HUMAN HEALTH RISKS ASSOCIATED WITH WASTEWATER TREATMENT IN ARCTIC CANADA

by

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Abstract

This dissertation provides the first estimates of microbial health risks attributable to wastewater treatment systems in Arctic Canada. A participatory quantitative microbial risk assessment was designed to model a range of exposures scenarios and mitigations.

In Chapter Two, the state of knowledge on wastewater treatment, exposure pathways, and waterborne disease in Inuit and Arctic communities is reviewed. A conceptual model is developed to guide the risk assessment. Chapter Three describes a screening-level quantitative microbial risk assessment model and estimates the probability of acute gastrointestinal illness (AGI) associated with worst-case exposure scenarios in five Nunavut case study sites. An annual incidence rate of 5.0 cases per person is predicted in Pangnirtung, where a mechanical treatment system discharges to a marine environment at low tide. An incidence rate of 1.2 cases per person is predicted in Naujaat, where an undersized passive system is used, with most cases predicted during spring freshet. These results are considered high and moderate, respectively, in comparison to literature-based estimates of AGI in the region. In Chapter Four, a more in-depth stochastic model is used to characterize risk for inferential Arctic wastewater exposure scenarios and results are compared to a global health guideline (10^{-3} annual risk of waterborne AGI). The 75th percentile risk level exceeds the guideline in three scenarios: shore recreation near mechanical treatment sites during low tide; consumption of shellfish harvested near mechanical treatment sites during low tide; and wetland travel near passive treatment sites during spring freshet. Rotavirus and *Salmonella* spp. project the highest risk of the six enteric pathogens included in the model. Two forms of mitigation are also evaluated (improved treatment, behavioural change), and both are shown to potentially reduce risk to varying degrees.

These findings suggest that wastewater exposures may be contributing to high AGI rates in some Arctic communities. Passive systems with controlled discharge and risk communication are recommended as the most appropriate wastewater treatment solution. This research has immediate application in Arctic regions and contributes to the broader socio-ecological understanding of water, sanitation, and health.

List of Abbreviations and Symbols Used

%	Percent
°C	Degrees Celsius
α	Slope of beta-Poisson model
AGI	Acute gastrointestinal illness
APHA	American Public Health Association
C_0	Initial concentration of indicator *E. coli* at effluent release point
CAD$	Canadian dollars
CAMRA	Center for Advancing Microbial Risk Assessment
$Cases_{all\ path}$	Annual expected cases of illness per exposure scenario
$Cases_{all\ path,location}$	Total annual expected cases of illness per location
$Cases_{path}$	Annual expected cases of illness per pathogen per exposure scenario
CCME	Canadian Council of the Ministers of the Environment
C_{dist}	Concentration of *E. coli* at distance of human exposure
CEFAS	Centre for Environment Fisheries & Aquaculture Science
CIHR	Canadian Institutes of Health Research
d	Dose
DALYs	Disability-adjusted life years
$d_{E.\ coli}$	*E. coli* dose
dist	Distance
d_{path}	Pathogen-specific dose
e	Base of the natural logarithm
E. coli	*Escherichia coli*
E. coli: Path	*E. coli*-to-pathogen inference ratio
EIEC	Enteroinvasive *E. coli*
ExpGroup	Number of individuals in exposure group per single event
freq	Frequency of exposure events per year
g	Grams
h	Hours
$Inc_{location}$	Annual individual incidence rate per location

$Inc_{location,1000}$	Annual incidence rate per 1000 persons per location
ITK	Inuit Tapiriit Kanatami
k	First-order reduction constant / slope of linear regression
L	Litres
Log_{10}	Logarithmic scale
m	Metres
M	Million
Mit. 1	Mitigation 1 – improved treatment
Mit. 2	Mitigation 2 – behavioural change
mL	Millilitres
MPN	Most probable number
MRSA	Methicillin resistant *Staphylococcus aureus*
MWWE	Municipal wastewater effluents
N_{50}	Median infectious dose
NSERC	Natural Sciences and Engineering Research Council
NTWWA	Northern Territories Water & Waste Association
$P(d)$	Probability of infection for a given dose
$\mathrm{P}_{\mathrm{ill}\,|\,\mathrm{inf}}$	Morbidity ratio
$P_{ill,\ annual}$	Annual individual probability of illness per exposure scenario
$P_{ill,path}$	Probability of illness per pathogen per single exposure
$P_{ill,path,total}$	Total probability of illness for all pathogens per single exposure event
$P_{inf,path}$	Probability of infection per pathogen per single exposure event
$Pop_{location}$	Location population
QMRA	Quantitative microbial risk assessment
r	Pathogen infectivity constant
REB	Research ethics board
spp.	Species pluralis
USEPA	United States Environmental Protection Agency
V	Volume
WHO	World Health Organization
WSP	Wastewater stabilization pond

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Chapter 1

Introduction

1.1 Rationale

In 2010, Dalhousie University and the Government of Nunavut launched a multi-year northern wastewater treatment research program. The primary objectives of the program were to characterize the efficacy of the treatment systems being used in communities across the Territory and the impact of effluent discharges on receiving environments. This program was spurred in response to nationwide treatment regulations put forth by Environment Canada (Canadian Council of the Ministers of the Environment [CCME] 2009; CCME 2014) and their disputed applicability to northern conditions (Inuit Tapiriit Kanatami [ITK] and Johnson 2008). The research program was designed from an engineering perspective with a principal focus on conventional environmental quality measurements to facilitate comparison with impending pollutant-based federal regulations.

One set of findings that emerged from this research program however, have direct human health implications: the research team confirmed that effluent being discharged to receiving waters near communities still contained pathogenic microorganisms (Huang et al. 2018). This information garnered attention from local communities, territorial health agencies, and other interested parties concerned about the risk posed to the public (Daley et al. 2015; Hennessy and Bressler 2016). The last known wastewater health risk assessments in Arctic Canada were conducted prior to the widespread implementation of community wastewater treatment systems (Michael 1984; Robinson and Heinke 1990). Inuit, who comprise 84 percent of the population of Nunavut, as well as other residents, rely on their local environment as a source of food, recreation, and overall well-being (Bjerregaard et al. 2004; Cunsolo Willox et al. 2012; Richmond and Ross 2009). If wastewater effluent discharge areas are overlapping with lands, water, and ice also being used for these vital services, potential exists for inadvertent human exposure (Nilsson et al. 2013). Exposure to microbial hazards commonly present in domestic wastewater can lead to acute gastrointestinal illness (AGI) in addition to other forms of infectious and chronic disease (Ashbolt 2004; Prüss et al. 2002).

Studies suggest that total food- and waterborne disease incidence rates in Inuit Nunangat, the Inuit homelands of Canada, and other Arctic regions are up to six times greater than Canadian averages (Dudarev et al. 2013; Harper et al. 2015a; Parkinson et al. 2014) and above rates in some less industrialized countries as well (Mathers et al. 2002; Thomas et al. 2013). The disease burden attributable specifically to wastewater exposure is unknown.

1.2 Research Purpose and Objectives

The purpose of this research is to provide the first contemporary estimates of human health risks attributable to wastewater exposure in Inuit Nunangat and other Arctic Canadian communities.

The specific objectives are to:

1) Review the state of knowledge on microbial health risks associated with wastewater treatment in Arctic Canada.
2) Develop a conceptual model of potential human exposure pathways in Arctic Canadian communities.
3) Characterize the probability of illness associated with specific exposure scenarios, using AGI as a health outcome.
4) Evaluate mitigations and management strategies to reduce risk, if necessary.

1.3 An Interdisciplinary Study

This dissertation is built on the premise that the health of populations is determined by a range of interrelated factors and conditions. In addition to individual characteristics, health is also shaped by the broader physical, social, and economic environments (Kindig and Stoddart 2003). Through studies of the interactions between health determinants, risks in individuals and communities can be predicted and prevention efforts can be developed (Young 2005).

Based on this population health perspective and the nature of the research problem, an interdisciplinary study was implemented. Complex, real world problems are rarely confined to boundaries of one academic discipline (Natural Sciences and Engineering Research Council of Canada [NSERC] 2012). Interdisciplinary research evolves to meet the demands of these types of problems by synthesizing links between two or more disciplines into a coordinated whole (Choi and Pak 2006; Canadian Institutes of Health Research [CIHR] 2005). This thesis specifically draws upon contributions from environmental engineering, epidemiology, and environmental studies. The following paragraphs describe specific concepts from each body of knowledge that inform the research. A detailed review situating the dissertation in the broader literature of each discipline is provided in Chapter Two.

Environmental engineering

Environmental engineering applies principles from the natural sciences to safeguard the quality of the environment and, in turn, protect human health (Davis and Cornwell 2015). Included in this domain are the evaluation and design of water supply and wastewater treatment systems. Ideally, environmental engineering research and projects adapt an appropriate technology strategy relevant to the context (Darrow and Saxenian 1993). Appropriate technology solutions not only meet technical requirements but also match the setting in terms of local capacity, affordability, and available materials to ensure long term sustainability (Murphy et al. 2009).

Epidemiology

Epidemiology, like environmental engineering, is an applied research discipline with links to several other fields such as mathematics, statistics, public health, and medicine. One practical definition of epidemiology is the study of the distribution, determinants, and deterrents of health-related behaviours and outcomes in human populations (Oleckno 2002). Epidemiology provides the basis for describing disease occurrence in a community as well as identifying risk factors and evaluating the efficacy of preventative options. Within the discipline, environmental epidemiologists, whose focus includes exposure to hazardous waste sites, have embraced participatory research approaches (Leung et al. 2004). Involving community members in the research process can lead to better informed hypotheses and data collection. And in turn, participatory approaches increase the likelihood that study results will genuinely benefit the people affected (O'Fallon and Dearry 2002).

Environmental studies

Environmental studies focuses on the human dimensions of environmental change and problem solving. Systems-based frameworks that often integrate data from the natural and social sciences are used to address intertwined environmental and societal challenges (Berkes et al. 2008). One approach for addressing complex challenges at the convergence of environment, society, and human health is ecohealth research (also referred to as ecosystem approaches to health). Among the core ecohealth principles are systems thinking, stakeholder participation, and knowledge-to-action (Charron 2012; Forget and Lebel 2001). Guided by these principles, ecohealth researchers, like environmental epidemiologists, often emphasize collaboration with people outside academia whom offer different perspectives and experiences in the form of citizen science, traditional knowledge (Waltner-Toews et al. 2003), and Indigenous ways of knowing (Cochran et al. 2008).

1.4 Research Design

A coordinated research design synthesizing the links between the interdisciplinary foundations is used. The design is comprised of two lines of inquiry: risk assessment and participatory research. A high-level overview is provided in the ensuing paragraphs and individual methods sections are included in each of the three manuscript chapters. Also, refer to Appendix A for a table detailing all model inputs and assumptions.

Risk assessment

Risk assessment is a public health research framework used to evaluate potential harm posed to human populations by agents in the environment. Methodologies used in risk assessment provide means of systematically organizing available information about processes, behaviours, or events that potentially expose people to a specified hazard (Rodricks 1994). Specifically, risk assessment involves use of models that employ data from a variety of sources, assumptions, mathematical formulas, and functions. The output or result of the process is a probability distribution or similar quantification that estimates the possible health consequences with a range of uncertainty and variation (Vose 2008).

Quantitative microbial risk assessment (QMRA) is a subfield of health risk assessment specific to microbial hazards (as opposed to chemical). The four steps involved are hazard identification, exposure assessment, dose-response, and risk characterization. QMRA continues to evolve as a distinct research field, having established its own modelling approaches and data sets. Interdisciplinary in nature, the basis is formed from a combination of fields including, but not limited to, engineering, epidemiology, mathematics, and microbiology (Haas et al. 2014). QMRA has previously been used in a variety of applications such as wastewater contact and reuse (Westrell et al. 2004), drinking water systems (Murphy et al. 2016a, Murphy et al. 2016b), recreational water (Schoen and Ashbolt 2010), and food safety (Haas et al. 2014). Additionally, QMRA is advantageous in terms of ranking relative risks among scenarios (Sales-Ortells and Medema 2014) and evaluating engineering controls or other forms of mitigation (Labite et al. 2010; Weir et al. 2011). While this thesis research is believed to represent the first use of QMRA in remote Arctic communities, research designs have previously been adapted for use in other data-limited settings within Africa and Asia (Ferrer et al. 2012; Howard et al. 2006; Hunter et al. 2009).

Participatory research

Participatory and community-based research approaches emphasize engagement, inclusion, and influence of nonacademic researchers in the knowledge creation process (Israel et al. 1998). As introduced in the previous subsections on epidemiology and environmental studies, participatory health research specifically refers to collaborative approaches involving community members and local organizational representatives from the impacted population. The benefits of the approach are a better understanding of the given issue, improved investigation, and greater potential for translating findings into practical health improvements.

