Nunavut, Canada, that took place in September 2014.

The literature review was conducted using the following three academic databases: PubMed, Web of Science, and Environmental Science and Pollution Management. A general internet search was also used for gray literature. Gray literature reviewed includes policy and guideline documents, trade journals, reports, and assessments from government and non-government organizations involved with public health, water, and wastewater issues in the Arctic. In all databases, queries were made using combinations of terms relevant to the topic such as risk assessment, wastewater, sanitation, arctic, indigenous/aboriginal health, exposure, and pathogen. Only English literature was included. Search results were screened by title and abstract, and documents deemed relevant were kept for full reading. Reference lists of these documents were also reviewed manually, and relevant citations were added to the collection of papers. As these papers were being reviewed, additional searches were conducted as needed for more in-depth information of specific subtopics. Traditional ecological knowledge (such as Inuit Qaujimajatuqangit) pertaining to the natural environment and health is increasingly, and deservedly, becoming more valued and included in scientific and gray literature. This was the case in many of the documents reviewed and is therefore duly represented.

Risk assessment framework

Human health risk assessment general considerations

Risk can be defined as a function of hazard and exposure (Robson and Ellerbusch 2007). Human health risk assessment is a process used to identify and evaluate the probability of adverse health effects in humans who may potentially be exposed to hazards in contaminated environmental media (Bartell 2005; United States Environmental Protection Agency 2012). The purpose of an assessment is to determine how best to measure exposures where and when they occur. This helps to more fully understand the effect of the contaminant on human health, deem what are acceptable concentrations in the environment, and establish monitoring and management practices to mitigate risk (Bartell 2005).

A risk assessment may involve a single hazard with a single associated health outcome in a single exposure scenario, such as the case with a chemical contaminant or in an occupational hazard assessment. Microbial risks in a community setting typically require a broader assessment as contaminated environmental media commonly contain multiple hazards with a range of associated health outcomes in individuals of different susceptibilities and numerous direct and indirect exposure scenarios (Haas et al. 2014). Therefore, an important first stage is clearly defining the specific problem and scope to be addressed in the risk assessment through the creation of a preliminary, conceptual model.

Conceptual model

A conceptual model is a depiction of the assumed relationship between hazard sources and exposed populations. Such models function as a communication tool between risk assessors and stakeholders and are directional guides for organizing and conducting the risk assessment (Suter 1999). Figure 1 presents a new conceptual model of potential exposure pathways between microbial pathogens originating from wastewater treatment systems and humans in an Arctic Canadian community. In particular, the model reflects an Inuit community in Nunavut, which relies heavily on local natural resources for food, water, recreation, and livelihood. The model could be tailored to any arctic region or community.

Within the model, we have divided the system being studied into five categories of primary factors, which are pathogen source, physical environment, biological environment, human activities, and transmission routes. Each category is subdivided into several processes or environmental pathways. As pathogens move from the source towards potential human receptors, the model illustrates the chain of events that could result in exposure. Tracing pathogen pathways through the model is a way to begin understanding the complexities involved, prioritizing potential exposures, and defining risk scenarios (Beaudequin et al. 2015). Ultimately, the tracing exercise increases the accuracy and practical utility of the microbial risk assessment. When conducting the actual assessment for a given pathway, each subcategory is expanded into a process model and quantified using an appropriate mathematical equation. Following the risk assessment framework section of this paper, the processes or human-environment interactions conceptualized in each of the five categories are discussed in the review section. The reader is encouraged to refer to this model when prompted in the text.

Quantitative microbial risk assessment

Quantitative microbial risk assessment (QMRA) is a structured, systematic, science-based approach that quantitatively estimates the level of exposure to microbial hazards and resulting risk to human health (Haas et al. 2014). It is particularly useful for evaluating background or endemic risk at low levels of exposure when health outcome end points or surveillance data is generally lacking (Haas et al. 2014). In cases with limited site-specific evidence, QMRA uses mathematical models to best estimate the probability of infection from existing databases and literature associated with human exposure experiments. The outputs are the attributed risk of

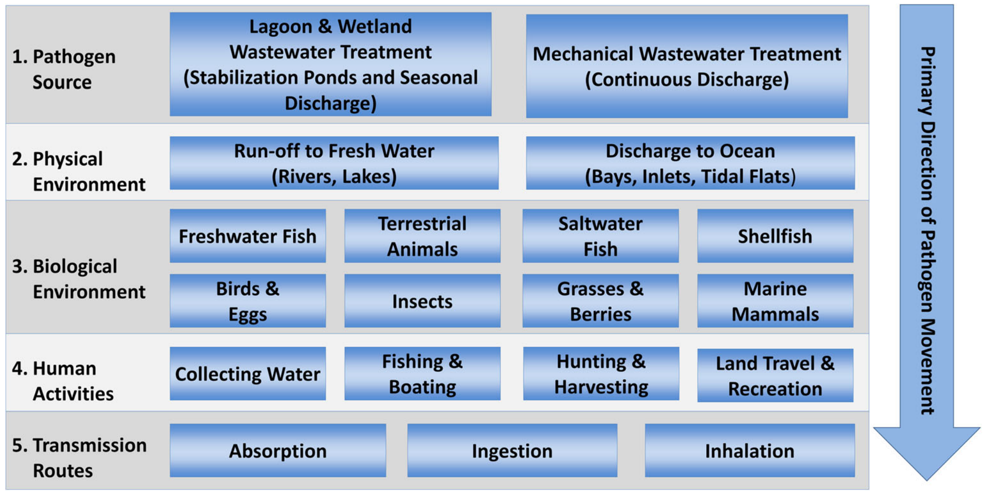

Fig. 1 A conceptual model of potential wastewater effluent exposure pathways in Arctic Canadian communities through five categories of factors

infection or disease for each defined exposure and can be expressed in individual or population terms. Depending on data availability, one of two modeling techniques can be used, point or stochastic. In point models, each parameter is represented by a single value, whereas in stochastic models, probability functions quantifying uncertainty about spatially and temporal varying processes are used. Stochastic models are theoretically superior for this reason (Haas et al. 2014).

QMRA research does not generate new empirical evidence on health effects in a manner similar to that of epidemiology or toxicology. Rather, it synthesizes estimates using existing scientific evidence and judgment (Bartell 2005). Although the assessments involve the use of assumptions, resulting in quantifications with a large range of variation, this approach is seen as useful for ranking risks and comparing possible interventions or controls (Sales-Ortells and Medema 2014; United States Environmental Protection Agency 2012). QMRA has been applied to drinking water systems, gray water and wastewater reuse, food safety, recreational water safety, and evaluation of new engineering controls for treatment (Beaudequin et al. 2015; Ferrer et al. 2012; Haas et al. 2014; Murphy et al. 2016a, 2016b; Schoen and Ashbolt 2010; Westrell et al. 2004). QMRA has also been shown as an appropriate approach to study health risks in settings with limited data and resources (Howard et al. 2006; Yapo et al. 2014).