Within health risk assessment methodologies, the exposure assessment stage is most amendable to participatory research concepts. This is the step wherein pathways and details of potential human exposure to hazardous agents are identified. Typically, this component of a QMRA relies heavily, if not exclusively, on literature-based assumptions derived from general populations (Haas et al. 2014). For this study, the exposure assessment necessitates understanding how Indigenous and other Arctic populations interact with their local environment. Such exposure scenarios differ substantially from those common to general populations in more industrialized settings as the immediate natural surroundings are a vital source of wild food, recreation, and livelihood to Arctic communities (Suk et al. 2004). Therefore, a modified participatory QMRA was designed wherein a model was applied in Arctic communities with consideration given to both the ecological and social environments. Information detailing people's activity patterns and food harvesting practices was collected via questionnaires, site-mapping exercises, and public forums in effort to characterize wastewater exposure scenarios distinct to Arctic Canadian populations and regions. Given the uncertainty and variability inherent with this type of data, some assumptions remain necessary in the exposure modelling process. However, combining traditional risk assessment frameworks with participatory research is emerging as an approach to strengthen models and increase the relevance of results within local policy and decision-making contexts (Nguyen-Viet et al. 2009; Ramirez-Andreotta et al. 2014).

Ensuring that results will be directly applicable at a local level is critically important when developing partnerships and undertaking research with Indigenous peoples and communities in Arctic Canada (ITK 2018; Tri-Council 2018). Historically, research involving Indigenous peoples in the Arctic, as well as other parts of Canada and globally, has primarily been carried out by non-Indigenous researchers and has under benefited, or even been detrimental to, the host communities (Battiste and Henderson 2000; Fletcher 2003). Self-determined priorities and reciprocal relationships are becoming more customary as obligatory forms of conduct when academic-based researchers seek partnerships with Indigenous communities (ITK 2018; Tuhwai Smith 2012).

This study builds on the established wastewater research partnership between Dalhousie University's Centre for Water Resource Studies, the Government of Nunavut's Department of Community & Government Services, the Nunavut Research Institute, and several Nunavut hamlets. Over the duration of the study, additional relationships have been formed with the Government of Nunavut's Department of Health. Preliminary results have also been shared and discussed regularly with the Northern Territories Water & Waste Association (NTWWA), a not-for-profit organization comprised of stakeholders involved in the provision of water, sanitation, and public health services at the local level in Arctic Canada (NTWWA 2020).

Procedural ethics and licensing

This research was given ethical approval by the Dalhousie University Research Ethics Board (REB # 2013-3021). Refer to Appendix B for the ethical approval letter. The study is also registered with the Nunavut Research Institute as a component of the *Northern Municipal Wastewater Effluent (MWWE) Discharge Quality Objectives in the Context of CCME MWWE Strategy and Environment Canada's Wastewater Systems Effluent Regulations* project. A research advisor from Nunavut Tunngavik Incorporated, the organization responsible for ensuring the implementation of the Nunavut Land Claims Agreement, was also consulted prior to initiating the study. No procedural ethical issues were encountered over the duration of this research.

1.5 Organization of Dissertation

This dissertation is organized into five chapters and follows a publication format. Included are an opening introductory chapter, three manuscript chapters, and a concluding chapter. Appendices and a complete reference list are also provided.

Chapter One provides the impetus for this study, the purpose and objectives, and an overview of the disciplinary contributions and research design.

Chapter Two provides a review of relevant literature on arctic wastewater treatment, potential human exposure pathways, and waterborne illness to scope and justify the research. A conceptual model based on this literature as well as discussions with key stakeholders in Arctic communities is then proposed as a directional guide for a microbial risk assessment. This chapter is published in the journal *Environmental Science and Pollution Research* as part of a special themed issue on Water, Sanitation, Pollution and Health in the Arctic (Daley et al. 2018a).

Chapter Three operationalizes the conceptual model proposed in Chapter Two. An initial screening-level risk assessment is presented estimating incidence of AGI attributable to wastewater exposures in five Nunavut case study sites. The results are placed in the context of total water- and foodborne gastrointestinal illness estimates within Inuit Nunangat, as sourced from literature. This chapter is published in the journal *Science of the Total Environment* (Daley et al. 2019).

Chapter Four builds on the findings of the previous chapter and presents an in-depth risk assessment of various Arctic wastewater exposure scenarios. An inferential model design is used with the intent of broadening the applicability of the assessment risk tool to include potential use in all Arctic communities in Canada. Results are compared to global tolerable risk guidelines from the World Health Organization (WHO). Risk mitigation possibilities are also assessed and discussed.

Chapter Five concludes the dissertation with a summary of the main findings and integrated discussion. The substantive contributions of the research, both scientific and practical, are highlighted. Recommendations for further research are also provided.

Chapter 2

Wastewater Treatment and Public Health in Nunavut: A Microbial Risk Assessment Framework for the Canadian Arctic

A version of this chapter has been published by Springer in the journal *Environmental Science and Pollution Research*. Refer to Appendix C for the copyright agreement to reproduce this material.

Daley, K., Jamieson, R., Rainham, D., and Truelstrup Hansen, L. (2018). Wastewater treatment and public health in Nunavut: a microbial risk assessment framework for the Canadian Arctic. *Environmental Science and Pollution Research* 25(33), 32860-32872.

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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 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, the rates are believed to be comparatively higher than other parts of Canada. This review offers a conceptual model 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 concurrently being operated.

2.1 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 works 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 such as existing lagoons, wetlands, and ocean bays. They are operated 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 percent 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 foraging 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 AGI, 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 territory of Nunavut is difficult, disease rates in Inuit communities are believed to be comparatively higher than other parts of Canada (Harper et al. 2011a, Harper et al. 2015a; 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 rely significantly on their immediate natural environment for food and water. The objective of this chapter is to propose a conceptual model of the socio-ecological system to enable 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 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 CCME (2009) endorsed a strategy for a harmonized, Canada-wide management framework of municipal wastewater effluent standards. 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 (ITK 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 (CCME 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 (CCME 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* (*E. 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; Huang 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 (Daley et al. 2015; Hennessy and Bressler 2016; Pardhan-Ali et al. 2013). 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 literature review of public health risks associated with wastewater treatment in Nunavut. 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 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 three academic databases: PubMed, Web of Science, and Environmental Science and Pollution Management. A general internet search was also used for grey literature. Grey 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; Inuit; exposure; and pathogen. Only English literature was reviewed. Search results were screened by title and abstract and documents deemed relevant were kept for full reading. Traditional Inuit knowledge (Inuit Qaujimajatuqangit) of health and the environment was included when found in the document review process. 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.

2.2 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 [USEPA] 2012a). 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).

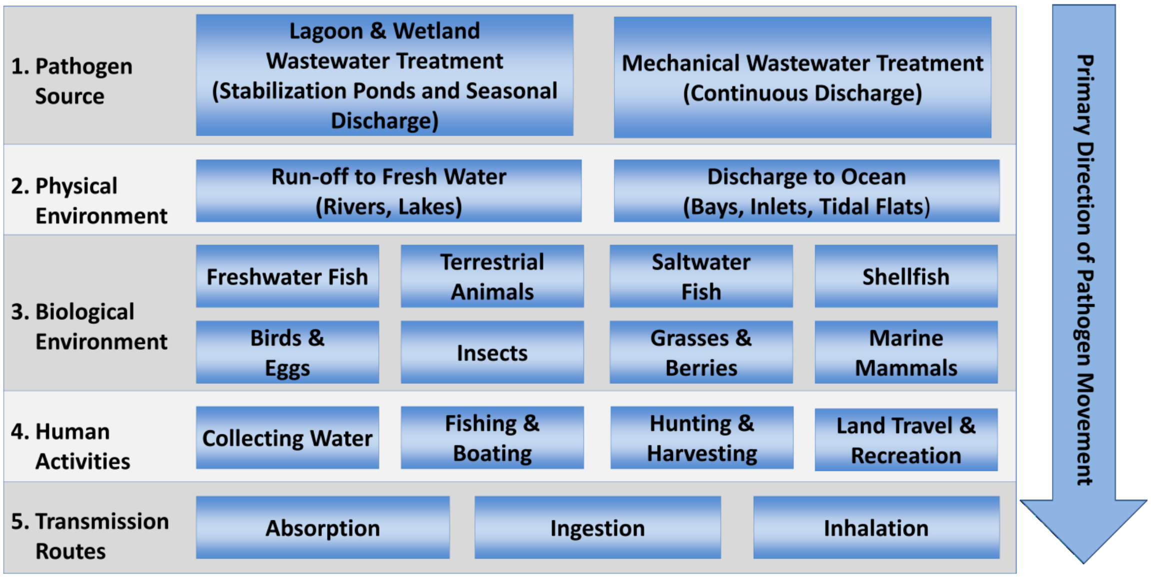
A risk assessment may involve a single hazard with a single associated health outcome in a single exposure scenario such as the case with a chemical contaminant or in an occupational hazard assessment. Microbial risks in a community setting typically require a broader assessment as contaminated environmental 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 2.1 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, recreation, and livelihood. The model could be tailored to any arctic region or community.

As pathogens move from the source towards potential human receptors, the model illustrates the environmental pathways, processes, and human activities 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 category is expanded into a process sub-model and quantified using an appropriate mathematical equation. Following the risk assessment framework section of this chapter, 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.

Figure 2.1 Potential wastewater effluent exposure pathways in Arctic Canadian communities.



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 infection or disease for each defined exposure and can be expressed in individual or population terms. Depending on data availability, one of two modelling 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 the manner of epidemiology or toxicology. Rather, it synthesizes estimates using existing scientific evidence and judgement (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; USEPA 2012a). QMRA has been applied to drinking water systems, grey 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, Murphy et al. 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 been developed (Center for Advancing Microbial Risk Assessment [CAMRA] 2015). 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 cases of illness or 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). In the case of Arctic communities described in this chapter, the pathogen removal capability of a typical wastewater treatment plant is known 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 types of evidence that are best suited and currently available to inform the hazard identification and exposure assessment steps of a QMRA of public health risks associated with wastewater treatment systems in Nunavut, Canada. 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 in these steps, such as differences in dose potencies resulting in illness among people of different ages and immune status, they are more general in nature and are not unique to an arctic context.

2.3 Review

2.3.1 Hazard Identification

The hazard identification stage of a QMRA involves identification of 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). Some of 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 *E. 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 is potentially fatal in sensitive populations such as immunodeficient patients (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 Figure 2.1 – category 1). The types of treatment are categorized into a sequence of steps that increase in effectiveness and complexity: 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/or remove contaminants or specific pollutants (Bitton 2005). Presently, most systems in Nunavut are classified as primary treatment with low levels of pathogen removal.

Most 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 for the winter which lasts from approximately September or October to May or June. As conditions warm, the wastewater influent begins to melt and a period of natural treatment occurs for two to four 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 ultra violet 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 community, wastewater is discharged directly to a marine outfall). 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*. 7, 600), use some form of a conventional mechanical wastewater treatment system. Treatment typically consists of preliminary screening of large debris and/or 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 carrying capacity of the system itself. Most of these systems provide only preliminary or primary treatment and a low level of pathogen removal (Bitton 2005) thus leading to local pollution problems, particularly when there is limited natural water exchange occurring in the receiving waters (Gunnarsdóttir et al. 2013). An environmental assessment that examined benthic invertebrates as indicators of wastewater effluent impact upon receiving waters showed significant variation between communities. 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 (Krumhansl et al. 2015).

In pond-wetland and mechanical wastewater treatment systems effluent discharge schedules are likely have a significant influence on the spatio-temporal variability of pathogens in the natural environment and subsequent human exposures. In comparable global examples, selected bodies of water that receive inadequately treated effluent, but are also used for drinking, recreation, or agriculture posed a daily combined risk of infection by enteric pathogens above the WHO limit of 10^{-4} (Teklehaimanot et al. 2015). Uncontrolled or continuous releases of effluent theoretically present less predictable occurrences of exposure and greater risk than controlled or scheduled intermittent releases.

Accurately estimating the disease burden associated with wastewater exposures in the remote communities of Arctic Canada is difficult due to an absence of regional surveillance and monitoring programs related to gastrointestinal illness, specific food- and waterborne diseases, and other sanitation related health outcomes (Harper et al. 2011b). To date, studies of the prevalence of waterborne pathogens in fecal samples collected from cases of AGI and enteric diseases in Arctic communities have been 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; Pardhan-Ali et al. 2012b). Although AGI is associated with many food- and waterborne pathogens, as well as being transmissible person-to-person, it may be the most relevant health outcome to use for Arctic wastewater risk assessments given the current absence of pathogen-specific data. AGI and enteric diseases related to waterborne pathogens often manifest in stomach flu-like symptoms that are rarely reported to front line clinicians or public health officials. Thus, endemic AGI rates in Inuit and other arctic communities may be higher than 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 less industrialized 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).

2.3.2 Exposure Assessment

The exposure assessment stage determines the types and levels of human exposure to the hazardous 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 behaviours, 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 thus 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 environmental media 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 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

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 environmental media (conceptualized in Figure 2.1 – category 2). Within general models, 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 eight to nine months per year, which has the potential to reduce the concentration of microorganisms in wastewater (Gunnarsdóttir 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 periods of minimal daylight during the mid-winter. Modelling 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 Figure 2.1 – 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 – 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 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 mL^{-1}, the latter being well above recreational water quality guidelines (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 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 raw 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 Figure 2.1 – 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 snow melt 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 are harvested in some Inuit communities, including at least two that use mechanical wastewater treatment systems that continuously discharge int o tidal areas. A study of the microbial quality of blue mussels (*Mytilus edulis*) in six Inuit communities in Nunavik, Quebec found the mussels examined to be of good bacterial and viral quality but did detect the presence of the potentially pathogenic protozoa *Giardia duodenalis* and C*ryptosporidium* spp. (Lévesque et al. 2010). Near-shore 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. A study in the Inuit region of Nunavik, which found high prevalence of *Giarida 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 was observed in younger seals and 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). These food harvesting scenarios pose additional potential pathways for zoonotic transmission to Inuit who consume raw shellfish or raw or aged seal meat that may have come into contact with the intestinal contents during the butchering process. Although swimming is rare in most Arctic communities, 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 Figure 2.1 – 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 operations sites in the Arctic (Jacques Whitford Limited 2005)

2.4 Suggested Research and Data to Address Gaps

Based on the reviewed literature, this section outlines the current state of knowledge as it relates to parameterizing variables for each category of the original conceptual model. In Table 2.1 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 in effort to collect data that can be used to underpin more comprehensive risk assessments in the future.

Table 2.1 State of knowledge and data needs for a QMRA of potential wastewater effluent exposure pathways in Inuit and Arctic 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 amongst 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 (Crites and Tchobanoglous 1998; Bitton 2005). • Data characterizing minimally engineered treatment systems performance in arctic conditions is available in published literature (Chouinard et al. 2014; Doku and Heinke 1995; Gunnarsdóttir 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 works departments.
2. Physical environment	Moderate	• Fate and transport modelling 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 Arctic Canada 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.

Category	State of knowledge[a]	Suggested research and data to address knowledge gaps
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 favoured as a food source, are present near treatment areas, and may be vectors are recommended. • 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 Arctic region and community. Consultation with community stakeholders, both via qualitative research methods or more informally, can help to narrow the list of possible exposures presented in the conceptual model and identify the most probable (Guyot et al. 2006). Most communities 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 (USEPA 2012a). However, these values may need to be adjusted using a proportional or corrective factor to be appropriate for Inuit populations; particularly relating to raw food consumption. Health Canada provides some supplemental guidance on human health risk assessment of locally harvested food (2010). • Community stakeholder consultation combined with human intake data from government food harvesting records may provide more accurate estimations.

[a]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.

2.5 Conclusion

While it appears that passive treatment systems are appropriate for Arctic regions, the human health risks associated with their use in this setting are yet to be assessed. In this chapter, a framework for a screening-level QMRA of wastewater management in Canadian Arctic communities is proposed. In the supporting literature review, the strength of available evidence necessary to begin developing the conceptual model into a practical risk assessment tool is evaluated. The state of knowledge pertaining to wastewater treatment systems (pathogen source), the fate and transport of pathogens in the physical environment, and the 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.

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 by 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. This 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 the North to decide upon appropriate wastewater treatment system designs, quantify and prioritize public health risks, and compare relative benefits of various risk mitigation options.

Chapter 3

Screening-level Microbial Risk Assessment of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

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Abstract

Most arctic communities use primary wastewater treatment systems that are capable of only low levels of pathogen removal. Effluent potentially containing 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 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 5.0 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 during this period ranges between 1.0×10^{-1} (shore recreation) and 6.0×10^{-1} (shellfish consumption). A moderate incidence rate of 1.2 episodes of AGI per person is estimated in Naujaat, where a treatment system consisting of a pond and tundra wetland is used, with the majority of cases occurring during spring. The pathway with the highest individual probability of AGI per single exposure event is wetland travel at 6.0×10^{-1}. All other risk probabilities per single exposure are $<1.0 \times 10^{-1}$. The AGI incidence rates estimated for the other three case study locations are <0.1. These findings suggest that wastewater treatment sites may be contributing to elevated rates of AGI in some Arctic Canadian communities. 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 decisions in the region.

3.1 Introduction

Communities in the Arctic employ basic wastewater treatment systems (Yates et al. 2012), which may be contributing to elevated rates of infectious disease in the region (Harper et al. 2015a). 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 (Hayward et al. 2014; Ragush et al. 2015) and low levels of pathogen removal (Huang et al. 2017). 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 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. 2015a; Thomas et al. 2013) and higher than average estimates from less industrialized countries (0.8 to 1.3) as well (Mathers et al. 2002; WHO 2006a). 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). However, enteric pathogens (Hastings et al. 2014; Thivierge et al. 2016) and potential risk of environmental contamination from wastewater treatment sites (Daley et al. 2015) remain as ongoing public health concerns among communities and officials in the region (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 socio-ecological system (Waltner-Toews et al. 2003) 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).

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 2012a). 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 less industrialized regions with limited data within Africa (Howard et al., 2006; Hunter et al., 2009) and Asia (Ferrer et al., 2012). QMRA has also been used in contexts where populations may be unknowingly exposed to wastewater effluent through food harvesting or recreational activities (Fuhrimann et al. 2017; Fuhrimann et al. 2016; Yapo et al., 2014). 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 chapter is to provide the first estimates of health risks attributable to microbial pathogen in wastewater within Inuit Nunangat and other Arctic Canadian communities. A simplified, point estimate QMRA model is designed and used to evaluate a broad range of potential exposure pathways and discern those that pose high levels of risk, warranting further attention. In Chapter Two, a conceptual model supported by a literature review was first developed to serve as a directional guide for this work (Daley et al. 2018a).

3.2 Methods

3.2.1 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 (USEPA 2012a; 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. The complete model and result sets are provided in Appendix D.

3.2.2 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 (pathogenic *E. coli*, *Salmonella* spp., and *Campylobacter* spp.); one virus (rotavirus); and two protozoa (*Giardia* spp. and *Cryptosporidium* spp.). All six agents are commonly present in partially-treated wastewater effluent and transmissible via fecal-oral routes (i.e., direct accidental ingestion of water, hand-to-mouth exchange following contact with contaminated water, or ingestion of contaminated food). Specific pathogenic infections affecting Arctic Canadian populations were also considered during the selection of microorganisms. The prevalence of *Giardia* spp., *Campylobacter* spp. (Goldfarb et al. 2013), *Salmonella* spp. (Pardhan-Ali et al. 2012b), and rotavirus (Desai et al. 2017) infections appears relatively high in the region. There has also been an emergence of *Cryptosporidium* spp. infections (Thivierge et al. 2016). The transmission patterns of these pathogens within Arctic Canada are not fully understood (Iqbal et al. 2015; Yansouni et al. 2016). As a simplification within the entire assessment, we refer to the pathogenic strains of these specific six agents known to be associated with AGI.

3.2.3 Exposure Assessment

Case study locations

Five Nunavut communities that previously participated in wastewater research were selected as QMRA case study locations based on sufficient water quality data having been collected in their receiving environments: Iqaluit, Pangnirtung, Pond Inlet, Sanikiluaq, and Naujaat (Figure 3.1). These sites represent examples of all the major treatment type and receiving environment combinations found in the Territory of Nunavut.

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 3.1

Figure 3.1 Map of five case study locations in the territory of Nunavut, Canada (Iqaluit, Naujaat, Pangnirtung, Pond Inlet, and Sanikiluq).

Table 3.1 Characteristics of the five case study locations included in the quantitative microbial risk assessment to estimate the burden of acute gastrointestinal illness 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[a] 63°44′40″N, 68°31′01″W	7740	Mechanical treatment (bulk solids removal)[a]	Continuous, year round	867 167	1.12×10^7	Inlet/small bay, 11.0
Pangnirtung[a] 66°08′47″N, 65°42′04″W	1481	Mechanical treatment (activated sludge)[a]	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).

[a] After the data collection phase of this research had concluded, the mechanical wastewater treatment plant in Pangnirtung was upgraded to a membrane bioreactor capable of achieving secondary treatment. A similar upgrade in scheduled for the plant in Iqaluit. However, neither of these upgraded treatment plants includes a disinfection stage; therefore pathogen removal levels will likely remain low.

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, using participatory epidemiology techniques, in order to accurately depict potential exposure scenarios (Barber and Jackson 2015). 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 min. 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. 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). Refer to Appendix E – Key Informant and Community Research Materials for more information on exposure scenario development.

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 in the subsequent paragraphs and a full summary of the human activity parameters used in the QMRA model are presented in Table 3.2. 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/h and is applicable to activities such as fishing and wading. A middle contact average rate of 5.8 mL/h is recommended for canoeing or kayaking with occasional capsizing and the high contact average rate of 10.0 mL/h 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. 2017; Fuhrimann et al. 2016; WHO 2006b). 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 2006b).

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, which 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 g 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 WSP 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 2006b).

Table 3.2 Summary of human activity parameters per case study location, receiving environment conditions, and exposure pathway included in the quantitative microbial risk assessment model to estimate acute gastrointestinal illness attributable to wastewater treatment systems in Arctic Canada.

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 (m)	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 (mL)	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8	22.8
Small craft boating										
Distance (m)	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 (mL)	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8	34.8
Netfishing										
Distance (m)	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 (mL)	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0	58.0
Shellfish harvesting										
Distance (m)	–	2000	–	1000	–	–	–	–	–	–
Frequency (per year)	–	40	–	40	–	–	–	–	–	–
Exposure group (persons)	–	100	–	50	–	–	–	–	–	–
Ingestion (mL)	–	50.0	–	50.0	–	–	–	–	–	–

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)*										
Shellfish consumption										
Distance (m)	–	2000	–	1000	–	–	–	–	–	–
Frequency (per year)	–	40	–	40	–	–	–	–	–	–
Exposure group (persons)	–	400	–	200	–	–	–	–	–	–
Ingestion (g)	–	75.0	–	75.0	–	–	–	–	–	–
Wetland travel										
Distance (m)	–	–	–	–	–	–	500	500	250	250
Frequency (per year)	–	–	–	–	–	–	50	50	35	45
Exposure group (persons)	–	–	–	–	–	–	50	50	50	50
Ingestion (mL)	–	–	–	–	–	–	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 WSPs 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 WSP, which thaws in the spring and freezes in the early fall. It differs from Sanikiluaq and Naujaat, however, in that the WSP 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 WSP. 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-h 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.

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. 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 (American Public Health Association [APHA] 2012). Concentrations were provided as the most probable number of *E. coli* in 100 mL (MPN/100 mL). Greenwood (2016), Hayward et al. (2018), and Neudorf et al. (2017) provide full descriptions of the wastewater sampling methods and analysis involved in the formation of the indicator *E.coli* dataset.

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 (McBride et al. 2012; Sokolova et al. 2015). Many health authorities have begun to supplement or replace traditional recreational water quality monitoring with such integrated approaches (Ashbolt et al. 2010; 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 (k, 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 noneffluent-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). The calculated reduction constants (k) from the regressions were then used in a first-order model (Equation 3.1) to predict *E. coli* concentrations at points of human exposure (C_{dist}) as a function of initial concentrations at effluent release points (C_0) and distance ($dist$), under similar treatment system and receiving environment conditions. The model constants represent varying levels of concentration reduction due to dilution, inactivation, and sedimentation associated with the different receiving environments and tidal conditions (refer to Appendix F – *E. coli* Concentration Modelling Materials for more information).

$$C_{dist} = C_0 \cdot e^{-k(dist)} \qquad [3.1]$$

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 3.3). 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.

Table 3.3 Referenced indicator *E. coli*-to-pathogen inference ratios (*E. coli: Path*) for use in the quantitative microbial risk assessment model estimating acute gastrointestinal illness 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[a]	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. (2014)
Giardia spp.	1 : 10^{-5}	Machdar et al. (2013) (*general protozoa ratio)*
Cryptosporidium spp.	1 : 10^{-6}	Fuhrimann et al. (2017)

[a] Ratio is non-pathogenic *Salmonella*: *Salmonella* in lieu of an available *E. coli*: *Salmonella* ratio.

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 (Centre for Environment Fisheries & Aquaculture Science [CEFAS] 2014).

3.2.4 Dose-Response Models

Dose-response models are mathematical functions 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 3.2) or the two-parameter beta-Poisson (Equation 3.3), have proven widely applicable to most microorganisms and exposure routes (Haas et al. 2014).

$$P(d) = 1 - e^{-rd} \qquad [3.2]$$

When using the exponential function (Equation 3.2), *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 (*r*) are pathogen infectivity constants.

$$P(d) = 1 - \left[1 + \left(\frac{d}{N_{50}}\right) \cdot \left(2^{1/\alpha} - 1\right)\right]^{-\alpha} \qquad [3.3]$$

With the beta-Poisson function shown (Equation 3.3), *P(d)* represents the probability of infection and *d* a single dose at exposure, with model slope parameter α and median infectious 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 3.4 (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 3.5).

Table 3.4 Dose-response models and parameters for use in the quantitative microbial risk assessment estimating acute gastrointestinal illness attributable to wastewater treatment systems in Arctic Canada.