Conducting a QMRA involves four steps: (1) hazard identification, (2) exposure assessment, (3) dose-response assessment, and (4) risk characterization (Haas et al. 2014). Hazard identification is the selection of the relevant agent(s) and associated health effect(s) for assessment. Exposure assessment is a function of the type, magnitude, duration, and timing of human exposure to the agent of interest. Measuring the true exposure is quite difficult as it requires the simultaneous presence of a defined concentration of contaminant and a human receptor in the same microenvironment. Often assessors rely on default assumptions about media contact such as water ingestion or contact rates. These rates are combined with human activity pattern estimations or scenarios to arrive at types and levels of exposure. The dose-response assessment describes the quantitative relationship between exposure and health outcome. A mathematical model is selected that predicts the relationship of health effect, or response, for any dose. Trusted dose-response curves for many microorganisms have already been developed (Center for Advancing Microbial Risk Assessment 2016). The risk characterization step combines information from the other three steps to estimate levels of response for the identified health effect to the agent of interest at the specific level of exposure in the defined population. The output is often, but not exclusively, expressed in terms of a distribution of attributed risk estimates or a disease burden measure such as disability-adjusted life years (DALYs). During risk characterization, the strength of all evidence, assumptions used, and any uncertainties with the estimate should be discussed. A sensitivity analysis of the assessment may be conducted to identify which inputs were most strongly correlated with the final health risk estimates and which variables are most responsible for high levels of uncertainties (Haas et al. 2014).

QMRA can serve as a suitable exploratory tool for early or screening-level assessment of health risks, prior to more detailed studies, environmental monitoring, or public health surveillance (Ashbolt et al. 2013; Sales-Ortells and Medema 2014). For the Arctic communities described in this paper, the pathogen removal capability of typical wastewater treatment systems has recently been characterized (Hayward et al. 2014; Huang et al. 2014; Ragush et al. 2015; Yates et al. 2012) and serves as a starting point, allowing the corresponding range of risks of infection to be estimated for assumed exposures. The following section is a discussion of the evidence that is best suited and currently available to inform the hazard identification and exposure assessment steps of such a QMRA of the public health risks associated with wastewater treatment systems in Nunavut, Canada. The majority of information is relevant to communities across the Canadian North and other arctic regions. The final two QMRA steps, dose-response assessment and risk characterization, are not included in this review. Although there are several inherent data limitations involved, such as differences in dose potencies resulting in illness among people of different ages and immune status, they are general in nature and are not unique to an arctic context.

Wastewater hazards and exposure pathways in Canadian arctic communities

Hazard identification

The hazard identification stage of a QMRA involves determining the microbial agents of concern, the contexts in which they are found, and the associated range of illnesses and diseases. Currently, there are no studies of associations that quantitatively link uptake of wastewater pathogens and health effects in an arctic community setting. However, related epidemiological studies investigating waterborne disease in the region are discussed.

From a public health perspective, the primary aim of wastewater treatment processes is the removal or inactivation of pathogenic microorganisms and parasites. The reduction or removal of organic materials, toxic metals, and nutrients (nitrogen and phosphorus) is also important to mitigate human health risks (Bitton 2005). However, the focus of this assessment is on microbial risks as they represent the more immediate health concern in the context being considered. Numerous bacterial, viral, and protozoan microbial pathogens are present in domestic wastewater (Leclerc et al. 2002). The major pathogenic bacteria that can be transmitted directly or indirectly by the waterborne route are *Salmonella*, *Shigella*, *Vibrio cholera*, *Campylobacter*, *Helicobacter pylori*, and pathogenic strains of *Escherichia coli*. Human exposure to these pathogens can cause salmonellosis, cholera, shigellosis, or other enteric infections affecting the gastrointestinal tract. Some human enteric virus groups include *Enterovirus*es, *Rotaviruses*, and norovirus (*Caliciviridae*). Viruses may result in a range of diseases including gastroenteritis, fever, skin rash, and respiratory infections. Specific viruses found in a particular community's wastewater reflect infections among the human population. The most common waterborne protozoan parasites affecting human health are *Giardia lamblia* and *Cryptosporidium*. Both affect the gastrointestinal tract resulting in diarrhea, nausea, fatigue, and weight loss. It is estimated that millions of cases of giardiasis occur annually worldwide, though it is rarely fatal (Bitton 2005). *Cryptosporidium* oocysts may persist in the environment for longer periods and cryptosporidiosis is potentially fatal in sensitive populations such as those who are immunodeficient (Bitton 2005).

Types of wastewater treatment in Nunavut: mechanical and passive systems

Wastewater may be treated through a combination of physical as well as biological and chemical processes (conceptualized in Fig. 1, category 1). The types of treatment are classified into a sequence of steps that increase in effectiveness and complexity, which are preliminary, primary, secondary, and tertiary (Bitton 2005). Preliminary treatment is the basic screening of large debris and solids. Primary treatment involves sedimentation of the influent to remove suspended solid waste and aid the breakdown of organic material present in the wastewater. Secondary treatment incorporates biological and chemical processes designed to remove soluble organic materials and provide some level of pathogenic inactivation. Tertiary or advanced treatment is any process implemented beyond the previous steps in effort to further disinfect and remove contaminants or specific pollutants (Bitton 2005). Presently, most systems in Nunavut are classified as primary treatment with low levels of pathogen removal.

Twenty one of the twenty-five communities in Nunavut use passive wastewater treatment systems typically consisting of either stabilization ponds and/or wetlands (Krkosek et al. 2012). Wastewater is continuously deposited into the ponds, where it remains frozen from approximately September to June. In June, as conditions warm, the wastewater influent begins to melt and a period of natural treatment occurs for 2 to 4 months depending on the location of the community (Ragush et al. 2015). These passive treatment systems result in sedimentation and microbial decomposition as well as some pathogen inactivation due to ultraviolet irradiation during the arctic daylight hours (Smith 1996). At the end of the treatment season, many of the wastewater ponds are then decanted into an adjoining natural wetland. This is typically done at a scheduled time to maximize the treatment period and controlled manually using a pump. However, in some instances, wastewater intermittently decants in an uncontrolled manner through a gravel berm into the wetland. Further sedimentation, filtration, and other natural processes may occur in the wetland continuing to treat the wastewater to some degree (Crites and Tchobanoglous 1998). The final receiving environments, after the effluent passes through the wetlands, are aquatic estuaries and ocean waters. In one Nunavut community, wastewater is discharged directly to a marine outfall without passing through a wetland. Passive treatment systems can reduce contaminant concentrations in an arctic climate (Chouinard et al. 2014; Doku and Heinke 1995; Hayward et al. 2014; Ragush et al. 2015; Schmidt et al. 2016; Yates et al. 2012). As noted by Hayward et al. (2014) and Yates et al. (2012), however, *E. coli* concentrations in the wetlands are highly variable over the treatment season.