Pathogen	Model	Parameters	References
Pathogenic *E. coli* (EIEC[a])	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 et al. (1986)
Giardia spp.	Exponential	$r = 0.020$	CAMRA (2015); Rendtorff (1954)
Cryptosporidium spp.	Exponential	$r = 0.057$	CAMRA (2015); Messner et al. (2001)

[a] Enteroinvasive *E. coli*

Table 3.5 Morbidity ratios estimating probability of illness conditional upon infection for selected pathogens ($P_{\text{ill} \mid \text{inf}}$) for use in the quantitative microbial risk assessment of acute gastrointestinal illness 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)

3.2.5 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 DALYs, they were chosen for their direct comparability to the limited epidemiological studies of AGI in Arctic Canada (Harper et al. 2015a), while still being relatable to disease burden measures used in some QMRA studies of wastewater exposures in other regions (Fuhrimann et al. 2017; Fuhrimann et al. 2016). The risk characterization equations used to estimate these outcomes are based on adapted versions from Fuhrimann et al. (2017; 2016), Haas et al. (2014), Howard et al. (2006), Sales-Ortells and Medema (2014), and WHO (2016). The model was developed using Microsoft Excel (2010).

Using the data described, individual probabilities of infection and illness were calculated (Equations 3.4, 3.5, and 3.6). $d_{E.\ coli}$, the dose of *E. coli* at exposure (MPN) was calculated by multiplying, C_{dist}, the concentration of *E. coli* at the exposure distance (MPN/mL) by V, the volume of or tissue (mL or g) ingested per exposure event.

$$d_{E.\ coli} = C_{dist} \cdot V \qquad [3.4]$$

$d_{E.\ coli}$ was then multiplied by *E. coli: Path*, an indicator *E. coli*-to-pathogen inference ratio from Table 3.3, to produce the corresponding pathogen-specific dose at exposure, d_{path} (MPN).

$$d_{path} = d_{E.\ coli} \cdot (E.coli\colon Path) \qquad [3.5]$$

The obtained doses of each pathogen, d_{path}, were then entered into corresponding dose-response models (Equations 3.2 and 3.3), described in Section 3.2.4, with parameters from Table 3.4 to obtain individual probability of infection per pathogen per single exposure event, $P_{inf,\ path}$. The morbidity ratios from Table 3.5, $P_{ill\ |\ inf}$, were then applied to determine the probability of illness per pathogen, per exposure pathway, $P_{ill,path}$.

$$P_{ill,path} = P_{inf,path} \cdot P_{ill\,|\,inf} \qquad [3.6]$$

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 3.7, 3.8, 3.9, and 3.10), based on the probability of illness, ($P_{ill,path}$).

$$P_{ill,path,total} = \sum P_{ill,path} \tag{3.7}$$

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.

$$Cases_{path} = \sum_{i=1}^{(freq)(ExpGroup)} P_{ill,path} \tag{3.8}$$

$Cases_{path}$ 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 3.2).

$$Cases_{all\ path} = \sum Cases_{path\ i\ldots j} \tag{3.9}$$

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

$$Cases_{all\ path,location} = \sum Cases_{all\ path} \tag{3.10}$$

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 3.11 and 3.12).

$$Inc_{location} = \frac{Cases_{all\ path,location}}{Pop_{location}} \qquad [3.11]$$

Annual individual incidence rate of AGI per location is denoted by $Inc_{location}$. Location population sizes, $Pop_{location}$, were presented in Table 3.1.

$$Inc_{location,1000} = Inc_{location} \cdot 1000 \qquad [3.12]$$

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

3.3 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.

3.3.1 Expected Total Annual Cases of AGI

The expected annual AGI cases attributable to wastewater exposures, by case study location, are presented in Table 3.6. The highest estimate of AGI cases per location occurs in Pangnirtung at 7420 episodes of AGI per year. Naujaat and Iqaluit follow with 1250 and 995 respective annual estimated cases. Considerably fewer cases are estimated in Pond Inlet and Sanikiluaq (36.7 and 3.65 episodes per year, respectively).

Table 3.6 Expected annual cases of acute gastrointestinal illness 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.

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	3.0×10^{-11}	797	$\leq 1.0 \times 10^{-16}$	508	3.03	$\leq 1.0 \times 10^{-16}$	3.0×10^{-4}	3.0×10^{-9}	6.42	8.0×10^{-6}
Small craft boating	4.0×10^{-11}	1.0×10^{-1}	$\leq 1.0 \times 10^{-16}$	711	33.6	$\leq 1.0 \times 10^{-16}$	3.0×10^{-4}	4.0×10^{-9}	9.73	1.0×10^{-5}
Netfishing	$\leq 1.0 \times 10^{-16}$	1.3×10^{-1}	$\leq 1.0 \times 10^{-16}$	841	1.1×10^{-1}	$\leq 1.0 \times 10^{-16}$	5.0×10^{-4}	5.0×10^{-9}	22.4	3.0×10^{-5}
Shellfish harvesting	–	6.54	–	356	–	–	–	–	–	–
Shellfish consumption	–	191	–	5000	–	–	–	–	–	–
Wetland travel	–	–	–	–	–	–	3.64	6.3×10^{-3}	1050	162
Total per location	995		7420		36.7		3.65		1250	

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 36.7 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 2 km 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). It is worth noting, however, that while water samples were being collected from the marine receiving environment at the Pond Inlet site during high tide conditions, strong winds combined with the ambient current caused the discharged effluent plume to attach to the shoreline and drift toward the central area of the community (Greenwood 2016; Krumhansl et al. 2015).

Of the two locations relying on WSP treatment systems with an adjoining wetland, only the estimated 1250 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 WSP 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., each at 3%. 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. typically die-off in seawater exposed to sunlight in ≤24 hours, which may reduce the number of infections; however, microbial inactivation is variable (Bitton 2005; Schoen and Ashbolt 2010). Viruses and *Cryptosporidium* spp. have potential to persist in seawater for up to six days (Johnson et al. 1997; Noble et al. 2004). These levels of environmental persistence may prove of importance as *Cryptosporidium* is an emerging pathogen of concern in the Arctic (Goldfarb et al. 2013; Yansouni et al. 2016) and a recent study found rotavirus to be the second leading cause of childhood AGI in Nunavut (Desai et al. 2017).

3.3.2 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 3.7. 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. 2015a).

Table 3.7 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 in five arctic case study locations, with comparison to all food- and waterborne AGI arctic estimate.

Location	**Iqaluit**	**Pangnirtung**	**Pond Inlet**	**Sanikiluaq**	**Naujaat**	**Food- and waterborne AGI Arctic estimate**[a]
Population	7740	1481	1671	882	1082	Not applicable
Incidence rate per person	0.1	5.0	0.02	0.004	1.2	2.9 – 3.9
Incidence rate per 1000 persons	130	5000	20	4	1200	2900 – 3900

[a] Reference for food- and waterborne AGI Arctic estimate: Harper et al. (2015a).

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 (0.1), Pond Inlet (0.02), and Sanikiluaq (0.004) seem reasonable estimates of the proportion of AGI attributable to wastewater exposure, with Naujaat (1.2) being moderately high but plausible. The per person incidence rate estimate for Pangnirtung (5.0) 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 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; Fuhrimann et al. 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 demonstrates that, in the worst-case scenario, potential does exist for an outbreak of waterborne disease.

Comparison of the two sites with WSPs and wetlands, Naujaat and Sanikiluaq, highlights the variation of potential human health risks even among 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 3.1 and 3.2. However, the annual incidence per person rate in Naujaat (1.2) 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 WSP during spring freshet is 1.73×10^6, compared to only 6.04×10^4 in Sanikiluaq.

3.3.3 Estimated Probability of AGI per Single Exposure Event

The estimated probabilities of AGI per person per a single exposure event for each of the developed scenarios are presented in Table 3.8. The probabilities correspond to AGI attributable to any of the modelled pathogens. Many of the risk probabilities are $\leq 2.5 \text{ x } 10^{-6}$ 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 (7.0×10^{-2}), and all exposures entirely in Sanikiluaq with the exception of wetland travel during spring (2.0×10^{-3}).

Table 3.8 Estimated probability of acute gastrointestinal illness, 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 model.

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	2.0×10^{-15}	8.0×10^{-2}	$\leq 1.0 \times 10^{-16}$	1.0×10^{-1}	6.0×10^{-3}	$\leq 1.0 \times 10^{-16}$	1.0×10^{-7}	8.0×10^{-13}	5.0×10^{-3}	4.0×10^{-9}
Small craft boating	4.0×10^{-15}	9.0×10^{-6}	$\leq 1.0 \times 10^{-16}$	1.0×10^{-1}	7.0×10^{-2}	$\leq 1.0 \times 10^{-16}$	2.0×10^{-7}	1.0×10^{-12}	8.0×10^{-3}	6.0×10^{-9}
Netfishing	$\leq 1.0 \times 10^{-16}$	2.0×10^{-5}	$\leq 1.0 \times 10^{-16}$	2.0×10^{-1}	2.0×10^{-4}	$\leq 1.0 \times 10^{-16}$	3.0×10^{-7}	2.0×10^{-12}	1.0×10^{-2}	1.0×10^{-8}
Shellfish harvesting	–	2.0×10^{-3}	–	2.0×10^{-1}	–	–	–	–	–	–
Shellfish consumption	–	1.0×10^{-2}	–	6.0×10^{-1}	–	–	–	–	–	–
Wetland travel	–	–	–	–	–	–	2.0×10^{-3}	3.0×10^{-6}	6.0×10^{-1}	7.0×10^{-2}

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

Estimated risk probabilities per single exposure are much higher for shellfishing harvesting (2.0×10^{-1}) and consumption (6.0×10^{-1}) in Pangnirtung. Lower estimates are seen for these pathways in Iqaluit (harvesting at 2.0×10^{-3} and consumption at 1.0×10^{-2}) 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 should be explored. Adjusting the effluent release schedules at the mechanical treatment plants to discharge primarily during high and outgoing tide cycles if operationally possible, 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.

This study placed emphasis on soliciting input and feedback from a broad array of community members during the development and parameterization of the exposure scenarios. Doing so allowed for differing perspectives to be incorporated into the research and exhibited 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 6.0×10^{-1}.

3.3.4 Limitations

This initial assessment of a complex socio-ecological 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.

3.4 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 WSP 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.

Chapter 4

Microbial Health Risks and Mitigation Options for Wastewater Treatment in Arctic Canada

A version of this chapter is in preparation for submission to an interdisciplinary, health-themed journal.

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Abstract

Populations in Arctic Canada are strongly connected to, and draw sustenance from, the physical environment. Recreation and food harvesting locations, however, may be impacted by the basic wastewater treatment and disposal processes used in the region. Within these mixed socio-ecological systems, people may unknowingly be exposed to wastewater pathogens, either by direct contact or indirectly through activities resulting in exposure to contaminated locally harvested food.

The objectives of this research are to estimate microbial health risks attributable to wastewater effluent exposure in Arctic Canada and evaluate potential mitigation options. A participatory quantitative microbial risk assessment (QMRA) approach was used. Specifically, community knowledge and information describing human activity patterns in wastewater-impacted environments was used with microbial water quality data to model a range of exposure scenarios and risk mitigation options.

In several exposure scenario results, estimated individual annual risk of acute gastrointestinal illness exceeds a proposed tolerable target of 10^{-3}. These scenarios include shore recreation and consumption of shellfish harvested near primary mechanical treatment plants at low tide, as well as travel in wetland portions of passive treatment sites during spring freshet. These results suggest that wastewater effluent exposures may be contributing to gastrointestinal illness in some Arctic communities. Mitigation strategies, including improved treatment and interventions aimed at deterring access to disposal areas reduce risk estimates across scenarios to varying degrees. Overall, well-designed passive systems appear to be the most effective wastewater treatment option for Arctic Canada in terms of limiting and managing associated microbial health risks. This research demonstrates a novel application of QMRA and provides science-based evidence to support public health, water, and sanitation decisions and investment in Arctic regions.

4.1 Introduction

Across Arctic Canada, traditionally semi-nomadic Indigenous populations balance food harvesting and recreational customs with the requisite sanitation and disease prevention measures of life in permanent settlements. Most Arctic communities utilize decentralized passive systems consisting of WSPs (lagoons) and adjoining wetlands, with a few operating mechanical treatment facilities that discharge directly to marine or fresh waters. A limitation of both types of systems, as they are currently designed and operated, is their minimal pathogen removal capabilities (Huang et al. 2018). Consequently, partially treated effluent potentially containing several microbial pathogens of risk to human health is released into the receiving environment (Huang et al. 2018; Krumhansl et al. 2015). Many of these pathogens can lead to AGI, including diarrhea and vomiting, as well as other diseases following exposure to even very low doses (Leclerc et al. 2002). Indigenous and non-Indigenous residents of Arctic communities maintain strong ties to their natural surroundings as a source of food, identity, and livelihood (Bjerregaard et al. 2004; Cunsolo Willox et al. 2012). Given the proximity of wastewater treatment sites to communities, effluent may inadvertently be released to areas used and valued by the local population. Subsequently, people may unknowingly be exposed to wastewater pathogens while fishing, hunting, and harvesting food or while engaged in other recreational and occupational activities (Donaldson et al. 2010; Nilsson et al. 2013).