Three communities in Nunavut, including the capital of Iqaluit (population ca. 7600), use some form of a conventional mechanical wastewater treatment system. Treatment typically consists of preliminary screening of large debris and basic sedimentation tanks. These systems continuously discharge into aquatic waters such as tidal bays bordering the community. Retention time within the treatment system before discharge into the receiving environment is dictated by the volume of influent entering the system and the carrying capacity of the system itself. Most of these systems provide preliminary or primary treatment and a low level of pathogen removal (Bitton 2005), thus leading to local pollution problems. Similar issues have also been observed in Greenland when untreated wastewater was released into areas with limited natural water exchange occurring in the receiving waters (Gunnarsdottir et al. 2013). An environmental assessment that examined benthic invertebrates as indicators of wastewater effluent impact upon receiving waters showed significant variation between communities (Krumhansl et al. 2015). In smaller communities (populations less than 2000), impacts to benthic communities generally occurred less than 200 m from the effluent discharge point. In contrast, significant impacts were detected up to 500 m from the effluent discharge point in the larger community of Iqaluit. The total volume and duration of effluent being discharged were suggested as the most important factors influencing the level of environmental impact.

In pond-wetland and mechanical wastewater treatment systems, effluent discharge schedules are likely to have a significant influence on the spatiotemporal variability of pathogens in the natural environment and subsequent human exposures. In one study of selected bodies of water that receive inadequately treated effluent but are also used for drinking, recreation and agriculture were estimated to pose a daily combined risk of infection by enteric pathogens above the World Health Organization limit of 10^{-4} (Teklehaimanot et al. 2015). Moreover, uncontrolled or continuous releases of effluent theoretically present less predictable occurrences of exposure and greater risk than controlled or scheduled intermittent releases.

Surveillance and monitoring programs related to gastrointestinal illness, specific foodborne and waterborne diseases, and other sanitation-related health outcomes in the Arctic are limited (Harper et al. 2011b), making it difficult to accurately estimate of the burden of disease associated with wastewater exposures in Canada's Arctic. Studies of the prevalence of several waterborne pathogens present in human fecal samples from cases of acute gastrointestinal illness (AGI) and enteric diseases in arctic communities were unable to determine an association with wastewater exposure (Goldfarb et al. 2013; McKeown et al. 1999; Messier et al. 2012; Pardhan-Ali et al. 2012a, 2012b, 2013). Although AGI is associated with many foodborne and waterborne pathogens as well as being transmissible person to person, it may be the most relevant health outcome to use for a risk assessment of wastewater systems in the region at this time given the absence of pathogen-specific data. AGI and enteric diseases related to waterborne pathogens often manifest in stomach flu-like symptoms that may not be recounted to frontline clinicians or public health officials. Thus, endemic AGI rates in Inuit and other arctic communities may be higher than officially reported (Dudarev et al. 2013; Harper et al. 2015b). Based on self-reporting, the incidence of AGI in these communities is higher than the Canadian average and comparable with some developing nations (Harper et al. 2015a). These associations may be further complicated by climate change already evident in arctic communities. Continued warming in the region could further threaten food and water security and increase the prevalence of infectious diseases (Hedlund et al. 2014; Hennessy and Bressler 2016; Nickels et al. 2005; Parkinson et al. 2014).

Exposure assessment

The exposure assessment stage determines the types and levels of human exposure to the agent. The multiple potential pathways from the contaminant point source to contact with a human receptor are described, often using scenarios. Creating scenarios involves consideration of human population characteristics such as behaviors, patterns of consumption, and knowledge of hazards. The fate and transport of the agent from the point source through the environment must also be assessed to predict the concentration, viability and/or infectivity of microorganisms, and the probability of their occurrence in water or food at the time of exposure (Haas et al. 2014). In this section, determinants of pathogen fate and transport in the natural environment are discussed. Northern populations, communities, and activities are described as the basis for suggesting environmental reservoirs and exposure pathways that may be priorities for risk scenarios to be fully assessed.

Indicator organisms

The direct detection of pathogenic bacteria, protozoa, and viruses within the environment is resource intensive in terms of cost, time, and expertise. Therefore, indicator organisms that are more easily detected are selected to infer the occurrence of fecal contamination. Microbial indicators are not necessarily human pathogens themselves, but if detected, indicate potential presence of enteric pathogens (Verhille 2013). Criteria for selecting a fecal indicator organism stipulate that the organism should be part of the intestinal microflora of warm-blooded animals, present when enteric pathogens are present and absent in uncontaminated samples, at least as or equally resistant to environmental stresses and disinfection as the contaminating pathogen, and relatively easy to detect (Bitton 2005).

Several indicators are used to detect fecal contamination including total coliforms, fecal coliforms, coliphages, *Clostridium perfringens*, enterococci, and *E. coli*; however, no single ideal indicator meets all criteria (Bitton 2005). Depending on the pathogens of interest, specific and multiple detection tests may be necessary to characterize the fate and transport of wastewater contamination in the receiving environment.

Fate and transport in physical environments

In order to elicit a disease outcome, pathogens released from the wastewater treatment system and transmitted through the natural environment (terrestrial or aquatic) must survive long enough to come into contact with another susceptible host. Fate and transport models are used to estimate the distribution patterns and inactivation of pathogens as they travel though the various environmental media (conceptualized in category 2 in Fig. 1). Within general models, the environmental fate of pathogens is largely related to ambient temperature, biotic activity, and sunlight (Nevers and Boehm 2011). Common parameters used in fecal indicator models of transport in surface water include rainfall, wave and current action, tidal stage, wind direction, and turbidity (Nevers and Boehm 2011). The strength and pressure of the initial wastewater plume will also influence the environmental mobility of pathogens contained in the effluent being released.

Given that temperature and sunlight are among the most important influences, it should be considered that fate and transport processes in an arctic environment may be unique (Simon et al. 2013). Temperatures in the region remain consistently below freezing for up to 9 months per year, which has the potential to reduce the concentration of microorganisms in wastewater (Gunnarsdottir et al. 2012). Rates of pathogen inactivation by sunlight may also differ as arctic summers include several weeks of 24-h daylight at higher latitudes. These periods are countered by months of minimal daylight during the mid-winter. Modeling the fate and transport of specific pathogens in the arctic environment requires parameterizing these factors.