Estimates of AGI incidence in Arctic Canada range up to six times greater than the national average (Harper et al. 2015a; Thomas et al. 2013) and above rates in many less industrialized countries (Harper 2015a; Mathers et al. 2002; WHO 2006a). The specific role water plays in AGI transmission is unclear. Numerous environmental and behavioural risk factors have been explored (Harper et al. 2015a; Masina et al. 2019; Mosites et al. 2018; Wright et al. 2018); however, as of yet, there is limited evidence of any specific associations with AGI (Goldfarb et al. 2013; Iqbal et al. 2015). As research on AGI in the Arctic continues (Hastings et al. 2014; Thivierge et al. 2016), the potential link with wastewater contamination (Daley et al. 2015) remains a concern among regional health authorities and communities, which are often limited in terms of financial, technical, and infrastructural resources (Hennessy and Bressler 2016; Pardhan-Ali et al. 2013).

The remoteness of the Arctic region often constrains extensive epidemiological, microbiological, and field-based studies of environmental health risks; thus, comprehensive datasets on local pollution sources are limited. Furthermore, the potential for quantifying exposures in this context are difficult as human behaviours leading to contact with contaminants and risk of disease are also shaped by cultural, economic, and social factors (Brown et al. 2011). Therefore, standard literature-based values pertaining to exposure frequencies and magnitudes may not be directly generalizable to Indigenous populations (Barber and Jackson 2015; Knibbs and Sly 2014) and Arctic communities (Suk et al. 2004).

QMRA is an approach employed to characterize health risks attributable to a microbial hazard. The disease burden can be estimated based on stochastic models and the concentration and distribution of indicator organisms when direct measurements of pathogens at points of exposure are not available or possible (WHO 2016). QMRA designs are flexible and have been adapted for use in data-limited settings within less industrialized global regions (Ferrer et al. 2012; Howard et al. 2006; Hunter et al. 2009). Additionally, this type of risk assessment has been previously applied in situations where inadvertent exposure to wastewater effluent may have occurred through food harvesting and recreation (Fuhrimann et al. 2017; Fuhrimann et al. 2016; Henao-Herreño et al. 2017; Yapo et al. 2014). Innovatively combining participatory research methods with traditional risk assessment frameworks is also increasing as a means of improving understanding of human interactions with contaminated areas (Ramirez-Andreotta et al. 2014). Engaging with the communities affected can lead to exposure models and risk management strategies that are more reflective of the population’s social and cultural practices (Nguyen-Viet et al. 2009).

The results of a QMRA can be compared to protective health-based targets. Currently in Arctic Canada, pollutant-based effluent quality standards are the predominant measure used to determine and manage the risk posed to human health by wastewater discharges (CCME 2009). Health-based targets offer a more directly comparable measure by establishing a tolerable level of additional disease burden attributable to a given exposure (Rose and Gerba 1991). The WHO tolerable risk level for water related infectious disease is 10^{-4}, which equates to an annual probability of illness of 1/10 000 (Mara et al. 2008; WHO 2006a). Governments can choose to adopt, or adapt-and-adopt, this guideline based on the state of knowledge concerning waterborne disease in their jurisdiction as well as social and economic conditions. Dependent on the local context, a less stringent tolerable risk of illness target of 10^{-3} (1/1000) may be more appropriate in combination with regular monitoring and incremental improvement efforts (Mara et al. 2008; WHO 2006a). QMRA can also be used to evaluate the potential impact of such efforts on risk reduction (WHO 2016). Types of mitigation include engineering controls and designs to improve treated water quality (Machdar et al. 2013; Weir et al. 2011) or behavioural interventions intended to limit human contact to contaminated environments (Katukiza et al. 2014; Labite et al. 2010).

Using a QMRA approach, the objectives of this research are to: 1) characterize the exposure pathways and risk of AGI associated with wastewater effluent in Arctic Canada and; 2) to identify and evaluate interventions that may be effective in reducing health risk. The guiding purposes of the research are to provide findings that serve as an initial evidence base on this issue and to offer an adaptable model that can be used further as a decision-making tool by stakeholders in the region.

4.2. Methods

4.2.1 Research Approach

This research was guided by an ecosystems approach to health (ecohealth). Ecohealth research attempts to address complex issues occurring at the intersection of environment, society, and human health, emphasizing core principles such as systems thinking, stakeholder participation, and knowledge-to-action (Charron 2012; Forget and Lebel 2001).

This research was based in the Territory of Nunavut, a region of Inuit Nunangat (the Inuit home land, water, and ice of Canada) and builds on an existing wastewater research relationship between the academic-based authors and the Government of Nunavut. In accordance with Inuit research priorities (ITK 2018; Tri-Council 2018), territorial government organizations and community-level stakeholders were engaged and included throughout the research process, with an end goal of producing results that translate into practical health improvements.

The research design was a form of participatory risk assessment, wherein a QMRA model was applied in an Arctic community setting. The conventional assessment framework and data sourcing methods were tailored to include local perspectives and experiences in effort to link Inuit knowledge (Inuit Qaujimajatuqangit) and scientific understanding of water, sanitation, and human health.

4.2.2 Model Overview

The model builds upon a conceptual framework presented in Chapter Two (Daley et al. 2018a) and an initial screening-level, point-estimate assessment of risk in case study sites presented in Chapter Three (Daley et al. 2019). Specifically, an inferential QMRA model – rather than community-specific – was designed to reflect hypothetical Arctic wastewater treatment systems, receiving environment conditions, and exposure pathways. Exposure scenarios were parameterized with probability distributions whenever possible. In instances where there was a lack of sufficient data to generate a distribution, point estimates were used. The input parameter values used in the model were sourced from water quality data, community knowledge, and peer-reviewed literature. The results represent probability distributions of annual AGI risk to individuals who partake in each activity. Base cases, which simulate current conditions, were assessed first. Risk mitigating interventions were then formulated and evaluated. Results are benchmarked against global tolerable waterborne risk guidelines (Mara et al. 2008; WHO 2006a). The inputs and equations involved in each of the four stages of QMRA (hazard identification, exposure assessment, dose-response, and risk characterization) are described in the following subsections.

4.2.3 Hazard Identification

The hazard source is partially-treated domestic wastewater effluent. The passive treatment systems in use in Arctic Canada vary greatly from site to site in terms of initial design, current condition, and operational management (Ragush et al. 2015; Schmidt et al. 2016). Subject to natural conditions, the effluent largely remains frozen within a WSP during the subzero (°C) period of the year, which is from approximately October to May in most of the region. During the warmer months effluent either continuously seeps from the WSP into a wetland, or alternatively if the holding cell is structurally sound, is detained within the WSP until being manually decanted using a pump. Upon release, the effluent flows through the wetland and into a receiving water body. In arctic conditions, these passive systems have typically been shown to provide a primary level of treatment (Balch et al. 2018; Hayward et al. 2014; Yates et al. 2012) and do not reliably remove human pathogens (Huang et al. 2018).

A few Arctic communities use mechanical wastewater treatment processes such as filters or aerobic treatment units. The systems are capable of providing secondary treatment under optimal conditions, though most achieve only preliminary or primary levels of treatment (Johnson et al. 2014). These systems continuously discharge effluent directly from an enclosed facility into receiving water environments. Mechanical treatment systems are less subjective to natural environmental processes than passive systems (Bitton 2005); however, the application of mechanical wastewater treatment in the Arctic has proven challenging in other regards. Mechanical systems require significantly more financial investment, energy, daily operation, maintenance, and technical expertise. These factors in combination with the extreme temperatures and remoteness of the region have resulted in extended periods of compromised treatment in some communities (Johnson et al. 2014). None of the current mechanical wastewater treatment systems being used in Arctic Canada have a disinfection process.

Six pathogenic agents that are routinely present in nondisinfected effluent and transmissible via accidental ingestion of contaminated water or food were included in the assessment. These included three bacteria (pathogenic *Escherichia coli*, *Salmonella* spp., and *Campylobacter* spp.), one virus (rotavirus), and two protozoa (*Giardia* spp. and *Cryptosporidium* spp.). The selections were based on microorganisms detected in Arctic wastewater treatment systems by Huang et al. (2018), as well as a review of important pathogenic infections in the region. Huang et al. (2018) demonstrated that pathogenic *E. coli* and *Salmonella* spp. were present in treated wastewater discharged into the receiving environment. These authors did not detect *Campylobacter* spp. within either of the two sites they studied. Nevertheless, *Campylobacter* spp., along with *Salmonella* spp. and *Giardia* spp., was included in the QMRA due to their significance as sources of AGI in the region (Pardhan-Ali et al. 2012b; Goldfarb et al. 2013). Manore et al. (2020) also detected accumulated *Giardia* in some samples of shellfish tissue in Iqaluit, Nunavut. *Cryptosporidium* spp. was also included based on a recent emergence of infections (Thivierge et al. 2016). Finally, rotavirus was included based on its global significance as a pathogen affecting children and as a reported source of AGI in Arctic Canada (Desai et al. 2017; Gurwith et al. 1983). For simplification purposes within the assessment, the pathogenic strains of each agent that are associated with AGI are implied.

4.2.4 Exposure Assessment

Pathogen concentrations in effluent-impacted environments

The concentrations of specific pathogenic agents within effluent-impacted environment at points of human exposure were estimated using an indirect method. The process is described in the subsequent paragraphs and a list of the corresponding QMRA model distributions, parameters, and references is presented in Table 4.1. Additional detail is available in Appendix F – *E. coli* Concentration Modelling Materials.

Table 4.1 Quantitative microbial risk assessment model parameters, distributions, and assumptions used to estimate pathogen concentrations in wastewater effluent-impacted environments in Arctic Canada.

Description	Units	Distribution and values
Concentration of indicator *E. coli* at effluent release (C_0)[a]		
Mechanical	MPN/100 mL	Pareto (1×10^4; 0.48)[b]
Passive	MPN/100 mL	Uniform (1×10^5; 1×10^6)[c]
Reduction rate coefficient (k)[a]		
Mechanical: low tide	1/m	Point estimate (−0.0048)
Mechanical: high tide	1/m	Point estimate (−0.0357)
Passive: spring	1/m	Point estimate (−0.0090)
Passive: summer	1/m	Point estimate (−0.0198)

[a] Refer to Appendix F – *E. coli* Concentration Modelling Materials for more information.
[b] Pareto distribution (location; shape).
[c] Uniform distribution (minimum; maximum).

To begin, a dataset of indicator *E. coli* concentrations (a common fecal indicator organism) in raw influent, treated effluent, and water from the immediate receiving environments in five Arctic sites was sourced. The dataset includes two sites operating mechanical systems (Iqaluit and Pangnirtung, Nunavut), and three using passive systems (Naujaat, Pond Inlet, and Sanikiluaq, Nunavut). In sites operating mechanical systems, where effluent is continuously discharged directly to marine waters, sampling took place during both high and low tide cycles to account for the noted impact of water exchange on contaminant concentration in tidal receiving environments (Gunnarsdóttir et al. 2013). At sites where effluent was discharged from a stabilization pond to a wetland, sampling was scheduled during spring freshet (June) and late summer (September) to capture the high variability that occurs over the span of the passive treatment season (Hayward et al. 2014; Yates et al. 2012).

Indicator *E. coli* analysis was conducted on the samples either using the Colilert-18 method and Quanti-Tray/2000 system in accordance with manufacturer’s instructions (IDEXX Laboratories Inc. 2013) or via standard methods at the Maxxam Analytics commercial laboratory in Montréal, Quebec (APHA 2012). Concentration results were in the form of the most probable number of *E. coli* in 100 mL (MPN/100mL). For full descriptions of the sampling and analysis methods, refer to Greenwood (2016), Hayward et al. (2018), and Neudorf et al. (2017). Field data were supplemented with literature values, input from municipal employees, and operational records estimating periods of reduced or failed treatment (City of Iqaluit 2015; Johnson et al. 2014; Westrell et al. 2003). Using this information base, probability distributions were fitted to parameter ranges to characterize the indicator *E. coli* concentrations at initial release (C_0).