Reservoirs

As pathogens are released from wastewater treatment plants and migrate through the immediate surroundings, there is also potential for deposition, storage, and concentration in reservoirs and biological organisms (conceptualized in Fig. 1, category 3). Indirect exposure to pathogens via recreational and occupational activities or food consumption (e.g., hunting, fishing) may also lead to potential illness or disease in humans. Attributing adverse health impacts to wastewater point sources via indirect exposures such as these by use of epidemiological studies is difficult unless several cases or an outbreak has occurred and an investigation can link the infected cases to a shared exposure. However, discharging wastewater effluent in close proximity to recreational and food-harvesting areas is likely to increase risk of human health effects associated with these activities (Holeton et al. 2011).

Bottom sediment of aquatic environments receiving effluent can serve as storage reservoirs for microbial pathogens. Accumulation leads to higher concentrations of pathogens in the sediment than in the overlying waters (Bitton 2005). Fecal coliform indicator organisms may be 100–1000 times more concentrated in such sediment (Ford 2005; Van Donsel and Geldreich 1971). Pathogen-loaded sediments can become disrupted and resuspended by rain and tides or aerosolized by breaking waves, creating potential exposure risks during recreational or occupational activities such as swimming, boating, or fishing (Bitton 2005).

Waterborne agents may also concentrate in fish or shellfish. Shellfish are particularly significant vectors of pathogens because they live in estuarine environments, which often receive sewage effluent. Filter-feeding bivalve mollusks, such as mussels, clams, oysters, scallops, and cockles, have the potential to accumulate pathogens because they filter between 4 and 20 L/h of water while feeding (Bitton 2005; Kay et al. 2008). The main environmental factors influencing shellfish contamination are season, water temperature, tidal cycle, and rainfall (Lee and Morgan 2003). Furthermore, shellfish is often eaten raw or undercooked. Infectious disease outcomes resulting from eating shellfish with concentrated fecal contaminants include campylobacteriosis, salmonellosis, cryptosporidiosis, and cholera (Ford 2005). Less is known about the potential human health risks of handling and consuming fish that live in marine water receiving wastewater effluent (Holeton et al. 2011). Loomer et al. (2008) reported increased concentrations of fecal coliforms on the skin of two species of fish, smelt (*Osmerus mordax*) and mummichog (*Fundulus heteroclitus*), collected at sites near wastewater outfalls in Saint John Harbour, New Brunswick, Canada. Water samples also collected from the sites showed a broad range of fecal coliform levels from a low of 21 to a high of 1.5×10^7 colony forming units (CFU)/100 mL, the latter being well above recreational water quality guidelines of ≤200 CFU/100 mL (Health Canada 2012). The role of marine and land mammals as well as fowl as reservoirs and carriers of human fecal inference organisms is also not well understood, as many enteric pathogens such as *Salmonella* species are natural inhabitants of the intestinal tracts of warm-blooded animals and water fowl (Fallacara et al. 2001; Ford 2005; Messier et al. 2007).

Inuit population and Arctic community activities

Many aspects of life in Arctic communities center on the natural environment. However, activities such as hunting, fishing, trapping, foraging, and consuming untreated drinking water place Inuit populations and other Arctic residents at elevated risk of exposure to pathogenic agents (Fleming et al. 2006; Suk et al. 2004). It is necessary to take the details of these activities into consideration to accurately define exposure pathways and risk scenarios (conceptualized in Fig. 1, category 4).

Many Inuit collect raw surface water from rivers and lake or melt ice as a preferred source of drinking water. The link between this practice and increased risk of gastroenteric diseases has been previously investigated in Inuit communities (Harper et al. 2011a; Martin et al. 2007). Results showed that the source water quality was impacted by rainfall and snowmelt events (Harper et al. 2011a). Also, the storage containers used to collect water were contaminated in some instances (Martin et al. 2007). Environmental monitoring of the collection sites was recommended as well as strategic collection of health information at the local health clinic (Harper et al. 2011a; Martin et al. 2007). Shellfish harvesting is common in many Inuit communities, including some that currently use mechanical wastewater treatment systems that continuously discharge into tidal areas. A study of the microbial quality of blue mussels (*Mytilus edulis*) in six Inuit communities in Nunavik, Quebec (Canada), found the mussels examined to be of good microbiological and viral quality but did detect the presence of the potentially pathogenic protozoa *Giardia duodenalis* and C*ryptosporidium* spp. (Lévesque et al. 2010). Nearshore fishing in marine waters by rod and net is also common among Inuit in the spring and fall seasons. Marine mammals are another important food sources for Inuit. Another study in the Inuit region of Nunavik, which found high prevalence of *G. duodenalis* in ringed and bearded seals, hypothesized sewage runoff into the marine environment as a potential source of the infection (Dixon et al. 2008). Furthermore, a relatively higher prevalence of the protozoan pathogen observed in younger seals may be associated with their summer habitat near the shore, which is likely more contaminated with pathogens from wastewater than are offshore habitats (Dixon et al. 2008). This scenario represents another potential set of pathways for zoonotic transmission to Inuit who consume raw or aged seal meat that may have come into contact with the intestinal contents during the butchering process. Although swimming is rare, other shore-based activities where low and intermediate exposure may occur include launching and anchoring small boats which can involve wading into the water and general recreational play by children whom tend to be very active along the shore in the long-daylight periods.

The three routes of exposure by which humans come into contact with a waterborne or foodborne pathogen are ingestion, inhalation, and absorption (conceptualized in Fig. 1, category 5). Most human health risk assessments assume default contact rates, such as an ingestion rate of 2 L of water per day for example. However, using consumption distributions, if available, that account for climatic, dietary, and urban-rural differences in populations lead to more accurate estimations (Hynds et al. 2012; Mons et al. 2007). This is an important consideration for Inuit populations as their diet includes a considerable amount of raw meat and fish. Amounts are likely far greater than the average consumption frequencies for raw foods used in many QMRAs (Ralson 1995). Once suitable case-specific information regarding potential exposure pathways and exposure routes has been obtained; these pieces of information can be combined to create risk scenarios, which are the situations that are actually quantitatively assessed. Tailored scenarios such as these were used in a human health risk assessment of exposures related to contaminated military operation sites in the Arctic (Jacques Whitford Limited 2005).

Suggested research and data to address gaps and support QMRA

Based on the reviewed literature, Table 1 outlines the current state of knowledge as it relates to parameterizing variables for each category of the original conceptual model. Within the table, the evidence base for each category is labeled with a status of "strong," "moderate," or "weak." The labels correspond to the strength and suitability of the applicable input for a quantitative microbial risk assessment. Additional studies, environmental monitoring, and health surveillance activities are suggested in areas where knowledge gaps are identified. Data from which can be used to underpin more comprehensive risk assessments in the future.

Conclusion

While it appears that passive wastewater treatment systems are appropriate for arctic regions, the human health risks associated with their use in this setting are yet to be assessed. We have proposed a framework for a screening-level QMRA of wastewater management in Canadian Arctic communities. In the supporting literature review, we evaluated the current strength of available evidence for each category of information necessary to begin developing the unparameterized model into a practical risk assessment tool. The state of knowledge pertaining to wastewater treatment systems (pathogen source), fate and transport of pathogens in the physical environment, and potential exposure pathways (human activities and transmission routes) are all moderate to strong. Information about the level of pathogens present in wildlife and fish (biological environment) is weak; however, we recommend the use of conservative estimates based on literature values until context-specific information becomes available. The Arctic is a distinct ecosystem, and the data sets, models, and assumptions that are necessary to evaluate most types of

Table 1 State of knowledge and data needs for a QMRA of potential wastewater effluent exposure pathways in Inuit communities

Category	State of knowledge[a]	Suggested research and data to address knowledge gaps
1. Pathogen source	Strong	• Infectious pathogens that are present in domestic wastewater are documented in general literature (Bitton 2005; Leclerc et al. 2002). Additional pathogens of particular interest in northern communities, although not among the most commonly monitored general suite, could also be considered. For instance, there is evidence of high prevalence of some antibiotic-resistant bacteria such as methicillin-resistant *Staphylococcus aureus* (MRSA) (Daloo et al. 2008; Golding et al. 2010).The general process of removing pathogens using mechanical or passive systems is well established (Bitton 2005; Crites and Tchobanoglous 1998) • Data characterizing minimally engineered treatment system performance in arctic conditions is available in published literature (Chouinard et al. 2014; Doku and Heinke 1995; Gunnarsdottir et al. 2013; Hayward et al. 2014; Krkosek et al. 2012; Ragush et al. 2015; Schmidt et al. 2016; Yates et al. 2012). Additional treatment performance data of a more basic nature such as influent volumes, discharge schedules, and discharge point *E. coli* levels may be available from municipal or territorial public work departments
2. Physical environment	Moderate	• Fate and transport modeling of wastewater pathogens in arctic environments requires a comprehensive research program. Studies on the viability and survival patterns of specific pathogens under arctic conditions have been proposed (Simon et al. 2013) • Until more comprehensive water monitoring and analysis capacity becomes available in the region, *E. coli* is a suitable fecal indicator in the Arctic, despite its limitations. Detection of *E. coli* indicates the presence of fecal material from warm-blooded animals. Agriculture is not widely practiced in the Arctic, so humans are the only significant source. However, caribou, sled dogs, and waterfowl such as geese may also have to be investigated as potential sources in some communities. *E. coli* have a survival pattern similar to bacterial pathogens but are less resistant to disinfection than viruses and protozoa (Bitton 2005). Since most treatment systems in the Canadian Arctic lack a disinfection stage, this is only a minor limitation • It is assumed that the inactivation or dilution of *E. coli* in either a treatment system or the environment can be used to conservatively predict the reduction of specific pathogenic bacteria (Nevers and Boehm 2011). Therefore, if the concentration reduction rates of *E. coli* are available, based on differences between influent and effluent, those rates can be applied to typical values of actual pathogens that would be present in raw sewage to generate estimates of pathogen concentrations in the environment at different locations (Schoen and Ashbolt 2010). Additional distinctions will be necessary to account for the differences in degradation rates within the physical environment between bacterial pathogens, viruses, and protozoans
3. Biological environment	Weak	• Information about the levels of pathogens present in specific wildlife and fish is necessary to build accurate probability distributions for human exposure • With the exception of shellfish, there is a lack of data about the uptake, latency, and transmission of wastewater pollution by animals that are common in the Inuit diet (Lévesque et al. 2010) • Studies and environmental monitoring of the microbiological quality of specific fish and animals that are favored as a food source and are present near treatment areas are recommended, as they may be vectors. • Currently, conservative estimates based on general values or uptake ratios that are available in human health risk assessment guideline documents must be used (United States Environmental Protection Agency 2012)
4. Human activity	Strong	• Human activities that allow for exposure pathways may be unique to each region and community in the Arctic. Consultation with community stakeholders, both via qualitative research methods or more informally, can help to narrow the broad list of possible exposures presented in the conceptual model and identify the most probable (Guyot et al. 2006). Most communities in Nunavut have local hunter and trapper organizations that are very knowledgeable in these matters • Territorial environmental health officers and epidemiologists are also an important source. Although the collection of surveillance data on gastroenteric disease at the community level is limited, these officials may provide direction on emerging foodborne and waterborne illness and suspected pathogens • Spatial and temporal details of food-harvesting and other activities can be used to create and prioritize risk scenarios
5. Transmission routes	Moderate	• High-priority risk scenarios must be further developed with the addition of contact rates and exposure frequencies • Default ingestion, inhalation, and absorption values can be found in available literature (United States Environmental Protection Agency 2012). However, these values may need to be adjusted using a proportional or corrective factor to be appropriate for Inuit populations, particularly relating to raw

Table 1 (continued)

Category	State of knowledge[a]	Suggested research and data to address knowledge gaps
		food consumption. Health Canada provides some supplemental guidance on human health risk assessment of locally harvested food (Health Canada 2010) • Community stakeholder consultation combined with human intake data from government food-harvesting records may provide more accurate estimations

[a] Legend for state of knowledge

Strong: sufficient data currently available to support QMRA including general parameter values from established literature as well as context-specific studies.

Moderate: some data currently available to support QMRA such as general parameter values from established literature but minimal context-specific information. Tailored studies are needed to improve understanding of localized conditions.

Weak: limited data currently available to support QMRA. Considerable knowledge gaps within established literature to inform parameter values resulting in high levels of uncertainty and use of conservative assumptions

environmental health risks in this context will likely always be trademarked by relatively high degrees of uncertainty. Overall, despite the limitations noted, we conclude that the current state of available data regarding wastewater treatment in Arctic communities is substantive enough to be applied in a predictive manner to assess the nature and size of associated public health risks.

QMRA can serve as a compliment to customary epidemiological, ecological, and engineering studies on public health and wastewater treatment in any rural and remote areas where data is extremely limited. This is particularly important in the Arctic, wherein basic sanitation techniques are being used by a population who rely on their local environment as a source of water, food, recreation, and livelihood. Our approach also allows for the inclusion of social and cultural aspects of life in Indigenous and other arctic communities by tailoring exposure pathways and scenarios based on local input. Ultimately, a fully developed QMRA will aid decision-makers in selecting appropriate wastewater treatment system designs, quantifying and prioritizing public health risks, and comparing relative benefits of various risk mitigation options.