Most human exposures to wastewater effluent are likely to occur at locations beyond the initial release points and immediate mixing zones where sampling occurred, as these areas are commonly recognized among community members as being heavily contaminated (Daley et al. 2015). Therefore, representative pathogen concentrations beyond that range, at distances where exposures are more likely to occur, were estimated using a first-order kinetic model. This model is widely applied to characterize microbial inactivation or decay within environmental media (Haas et al. 2014; Stetler et al. 1992). The natural logarithms of the observed *E. coli* concentrations in the dataset were first plotted and linearly regressed against distance from the effluent release points for each of the five sites under varying tidal or seasonal conditions. Next, first-order concentration reduction constants (k, m^{-1}) were derived from each slope line. From among the calculated reduction constants, the modelling coefficients that were most representative of typical systems and conditions found across the Arctic were chosen. The coefficients were then used as reduction rate constants (k) in a first-order model (Equation 4.1) to predict *E. coli* concentrations (C_{dist}) as a function of initial concentration at effluent release points (C_0) and distance ($dist$), under similar base case conditions.

$$C_{dist} = C_0 * e^{-k(dist)} \qquad [4.1]$$

Exposure scenario development

All behavioural elements of the exposure scenarios included in the QMRA model were grounded in community-based information. Localized knowledge and descriptions of human-environment interactions formed the primary data source. These data were supplemented with literature based exposure values. Corrective factors were assumed in some instances to adapt standard exposure magnitude and frequency values to the local context and population, as has been practiced in other QMRA models (Barker et al. 2014; Fuhrimann et al. 2016). The local data were collected using participatory epidemiology techniques (Barber and Jackson, 2015; Leung et al. 2004; O'Fallon and Dearry 2002) in the five aforementioned Nunavut communities. Between 2013 and 2016, a total of 42 interviews were held with key informants, which included wastewater operators, public health staff, wildlife conservation officers, and subsistence hunters, fishers, and harvesters. The interviews included site-mapping exercises and questionnaires designed to gather information regarding activity patterns, food harvest amounts, and awareness of potential hazards in and near wastewater treatment areas. Community forums were also held, during which approximately 100 additional members of the public provided feedback and validation of preliminary exposure scenarios. Site assessments of the treatment and potential exposure areas, led by engineers and local partners, were also carried out in each community. It was assumed that a suite of exposures based on conditions in these five communities, which span a range of treatment systems, population sizes, and receiving environments, provides a reasonably representative range of base case model scenarios for Arctic Canada. Refer to Appendix E – Key Informant and Community Research Materials for more information on exposure scenario development.

Six activities were included as exposure pathways in the base case model: shoreline recreation; small craft boating; netfishing; shellfish harvesting; shellfish consumption; and wetland travel. Each pathway is described in the following paragraphs and a summary of all the corresponding distributions, parameters, and literature references is provided in Table 4.2. Input variables include distance (*dist*), which is the location where the exposure event occurs as measured in metres from the effluent release point, and exposure frequency (*freq*), the number of exposure events per person per year. Values for both variables were estimated based on localized data. Ingestion volumes (*V*), the amount of media ingested per person per exposure event, are literature based assumptions. The transmission route in five of the six exposures is accidental ingestion of contaminated water (i.e. droplets or hand-to-mouth contact). The exception is the shellfish consumption scenario wherein the route is ingestion of contaminated tissue. The parameters of accidental water ingestion volume for shoreline recreation, small craft boating, and netfishing are based on water recreation exposure values (Dorevitch et al. 2011; McBride et al. 2013). Dorevitch et al. (2011) group activities as either low, mid, or high contact exposures with average ingestion rates per hour of 3.8, 5.8, and 10.0 mL, respectively, and advise using three times the average hourly rate as a conservative maximum estimate. Values associated with wetland travel and shellfish harvesting exposures were sourced from assessments of agricultural and aquacultural labour in wastewater-irrigated settings that estimated an accidental water ingestion maximum of 50.0 mL per day (Fuhrimann et al. 2017; Fuhrimann 2016; WHO 2006b). Triangular distributions (minimum; most likely; maximum) were assumed and fitted to this maximum value. In absence of reliable estimates of shellfish harvest yields in Arctic Canada (Priest and Usher 2004), the shellfish consumption value per exposure event was established upon a standard seafood portion for North American Indigenous populations (Health Canada 2007; Moya 2004). Separate exposure scenarios were constructed for each set of physical environment conditions (low tide / high tide or spring / summer, as applicable) as human activity parameters varied in some instances. The model assumed no human exposures of any kind during the non-open water months (approximately October thru May).

Shoreline recreation: Shorelines are hubs of recreational and work-related activity in Arctic communities. Serving multiple purposes, shorelines provide access points to fresh and marine waters as well as storage space for boats and equipment. They also function as walking paths, children's play areas, and rod fishing locations. Shallow wading and splashing as well as handling of wet fish and equipment are expected; however, swimming or full submersion is infrequent. A low-contact exposure rate (Dorevitch et al. 2011; McBride et al. 2013) was therefore applied and an event duration of two hours.

Small craft boating: Small water craft are widely used across Arctic Canada for recreation, transportation, work, and food harvesting in aquatic environments. Small open-top crafts with outboard motors are most common in addition to larger motorized boats as well as canoes and kayaks. While boating, accidental ingestion of water could occur via launching from shore, fishing, spray, or splash from motors or paddles, or a fall into the water. A mid-contact exposure rate classification (Dorevitch et al. 2011; McBride et al. 2013) and two-hour event duration were designated.

Netfishing: Netfishing involves the setting and retrieving of large weighted nets, ropes, and buoys, typically by hand, from aboard a boat. Accidental water ingestion is plausible during all stages of the process. Similar to small craft boating, this scenario was also valued as a mid-contact exposure (Dorevitch et al. 2011; McBride et al. 2013). A corrective factor of five times the average, rather than three, was applied as a maximum parameter however, due to the intensified actions and submerged equipment. Non-commercial netfishing, hence no use of specialized clothing or decontamination measures, was assumed. The assumed event duration was two hours.

Wetland travel: The wetland travel exposure pathway is only applicable in locations operating passive wastewater treatment systems. While it is commonly known within communities that the WSP is a hazardous area to be avoided, the potential health risk posed in the adjoining, effluent-impacted wetland is less apparent. Fencing and signage are often erected around the perimeter of the stabilization pond but they usually do not extend to the wetland portions of the treatment areas. People may enter these areas while hunting small game, picking berries, collecting geese eggs, or on route elsewhere. Means of travel include walking, all-terrain vehicle, or snowmobile during the spring when snow is still present within the wetland. Accidental water ingestion could occur following contact with soil, vegetation, clothing, or equipment that has been contaminated with effluent. Additionally, all-terrain vehicles and snowmobiles will, as they traverse the wetland, spray soil particles and create droplets of water, which may be inadvertently ingested by the vehicle riders.

Shellfish harvesting: The shellfish harvesting exposure scenario was only included in the mechanical QMRA assessment, and only during low tide conditions. This modelling decision was based on local descriptions of the locations where this activity is commonly practiced. Shellfish, predominantly clams, are harvested by digging them from the exposed sea bed in coastal areas during low tide, either by hand or with a shovel. Fecal coliforms can become concentrated within the bottom sediment of the sea bed in effluent-impacted waters (Ford 2005; Heaney et al. 2012). Exposure may occur following the handling of shellfish and contact with contaminated water, soil, or tools.

Shellfish consumption: Shellfish consumption, also only applicable in mechanical system sites and during low tide, was assessed independently of harvesting. Shellfish filter large quantities of seawater and pathogens can become concentrated within their digestive tissue (Bitton 2005). Infective agents are then communicable to humans via ingestion (Ford 2005). To account for the accumulation of pathogens within the raw tissue, a factor of 10 times the *E. coli* concentration in the water at the harvest location was assumed based on a critical review of published data (CEFAS 2014). Most infectious pathogens can be killed or inactivated through cooking; however, shellfish is commonly consumed raw or partially cooked (Butt et al. 2004). Community data did in fact reveal a predilection for raw or lightly cooked shellfish among some residents in the region. To reflect this local practice, a reduction factor of 0.5 was then assumed and applied to the *E. coli* concentration within the tissue.

Table 4.2 Quantitative microbial risk assessment model parameters, distributions, and assumptions used to develop exposure scenarios in wastewater effluent-impacted environments in Arctic Canada.

Treatment system	**Exposure pathway and parameters**	**Conditions**	**Units**	**Distribution and values**	**References**
Mechanical	**Shoreline recreation**				
	Distance (*dist*)	Low tide / high tide	m	Uniform (1000; 1500)[a]	Appendix E
	Frequency (*freq*)	Low tide / high tide	m	Point estimate (105)	Appendix E
	Ingestion volume (*V*)	Low tide / high tide	mL	Triangular (3.8; 7.6; 22.8)[b]	Dorevitch et al. 2011; McBride et al. 2013
Mechanical	**Small craft boating**				
	Distance (*dist*)	Low tide	m	Uniform (2000; 3500)[a]	Appendix E
	Distance (*dist*)	High tide	m	Uniform (1000; 1500)[a]	Appendix E
	Frequency (*freq*)	Low tide / high tide	m	Point estimate (105)	Appendix E
	Ingestion volume (*V*)	Low tide / high tide	mL	Triangular (5.8; 11.6; 34.8)[b]	Dorevitch et al. 2011; McBride et al. 2013
Mechanical	**Netfishing**				
	Distance (*dist*)	Low tide	m	Uniform (2000; 3500)[a]	Appendix E
	Distance (*dist*)	High tide	m	Uniform (1500; 2500)[a]	Appendix E
	Frequency (*freq*)	Low tide / high tide	m	Point estimate (85)	Appendix E
	Ingestion volume (*V*)	Low tide	mL	Triangular (3.8; 7.6; 58.0)[b]	Dorevitch et al. 2011; McBride et al. 2013
Mechanical	**Shellfish harvesting**				
	Distance (*dist*)	Low tide	m	Uniform (1000; 2500)[a]	Appendix E
	Frequency (*freq*)	Low tide	m	Point estimate (40)	Appendix E
	Ingestion volume (*V*)	Low tide	mL	Triangular (10.0; 35.0; 50.0)[b]	Fuhrimann et al. 2017, Fuhrimann et al. 2016; WHO 2006b
Mechanical	**Shellfish consumption**				
	Distance (*dist*)	Low tide	m	Uniform (1000; 2500)[a]	Appendix E
	Frequency (*freq*)	Low tide	m	Point estimate (40)	Appendix E
	Ingestion volume (*V*)	Low tide	g	Triangular (15.0; 60.0; 75.0)[b]	Health Canada 2007; Moya 2004
	Accumulation factor	Low tide	−	Point estimate (10)	CEFAS 2014
	Cooking reduction factor	Low tide	−	Point estimate (0.5)	Appendix E

Treatment system	Exposure pathway and parameters	Conditions	Units	Distribution and values	References
Passive	**Shoreline recreation**				
	Distance (*dist*)	Spring / summer	m	Uniform (1500; 2000)[a]	Appendix E
	Frequency (*freq*)	Spring	m	Point estimate (25)	Appendix E
	Frequency (*freq*)	Summer	m	Point estimate (40)	Appendix E
	Ingestion volume (*v*)	Spring / summer	mL	Triangular (3.8; 7.6; 22.8)[b]	Dorevitch et al. 2011; McBride et al. 2013
Passive	**Small craft boating**				
	Distance (*dist*)	Spring / summer	m	Uniform (1500; 2000)[a]	Appendix E
	Frequency (*freq*)	Spring	m	Point estimate (25)	Appendix E
	Frequency (*freq*)	Summer	m	Point estimate (40)	Appendix E
	Ingestion volume (*V*)	Spring / summer	mL	Triangular (3.8; 11.6; 34.8)[b]	Dorevitch et al. 2011; McBride et al. 2013
Passive	**Netfishing**				
	Distance (*dist*)	Spring / summer	m	Uniform (1500; 2000)[a]	Appendix E
	Frequency (*freq*)	Spring	m	Point estimate (35)	Appendix E
	Frequency (*freq*)	Summer	m	Point estimate (50)	Appendix E
	Ingestion volume (*V*)	Spring / summer	mL	Triangular (5.8, 11.6, 58.0)[b]	Dorevitch et al. 2011; McBride et al. 2013
Passive	**Wetland travel**				
	Distance (*dist*)	Spring / summer	m	Uniform (250; 1000)[a]	Appendix E
	Frequency (*freq*)	Spring	m	Point estimate (35)	Appendix E
	Frequency (*freq*)	Summer	m	Point estimate (45)	Appendix E
	Ingestion volume (*V*)	Spring /summer	mL	Triangular (10; 35; 50)[b]	Fuhrimann et al. 2017; Fuhrimann et al. 2016; WHO 2006b

[a] Uniform distribution (minimum; maximum).

[b] Triangular distribution (minimum; most likely; maximum).

4.2.5 Dose-Response

The dose-response stage of a QMRA describes the relationship between levels of exposure a person experiences and the probability of a health outcome. The health outcome modelled in this research was AGI. The steps and equations involved are described in the ensuing paragraphs and the corresponding parameters, distributions, and assumptions are listed in Table 4.3.