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References

Ashbolt N (2004) Microbial contamination of drinking water and disease outcomes in developing regions. Toxicology 198:229–238

Ashbolt N, Amézquita A, Backhaus T, Borriello P, Brandt KK, Collignon P, Coors A, Finley R, Gaze WH, Heberer T, Lawrence JR, Larsson DGJ, McEwen SA, Ryan JJ, Schönfeld J, Silley P, Snape JR, Van den Eede C (2013) Human health risk assessment for environmental development and transfer of antibiotic resistance. Environ Health Persp 121(9):993–1001

Bartell S (2005) Risk assessment. In: Frumkin H (ed) Environmental health: from global to local. Jossey-Bass, San Francisco, pp 940–960

Beaudequin D, Harden F, Roiko A, Stratton H, Lemckert C, Mengersen K (2015) Modelling microbial risk of wastewater reuse: a systems perspective. Environ Int 84:131–141

Bitton G (2005) Wastewater microbiology, 3rd edn. Wiley, Hoboken, NJ

Bjerregaard P, Berner J, Oyvind J (2008) Chapter 10: environment and living conditions. In: Young K, Bjerregaard P (eds) Health transitions in arctic populations. University of Toronto Press Incorporated, Toronto, pp 173–191

Canadian Broadcast Corporation (2015) February 11: Pond Inlet declares state of emergency over water, sewage crisis. CBC News. http://www.cbc.ca/news/canada/north/pond-inlet-declares-state-of-emergency-over-water-sewage-crisis-1.2953531. Accessed 15 June 2016

Canadian Council of Ministers of the Environment (2009) Canada wide strategy for the management of municipal wastewater effluent. http://www.ccme.ca/ assets/pdf/cda_wide_strategy_mwwe_final_e.pdf. Accessed 15 June 2016

Canadian Council of Ministers of the Environment (2014) Canada-wide strategy for the management of municipal wastewater effluent: 2014 progress report. http://www.ccme.ca/en/resources/water/municipal_wastewater_effluent.html . Accessed 15 June 2016

Center for Advancing Microbial Risk Assessment (2016) Quantitative microbial risk assessment wiki http://qmrawiki.canr.msu.edu/

index.php/Quantitative_Microbial_Risk_Assessment_(QMRA)_Wiki. Accessed 15 June 2016

Chouinard A, Yates CN, Balch GC, Jørgensen SE, Wootton BC, Anderson BC (2014) Management of tundra wastewater treatment wetlands within a lagoon/wetland hybridized treatment system using the SubWet 2.0 wetland model. Water 6(3):439–454

Crites R, Tchobanoglous G (1998) Small and decentralized wastewater management systems. McGraw-Hill, New York

Daley K, Castleden H, Jamieson R, Furgal C, Ell L (2015) Water systems, sanitation, and public health risks in remote communities: Inuit resident perspectives from the Canadian Arctic. Soc Sci Med 135:124–132

Daloo A, Sobol I, Palacios C, Muluey M, Gravel D, Panaro C (2008) Investigation of community-associated methicillin-resistant *Staphylococcus aureus* in a remote northern community, Nunavut, Canada. Can Commun Dis Rep 35:1–7

Dixon B, Parrington L, Parenteau M, Leclair D, Santin M, Fayer R (2008) Giardia duodenalis and cryptosporidium spp. in the intestinal contents of ringed seals (*Phoca hispida*) and bearded seals (*Erignathus barbatus*) in Nunavik, Quebec, Canada. J Parasitol 94(5):1161–1163

Doku IA, Heinke GW (1995) Potential for greater use of wetlands for waste treatment in northern Canada. J Cold Reg Eng 9(2):75–88

Dudarev A, Dorofeyev V, Dushkina E, Alloyarov P, Chupakhin V, Sladkova Y, Kolesnikova T, Fridman K, Nilsson LM, Evengard B (2013) Food and water security issues in Russia III: food- and waterborne diseases in the Russian Arctic, Siberia and the Far East, 2001–2011. Int J Circumpol Heal 72:21856

Environment Canada (2015) Wastewater systems effluent regulations. http://www.ec.gc.ca/eu-ww/. Accessed 15 June 2016

Fallacara DM, Monahan CM, Morishita TY, Wack RF (2001) Fecal shedding and antimicrobial susceptibility of selected bacterial pathogens and a survey of intestinal parasites in free-living waterfowl. Avian Dis 45:128–135

Ferrer A, Nguyen-Viet H, Zinsstag J (2012) Quantification of diarrhea risk related to wastewater contact in Thailand. EcoHealth 9:49–59

Fleming LE, Broad K, Clement A, Dewailly É, Elmir S, Knap A, Pomponi SA, Smith S, Solo Gabriele H, Walsh P (2006) Emerging public health risks in the marine environment. Mar Pollut Bull 53(10–12):545–560

Ford T (2005) Water and health. In: Frumkin H (ed) Environmental health: from global to local. Jossey-Bass, San Francisco, pp 454–518

Goldfarb DM, Dixon B, Moldovan I, Barrowman N, Mattison K, Zentner C, Baikie M, Bidawid S, Chan F, Slinger R (2013) Nanolitre real-time PCR detection of bacterial, parasitic, and viral agents from patients with diarrhoea in Nunavut, Canada. Int J Circumpol Heal 72:19903

Golding G, Levett P, McDonald R, Irvine J, Nsungu M, Woods S, Horbal A, Siemens C, Khan M, Ofner-Agostini M, Mulvey M, Partnership NAR (2010) A comparison of risk factors associated with community-associated methicillin-resistant and susceptible *Staphylococcus aureus* infections in remote communities. Epidemiol Infect 138(5):730–737

Gunnarsdottir R, Mueller K, Jenssen PE (2012) Effect of long-term freezing and freeze-thaw cycles on indigenous and inoculated microorganism in dewatered blackwater. Environ Sci Technol 46(22):12408–12416

Gunnarsdottir R, Jenssen P, Jensen PE, Villumsen A, Kallenborn R (2013) A review of wastewater handling in the Arctic with special reference to pharmaceuticals and personal care products (PPCPs) and microbial pollution. Ecol Eng 50:76–85

Guyot M, Dickson C, Paci C, Furgal C, Chan HM (2006) Local observations of climate change and impacts on traditional food security in two northern aboriginal communities. Int J Circumpol Heal 65(5):403–415

Haas G, Rose J, Gerba C (2014) Quantitative microbial risk assessment. Wiley, New York

Harper S, Edge V, Shuster-Wallace C, Berke O, McEwen S (2011a) Weather, water quality and infectious gastrointestinal illness in two Inuit communities in Nunatsiavut, Canada: potential implications for climate change. EcoHealth 8:93–108

Harper SL, Edge VL, Schuster-Wallace CJ, Ar-Rushdi M, McEwen SA (2011b) Improving aboriginal health data capture: evidence from a health registry evaluation. Epidemiol Infect 139(11):1774–1783

Harper SL, Edge VL, Ford J, Thomas MK, Pearl DL, Shirley J, IHACC Research Group, McEwen S (2015a) Acute gastrointestinal illness in two Inuit communities: burden of illness in Rigolet and Iqaluit, Canada. Epidemiol Infect 143(14):3048–3063

Harper SL, Edge VL, Ford J, Thomas MK, Rigolet Inuit Community Government, IHACC Research Group, McEwen S (2015b) Lived experience of acute gastrointestinal illness in Rigolet, Nunatsiavut: "just suffer through it". Soc Sci Med 126:86–98

Hayward J, Jamieson R, Boutilier L, Goulden T, Lam B (2014) Treatment performance assessment and hydrological characterization of an arctic tundra wetland receiving primary treated municipal wastewater. Ecol Eng 73:786–797

Health Canada (2010) Federal contaminated site risk assessment in Canada: supplemental guidance on human health risk assessment of country foods, catalogue no H128–1/11-641E-PDF. www.healthcanada.gc.ca. Accessed 15 June 2016

Health Canada (2012) Guidelines for Canadian recreational water quality, 3rd edn, catalogue no H129–15/2012E. www.healthcanada.gc.ca/waterquality. Accessed 15 June 2016

Hedlund C, Blomstedt Y, Schumann B (2014) Association of climatic factors with infectious diseases in the Arctic and subarctic region: a systematic review. Glob Health Action 7:24161

Hennessy T, Bressler J (2016) Improving health in the Arctic region through safe and affordable access to household running water and sewer services: an Arctic council initiative. Int J Circumpol Heal 75:31149

Holeton C, Chambers PA, Grace L (2011) Wastewater release and its impact on Canadian waters. Can J Fish Aquat Sci 68:1836–1869

Howard G, Pedley S, Tibetemwa S (2006) Quantitative microbial risk assessment to estimate health risks attributable to water supply: can the technique be applied in developing countries with limited data? Journal Wat and Health 4(1):49–65

Huang Y, Ragush C, Stea E, Jackson A, Lywood J, Jamieson R, Truelstrup Hansen L (2014) Removal of human pathogens in waste stabilization ponds in Nunavut. Paper presented at the Canadian Society for Civil Engineering 2014 Annual Conference & 13th International Environmental Specialty Conference. Halifax, Nova Scotia. doi:10.13140/2.1.3479.1689

Hynds PD, Misstear BD, Gill LW (2012) Investigation of water consumption patterns among Irish adults for waterborne quantitative microbial risk assessment. J Water Health 10(3):453–464

Jacques Whitford Limited (2005) Human health and ecological risk assessment for CAM-F DEW Line Site: Sarcpa Lake, Nunavut Territory. Nunavut Impact Review Board. www.nirb.ca. Accessed 15 June 2016

Johnson K, Prosko G, Lycon D (2014) The challenges with mechanical wastewater systems in the Far North. Published in the proceedings of the 2014 Annual Conference of Western Canada Water & Waste Association, September 23–26 2014, Regina, Saskatchewan. www.wcwwa.ca. Accessed 15 June 2016

Inuit Tapiriit Kanatami, Johnson K (2008) National Inuit position paper regarding the CCME Canada-wide strategy for the management of municipal wastewater effluent and Environment Canada's proposed regulatory framework for wastewater. https://www.itk.ca/publication/inuit-position-management-municipal-wastewater. Accessed 15 June 2016

Kay D, Kershawn S, Lee R, Wyer M, Watkins J, Francis C (2008) Results of field investigations in the impact of intermittent sewage discharges on the microbiological quality of wild mussels (*Mytilus edulis*) in a tidal estuary. Water Res 42:3033–3046

Krkosek WH, Ragush C, Boutlier L, Sinclair A, Krumhansl K, Gagnon GA, Lam B (2012) Treatment performance of wastewater stabilization ponds in Canada's Far North. In Morse B, Doré G (eds) Cold regions engineering 2012: Sustainable infrastructure development in a changing cold environment. doi: 10.1061/9780784412473.061

Krumhansl K, Krkosek W, Greenwood M, Ragush C, Schmidt J, Grant J, Barrell J, Lu L, Lam B, Gagnon G, Jamieson R (2015) Assessment of Arctic community wastewater impacts on marine benthic invertebrates. Environ Sci Technol 49(2):760–766

Lam B, Livingston T (2011) Active research into passive systems: a study of wastewater in Nunavut. Journal of the Northern Territories Water and Waste Association 7:42–45 http://www.ntwwa.com/journal.asp. Accessed 15 June 2016

Leclerc H, Schwartzbrod L, Dei-Cas E (2002) Microbial agents associated with waterborne disease Crit Rev Microbiol 28:371–409

Lee RJ, Morgan OC (2003) Environmental factors influencing the microbiological contamination of commercially harvested shellfish. Water Sci Technol 47(3):65–70

Lévesque B, Barth C, Dixon B, Parrington L, Martin D, Doidge B, Proulx JF, Murphy D (2010) Microbiological quality of blue mussels (*Mytilus edulis*) in Nunavik, Quebec: a pilot study. Can J Microbiol 56:968–977

Loomer HA, Kidd KA, Vickers T, McAslan A (2008) Swimming in sewage: indicators of fecal waste on fish in the Saint John Harbour, New Brunswick. Water Qual Res J Can 43(4):283–290

Martin D, Bélanger D, Gosselin P, Brazeau J, Furgal C, Déry S (2007) Drinking water and potential threats to human health in Nunavik: adaptation strategies under climate change conditions. Arctic 60(2): 195–202

McKeown I, Orr P, Macdonald S, Kabani A, Brown R, Coghlan G, Dawood M, Embil J, Sargent M, Smart G, Bernstein C (1999) *Helicobacter pylori* in the Canadian arctic: Seroprevalence and detection in community water samples. Am J Gastroenterol 94(7): 1823–1829

Messier V, Lévesque B, Proulx JF, Ward B, Libman M, Couillard M, Martin D, Hubert B (2007) Zoonotic diseases in drinking water and gastroenteritis in Nunavik: a brief portrait. Institute national de santé publique du Québec. http://www.inspq.gc.ca. Accessed 15 June 2016

Messier V, Lévesque B, Proulx JF, Rochette L, Serhir B, Couillard M, Ward BJ, Libman MD, Dewailly É, Déry S (2012) Seroprevalence of seven zoonotic infections in Nunavik, Quebec, Canada. Zoonoses Public Hlth 59:107–117

Mons MN, van der Wielen JM, Blokker EJ, Sinclair MI, Hulshof IKF, Dangenforf F, Hunter PR, Medema GJ (2007) Estimation of the consumption of cold tap water for microbial risk assessment: an overview of studies and statistical analysis of data. J Water Health 5(1):151–170