The dose of *E. coli* ($d_{E.\ coli}$) a person ingests at exposure (MPN) was calculated by multiplying, C_{dist}, the concentration of indicator *E. coli* in the environmental media at the exposure distance (MPN/mL) by the volume (V) of water or tissue (mL or g) accidently ingested per event (Equation 4.2).

$$d_{E.\ coli} = C_{dist} \cdot V \qquad [4.2]$$

Indicator *E. coli* was the only obtainable organism data. It was assumed that the reduction in *E. coli*, obtained using the first-order model (Equation 4.1), can be used to conservatively predict the inactivation, dilution, or sedimentation of specific enteric pathogens within the effluent-receiving environment (Nevers and Boehm 2011; Schoen and Ashbolt 2010). Ratios were sourced from wastewater literature, or surface and drinking water literature when necessary, to infer the level of relationship between indicator *E. coli* and each pathogen included in the assessment. The pathogen-specific doses, d_{path} (MPN) are then obtained by multiplying $d_{E.\ coli}$ by corresponding inference ratios, (*E. coli: Path*) (Equation 4.3).

$$d_{path} = d_{E.\ coli} \cdot (E.coli\!: Path) \qquad [4.3]$$

The probability of infection [*P(d)*] at a single dose (*d*) for each pathogen was estimated using either the exponential (Equation 4.4) or beta-Poisson model (Equation 4.5), which are established as applicable to most microorganisms and exposures (Haas et al. 2014). With the exponential function (Equation 4.4), the natural logarithm base (*e*) and the probability that one organism survives to cause an infection within the human host (*r*) are pathogen-specific constants. The beta-Poisson model (Equation 4.5) is a two-parameter function with slope parameter α and median infectious dose N_{50}.

$$P(d) = 1 - e^{-rd} \qquad [4.4]$$

$$P(d) = 1 - \left[1 + \left(\frac{d}{N_{50}}\right) \cdot \left(2^{1/\alpha} - 1\right)\right]^{-\alpha} \qquad [4.5]$$

Morbidity ratios ($P_{ill\,|\,inf}$) sourced from literature were then applied to these probabilities to estimate the number of infections that resulted in symptomatic cases, which represents the probability of illness following a single exposure event ($P_{ill,path}$) (Equation 4.6).

$$P_{ill,path} = P(d) \cdot P_{ill\,|\,inf} \qquad [4.6]$$

Table 4.3 Dose-response model parameters, distributions, and assumptions used in quantitative microbial risk assessment of acute gastrointestinal illness associated with wastewater effluent-impacted environments in Arctic Canada.

Description	Distribution and values	References
Ratio of pathogenic organism per indicator *E. coli* (*E.coli: Path*)		
Pathogenic *E. coli*	Point estimate (0.08)	Haas et al. (1999); Howard et al. (2006)
Salmonella spp.	Triangular (1×10^{-4}; 1×10^{-3}; 1×10^{-2})[a]	Craig et al. (2003); Fuhrimann et al. (2016)[f]
Campylobacter spp.	PERT (1×10^{-6}; 5.5×10^{-6}; 1×10^{-5})[b]	Fuhrimann et al. (2016); WHO (2006b)
Rotavirus	PERT (1×10^{-6}; 5.5×10^{-6}; 1×10^{-5})[b]	Fuhrimann et al. (2017); Katukiza et al. (2014)
Giardia spp.	Uniform (1×10^{-7}; 1×10^{-5})[c]	Machdar et al. (2013)[g]
Cryptosporidium spp.	PERT (1×10^{-7}; 5.5×10^{-7}; 1×10^{-6})[d]	Fuhrimann et al. (2017); WHO (2006b)
Dose-response models [*P(d)*]		
Pathogenic *E. coli* (EIEC)	Beta-Poisson (0.16; 2.11×10^{6})[d]	CAMRA (2015); Dupont et al. (1971)
Salmonella spp.	Beta-Poisson (0.389; 1.68×10^{4})[d]	CAMRA (2015); McCullough and Eisele (1951)
Campylobacter spp.	Beta-Poisson (0.14; 890.38)[d]	Black et al. (1988); CAMRA (2015)
Rotavirus	Beta-Poisson (0.253; 6.17)[d]	CAMRA (2015); Ward (1986)
Giardia spp.	Exponential (0.020)[e]	CAMRA (2015); Rendtorff (1954)
Cryptosporidium spp.	Exponential (0.057)[e]	CAMRA (2015); Messner et al. (2001)
Morbidity ratios ($P_{ill \mid inf}$)		
Pathogenic *E. coli*	0.35	Fuhrimann et al. (2017); Machdar et al. (2013); Westrell (2004)
Salmonella spp.	0.80	Westrell (2004); WHO (2006b)
Campylobacter spp.	0.30	Fuhrimann et al. (2017); Machdar et al. (2013); Westrell (2004)
Rotavirus	0.50	Barker et al. (2014); Westrell (2004); WHO (2006b)
Giardia spp.	0.90	Schoen and Ashbolt (2010)
Cryptosporidium spp.	0.79	Fuhrimann et al. (2017)

[a] Triangular distribution (minimum, most likely; maximum).

[b] Project evaluation and review techniques distribution (PERT) (minimum; most likely; maximum).

[c] Uniform distribution (minimum; maximum).

[d] Beta-Poisson distribution (α; N_{50}).

[e] Exponential distribution (r).

[f] In lieu of an inference ratio between indicator *E. coli* and pathogenic *Salmonella*, a ratio between non-pathogenic and pathogenic *Salmonella* was used.

[g] General protozoa ratio. Machdar et al. (2013) provide values only, so uniform distribution is assumed.

4.2.6 Risk Characterization

Individual annual risk of acute gastrointestinal illness

Monte Carlo simulations were used in the risk characterization stage of the QMRA. Samples from the pre-specified data distributions were repeatedly drawn (10 000 iterations) to model the probability of the health outcome (Haas et al. 2014). The probability of illness from a single exposure event ($P_{ill,path}$), as calculated with Equation 4.6, was combined with the frequency of exposure events per person per year (*freq*) to arrive at the individual annual probability of AGI ($P_{ill,\ annual}$) associated with each exposure scenario (Equation 4.7).

$$P_{ill,annual} = 1 - \left(1 - P_{ill,path}\right)^{freq} \qquad [4.7]$$

The risk results only apply to individuals in the specified exposure group (e.g. shellfishers harvesting near the mechanical treatment plant during low tide), and not an entire community population. It is assumed that individuals can simultaneously belong to more than one exposure group (e.g. an individual may be a shellfisher and a netfisher). The model was developed using Crystal Ball software (Oracle 2017).

Sensitivity analysis

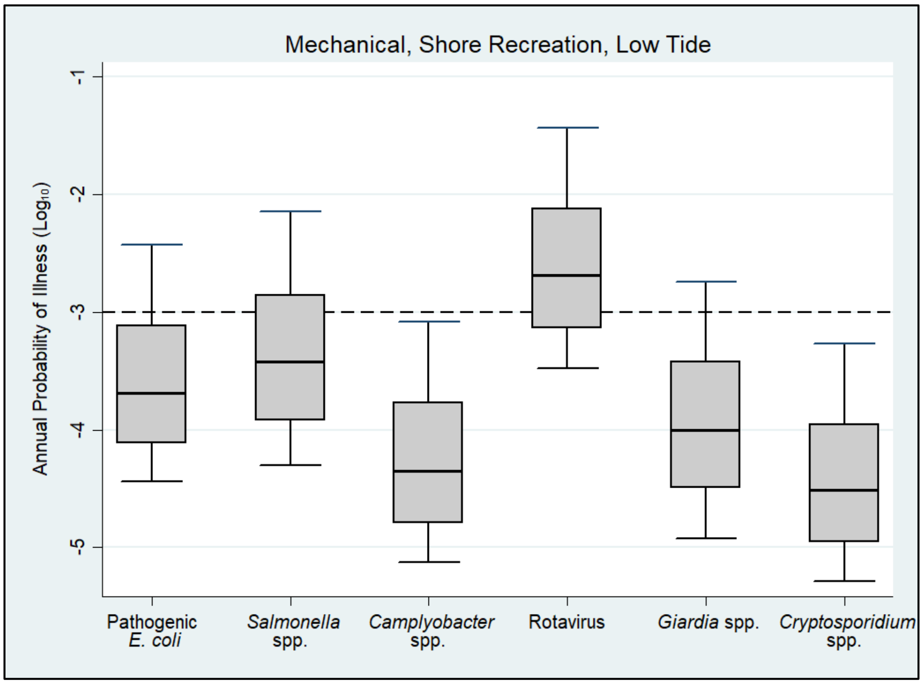
Sensitivity analysis was conducted to prioritize potential control points in the system where risk reducing mitigations may be effective. Specifically, rank order correlation was used to evaluate the impact of the variability and uncertainty within the model inputs on the base case risk results. Rank order correlation is a nonparametric approach, which is based on less stringent assumptions and provides relatively conservative estimates. This feature is beneficial in risk assessment research when the actual distributions of input variables are typically unknown (Vose 2008). Based on this analysis, potential mitigations were configured and assessed.

4.3 Results and Discussion

4.3.1 Base Case Scenarios

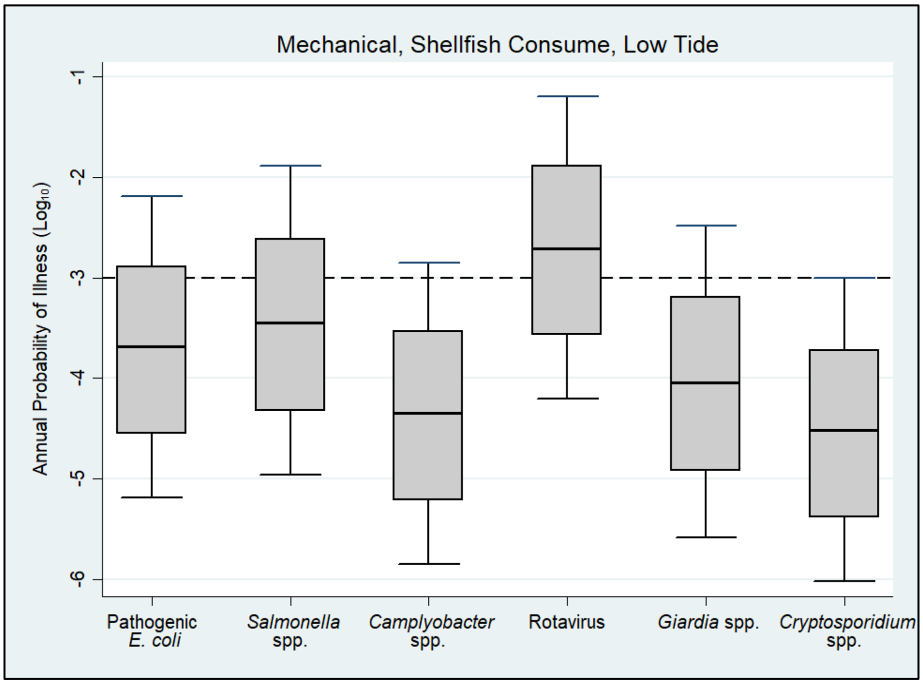
Figures 4.1, 4.2, and 4.3 present box-and-whisker plots of the three exposure scenarios with the highest individual annual risk estimates. Of the three scenarios, two are activities associated with the mechanical treatment and low tide conditions: shore recreation and shellfish consumption. The third scenario, wetland travel during spring freshet, is from the passive treatment model. Of the six pathogens modeled, rotavirus and *Salmonella* spp. were projected to pose the highest risk, followed by pathogenic *E. coli*, *Giardia* spp., *Campylobacter* spp., and *Cryptosporidium* spp. In each of the three presented exposures scenarios, the 75th percentile risk level for at least two pathogens exceeded the proposed target of 10^{-3} as a maximum tolerable risk level. Although not included in the figure, it should also be noted that the 75th percentile risk level for rotavirus, singly, was near 10^{-3} in the mechanical-shellfish harvest-low tide and passive-wetland travel-summer scenarios. Most of the annual risk probabilities were log-normally distributed. Exceptions were some pathogens in very low risk scenarios ($\leq 10^{-12}$). These lower probabilities followed Weibull or Gamma distributions, which are similar to log-normal (Vose 2008).

Figure 4.1 Box-and-whisker graph of individual annual probabilities of acute gastrointestinal illness caused by enteric pathogens associated with 'mechanical, shore recreation, low tide' wastewater effluent exposure scenario in Arctic Canada under baseline conditions.



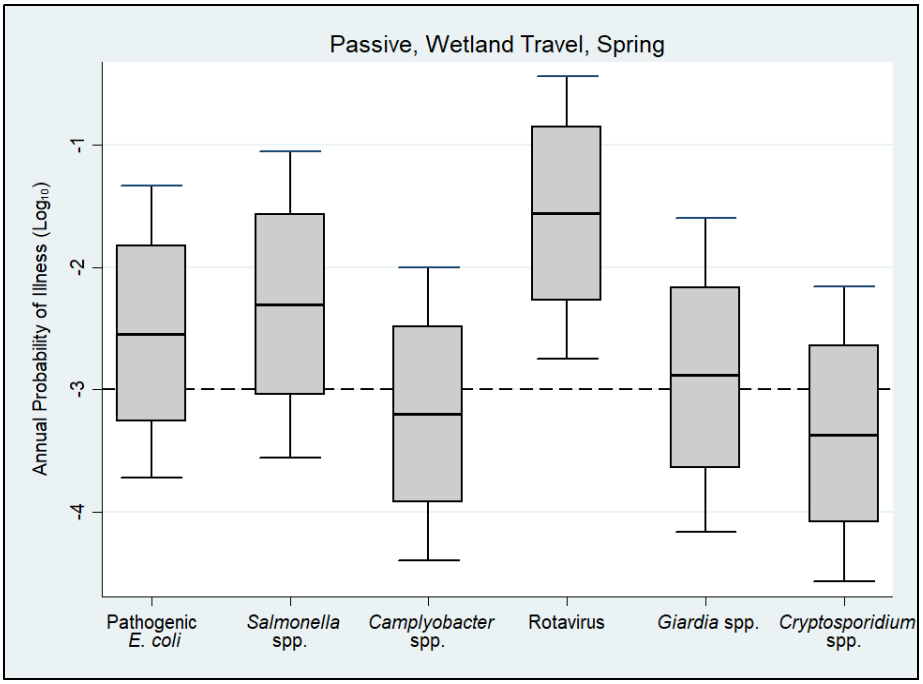
The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed line denotes a potential tolerable risk guideline (10^{-3}).