Murphy HM, Thomas MK, Medeiros DT, McFayden S, Pintar KDM (2016a) Estimating the number of cases of acute gastrointestinal illness associated with Canadian municipal drinking water systems. Epidemiol Infect 144(7):1371–1385

Murphy HM, Thomas MK, Schmidt PJ, Medeiros DT, McFayden S, Pintar KDM (2016b) Estimating the burden of acute gastrointestinal illness due to *Giardia*, *Cryptosporidium*, *Camplyobacter*, *E. coli* O157 and norovirus associated with private wells and small water systems in Canada. Epidemiol Infect 144(7):1355–1370

Nevers MB, Boehm AB (2011) Modeling fate and transport of fecal bacteria in surface water. In: Sadowsky MJ, Whitman RL (eds) The fecal bacteria. American Society for Microbiology, Washington, pp 165–187

Nickels S, Furgal C, Buell M, Moquin H (2005) Unikkaaqatigiit: putting the human face on climate change: perspectives from Inuit in Canada. Joint publication of Inuit Tapiriit Kanatami, Nasivvik Centre for Inuit Health and Changing Environments, and the Ajunniginiq Centre at the National Aboriginal Health Organization. https://www.itk.ca/canadian-inuit-perspectives-climate-change-unikkaaqatigiit/. Accessed 15 June 2016

Nunavut Bureau of Statistics (2014) Population estimates. http://www.stats.gov.nu.ca. Accessed 15 June 2016

Pardhan-Ali A, Berke O, Wilson J, Edge VL, Furgal C, Reid-Smith R, Santos M, McEwen SA (2012a) A spatial and temporal analysis of notifiable gastrointestinal illness in the northwest territories, Canada, 1991–2008. Int J Health Geogr 11:17

Pardhan-Ali A, Wilson J, Edge,VL, Furgal C, Reid-Smith R, Santos M, McEwen SA (2012b) A descriptive analysis of notifiable gastrointestinal illness in the northwest territories, Canada, 1991–2008. BMJ Open 2:e000732

Pardhan-Ali A, Wilson J, Edge VL, Furgal C, Reid-Smith R, Santos M, McEwen SA (2013) Community-level risk factors for notifiable gastrointestinal illness in the northwest territories, Canada, 1991–2008. BMC Public Health 13:63

Parkinson AJ, Evengard B, Semenza JC, Odgen N, Børensen ML, Berner J, Brubaker M, Sjöstedt A, Evander M, Hondula DM, Menne B, Pshenichnaya N, Gounder P, Larose T, Revich B, Hueffer K, Albihn A (2014) Climate change and infectious diseases in the Arctic: establishment of a circumpolar working group. Int J Circumpol Heal 73:25163

Prüss A, Kay D, Fewtrell L, Bartam J (2002) Estimating the burden of diseases from water, sanitation, and hygiene at a global level. Environ Health Persp 110(5):537–542

Ragush C, Schmidt J, Krkosek W, Gagnon G, Truelstrup Hansen L, Jamieson R (2015) Performance of municipal waste stabilization ponds in the Canadian Arctic. Ecol Eng 83:413–421

Ralson K (1995) Identifying frequent consumers of foods associated with foodborne pathogens. In: Roberts T, Jensen H, Unnevehr L (eds) Tracking foodborne pathogens from farm to table: data needs to evaluate control options. Miscellaneous Publication 1532. United States Department of Agriculture, Economic Research Service, Washington, pp 41–50 Reproduced in Haas et al., 2014

Robson M, Ellerbusch F (2007) Introduction to risk assessment in public health. In: Robson M, Toscano W (eds) Risk assessment for environmental health. Jossey-Bass, San Franciso, pp 1–10

Sales-Ortells H, Medema G (2014) Screening-level microbial risk assessment of urban water locations: a tool for prioritization. Environ Sci Technol 48:9780–9789

Schmidt J, Ragush C, Krkosek W, Gagnon G, Jamieson R (2016) Characterizing phosphorus removal in passive waste stabilization ponds in Arctic communities. Arctic Science 2:1–14

Schoen ME, Ashbolt NJ (2010) Assessing pathogen risk to swimmers at non-sewage impacted recreational beaches. Environ Sci Technol 44(7):2286–2291

Simon A, Bigras Poulin M, Rousseau A, Odgen N (2013) Fate and transport of *Toxoplasma gondii* in seasonally snow covered watersheds: a conceptual framework from a melting snowpack to the Canadian Arctic coasts. Int J Environ Res Public Health 10:994–1005

Smith DW (1996) Cold regions utilities monograph, 3rd edn. American Society of Civil Engineers, Reston

Suk W, Avakian M, Carpenter D, Groopman J, Scammell M, Wild C (2004) Human exposure monitoring and evaluation in the Arctic: the importance of understanding exposures to the development of public health policy. Environ Health Persp 112(2):113–120

Suter G (1999) Developing conceptual models for complex ecological risk assessments. Hum Ecol Risk Assess 5(2):375–396

Teklehaimanot G, Genthe B, Kamika I, Momba MNB (2015) Prevalence of enteropathogenic bacteria in treated effluents and receiving water

bodies and their potential health risks. Sci Total Environ 518-519: 441–449
Thomas MK, Murray R, Flockhart L, Pintar K, Pollari F, Fazil A, Nesbitt A, Marshall B (2013) Estimates of the burden of foodborne illness in Canada for 30 specified pathogens and unspecified agents, circa 2006. Foodborne Pathog Dis 10(7):639–651
United States Environmental Protection Agency (2012) Human health risk assessment. http://www.epa.gov/risk/health-risk.htm. Accessed 15 June 2016
Van Donsel DJ, Geldreich EE (1971) Relationships of *Salmonellae* to fecal coliforms in bottom sediments. Water Res 5:1079–1087
Verhille S (2013) Understanding microbial indicators for drinking water assessment: interpretation of test result and public health significance. National Collaborating Centre for Environmental Health. http://www.ncceh.ca/publications-products/guidance-documents?f[0]=field_topic%3A493. Accessed 15 June 2016
Westrell T, Schonning C, Stenstrom TA, Ashbolt N (2004) QMRA and HACCP for management of pathogens in wastewater and sewage sludge treatment and reuse. Water Sci Technol 50(2):23–30
Yapo R, Koné R, Bonfoh B, Cissé G, Zinsstag J, Nguyen-Viet H (2014) Quantitative microbial risk assessment related to urban wastewater and lagoon reuse in Abidjan, Côte d'Ivoire. J Water Health 12(2): 301–309
Yates C, Wootton B, Murphy S (2012) Performance assessment of arctic tundra municipal wastewater treatment wetlands through an arctic summer. Ecol Eng 44:160–173