Figure 4.2 Box-and-whisker graph of individual annual probabilities of acute gastrointestinal illness caused by enteric pathogens associated with 'mechanical, shellfish consumption, low tide' wastewater effluent exposure scenario in Arctic Canada under baseline conditions.



The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed line denotes a potential tolerable risk guideline (10^{-3}).

Figure 4.3 Box-and-whisker graph of individual annual probabilities of acute gastrointestinal illness caused by enteric pathogens associated with 'passive, wetland travel, spring' wastewater effluent exposure scenario in Arctic Canada under baseline conditions.



The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed line denotes a potential tolerable risk guideline (10^{-3}).

Of the remaining passive system scenarios, the majority of annual risk estimates were much lower than the wetland travel-spring exposure, with 90th percentiles $\leq 10^{-6}$. Engineering assessments of arctic wetland treatment systems have also emphasized the spring freshet as a period of higher risk if the adjoining WSP is undersized or has a breached berm (Hayward et al. 2018). Under such circumstances, wastewater that has been accumulating and remained frozen within the WSP throughout the winter thaws quickly and is discharged into the wetland at a high rate (Hayward et al. 2014; Yates et al. 2012). The consequence is an influx of untreated contaminants in the wetland treatment area and receiving water body (Huang et al. 2018). Community input shows that spring is also a potential time for increased human activity within treatment wetlands. As sea and lake ice begin to thin and melt, people travelling by all-terrain vehicles begin to alter their inland routes toward these areas, consequently increasing exposure frequencies.

The mechanical treatment estimates exhibited a pronounced difference in risk between low and high tidal conditions. All exposures modelled during high tide produced 90th percentile risk estimates less than or equal to 10^{-16}. Aside from the highest risk pathways noted above, the remaining low tide exposures, small craft boating and netfishing, had 90th percentile risk levels between 10^{-4} and 10^{-6}. Despite the marked difference in risk estimates between tidal conditions, it is unlikely that an operational change whereby effluent is only released from the plant during high tide would be possible. The current mechanical systems operating in Arctic Canada are not designed with the holding capacity to detain large volumes of wastewater, as would be necessary between tidal cycles. One such system, in Iqaluit, is semi-centralized so raw influent is continuously being piped into the plant; therefore, it must be processed and discharged in a timely manner. The community of Pangnirtung has a decentralized system with all homes and buildings serviced by wastewater pump trucks, which then discharge to the treatment plant. The restrictions that would be necessary to align pump truck service with tidal schedules would be severely disruptive to community life. Such practices may simply create additional sanitation issues at the household level through backups and overflows as home wastewater holding tanks require emptying via pump truck multiple times per week (Daley et al. 2014). Again in this instance the QMRA results align with engineering-based assessments, suggesting that mechanical treatment systems are not well-suited for Arctic conditions from both an ecological and health risk perspective. Greenwood (2016) and Krumhansl et al. (2015) demonstrated that the continuous discharge of nondisinfected effluent can have a negative environmental impact on the receiving water habitat over 500 m from the effluent source. These QMRA results show that such wastewater management practices also have potential to elevate human health risks in the region. This is particularly pronounced when effluent is discharged during low tide conditions; a period when the sea bed is exposed and minimal dilution occurs (Gunnarsdóttir et al. 2013).

In Arctic Canada, territorial health departments are authorized to inspect and respond to wastewater-related issues (Government of Nunavut 1990), although there are no specific health-based targets applied to wastewater discharges. Also, the Canadian Shellfish Sanitation Program – an intended nationwide food safety program – has never been established in northern Canada (Canadian Food Inspection Agency 2019). In the absence of documented health-based targets for the region, the WHO adapt-and-adopt value of 10^{-3}, one order of magnitude higher than the WHO global standard, was selected as a comparative benchmark for these QMRA results. This choice was based on limited epidemiological data on waterborne and shellfish-related illness in the Arctic as well as the nature of the exposure pathways. Most established waterborne illness guidelines are drawn from recreational water settings or wastewater reuse for agriculture and aquaculture. Recreational water criteria suggest an annual tolerable risk of approximately 3.0×10^{-2} episodes of seasonal gastrointestinal illness for exposures such as swimming at a beach (USEPA 2012b). In agriculture and aquaculture settings where wastewater is intentionally used for irrigation purposes, an annual tolerable risk of illness of either 10^{-4} or 10^{-3} is applied for both fieldworkers and consumers (Mara et al. 2008; WHO 2006a). The exposure pathways in the wastewater-impacted environment in Arctic Canada, however, differ from those in the reviewed guidelines. Some, such as shore recreation and small craft boating, classify as recreational but others are unique to this setting. Foraging activities such as netfishing and shellfish harvesting compare somewhat to agriculture and aquaculture, but with the distinction that the food being harvested is wild and not farmed. This distinction is important given the central role of subsistence activities in Indigenous communities (Suk et al. 2004), view of the immediate environment as a vital source of nourishment (Cunsolo Willox et al. 2012), and risk of contaminant bioaccumulation in the diets of Arctic Indigenous populations (Donaldson et al. 2010). Until more is known epidemiologically about AGI rates in the region, a tolerable disease risk attributable to wastewater of 10^{-3} appears to be an appropriate objective to protect health. This objective should come with the understanding, however, that if the WHO global standard of 10^{-4} was instead applied; additional exposure scenarios would exceed the guideline under baseline conditions.

4.3.2 Sensitivity Analysis and Risk Mitigation Options

The results of the sensitivity analysis conducted on the three base case exposure scenarios that exceeded the risk benchmark are presented in Table 4. Distance from the effluent release to exposure location (*dist*) was identified as the parameter with the highest mean correlation coefficient across the three scenarios (−0.71), followed by concentration of indicator *E. coli* at effluent release (C_o) (0.53). The ratio of pathogenic organism per indicator *E. coli* (*E. coli: Path*) and ingestion volume (V) correlation coefficients values were lower with means of 0.22 and 0.16, respectively.

Table 4.4 Sensitivity analysis of base case scenarios that exceeded a tolerable risk benchmark (10^{-3}) of individual annual probability of acute gastrointestinal illness caused by enteric pathogens in an Arctic Canada wastewater exposure risk assessment model.

Parameters[a]	**Correlation coefficients**		
Treatment system Exposure pathway Conditions	Mechanical Shore recreation Low tide	Mechanical Shellfish consume Low tide	Passive Wetland travel Spring
Distance (*dist*)[b]	−0.43 – −0.38	−0.80 – −0.76	−0.95 – −0.88
E. coli at effluent release (C_o)	0.74 – 0.84	0.51 – 0.54	0.24 – 0.27
Inference ratio (*E. coli: Path*)	0.18 – 0.40	0.10 – 0.26	0.13 – 0.32
Ingestion volume (V)	0.21 – 0.24	0.12 – 0.12	0.14 – 0.15

[a] Full definition of parameters available in Tables 4.1, 4.2, and 4.3.
[b] Negative values indicate inverse relationship between variable and $P_{ill,\ annual}$.
Values represent the range (min to max) of the rank order correlation coefficients across modelled pathogens for input variables in relation to individual annual probability of illness ($P_{ill,\ annual}$)

The sensitivity analysis was used to identify leverage points where risk reducing mitigations may be most effective. Two specific mitigations were theorized and modelled: one targeted at decreasing the concentration of indicator *E. coli* within effluent at initial release points (C_0) and the second at increasing the distance between effluent release points and locations of human activity where exposure is likely to occur (*dist*). The mitigation designs, including the corresponding model parameter adjustments are described in the following paragraphs. Figures 4.4, 4.5, and 4.6 present the impact of the mitigations on estimated individual annual risk for the three exposure scenarios that exceeded the benchmark, per pathogen, as compared to base case results.

Mitigation 1 – Improved treatment

Mitigation 1 is an engineering control aimed at improving wastewater treatment and thus reducing the initial concentration of pathogen in the effluent being discharged into the receiving environment. For mechanical systems, this reduction could be accomplished by adding a disinfection stage such as chlorination to the treatment process. Within the model, initial concentration of *E. coli* (C_o) is characterized by a Pareto distribution. The improved treatment was parameterized by first adjusting the location parameter, which determines the minimum possible value, from 10^4 to 10^2, which is the achievable treatment level by chlorination (Bitton 2005). In turn, the shape parameter was adjusted from 0.48 to 0.15 to maintain a fit that represents the documented 5 – 10% failure rate of mechanical systems in Arctic Canada (City of Iqaluit 2015). Upon reassessing shore recreation and shellfish consumption at low tide conditions, an approximate 10 times reduction was seen at the median risk level across pathogens for both scenarios; dropping them all below the 10^{-3} benchmark. Note that in both scenarios the 90th percentile risk level was similar with or without mitigation, remaining above the benchmark for several pathogens. This result is due to the incorporated failure rate in the design, currently a reality of these systems in arctic conditions (Johnson et al. 2014).

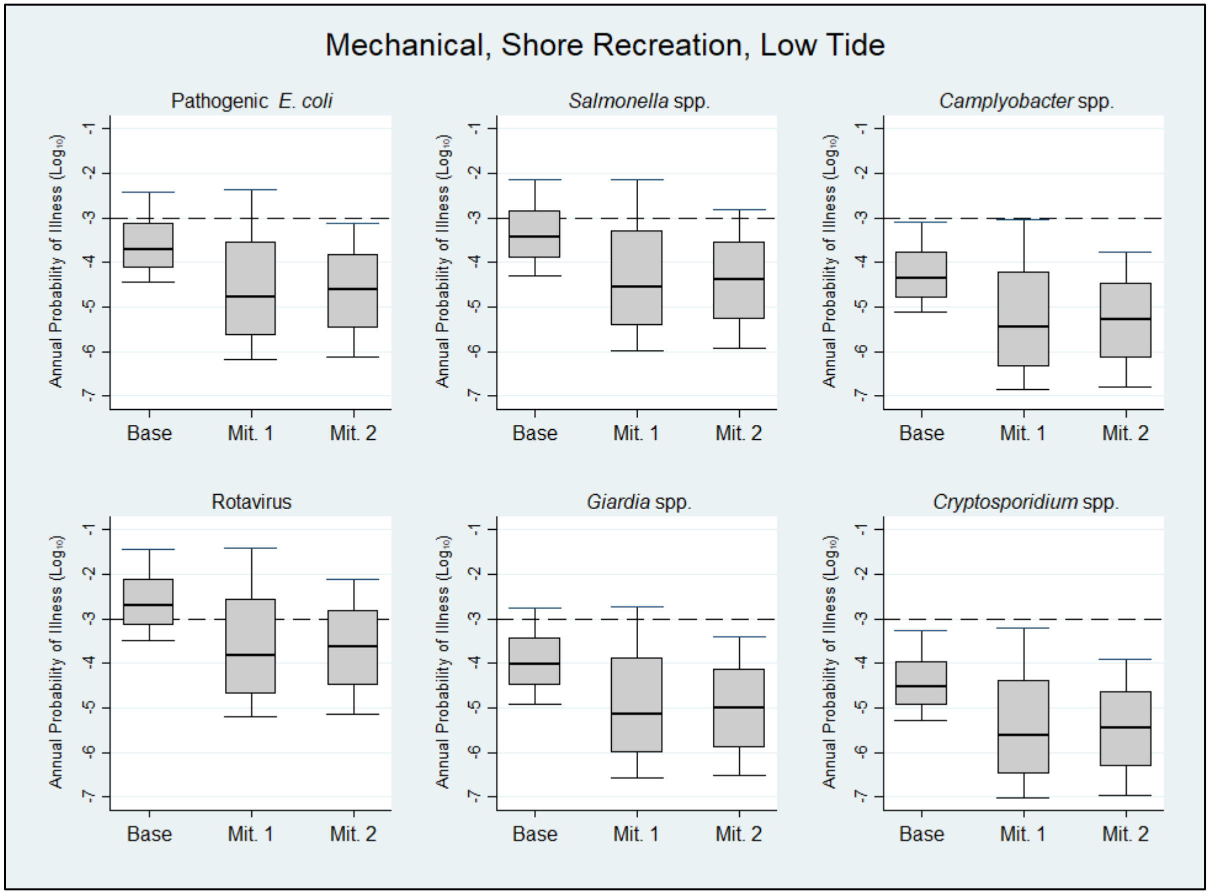
In passive systems, improved treatment requires designing and constructing an adequately sized WSP pond capable of eliminating overflow and leakage. The effect is that wastewater would be detained within the WSP, undergoing a full passive treatment season, rather than continuously seeping from the onset of spring freshet. Effluent would then be manually decanted from the WSP in a controlled discharge exclusively during a one-month period in late summer, just prior to freeze-up. The adjoining wetland could also be engineered to slow and direct the flow of effluent. The improved stabilization pond would produce a 1-log reduction in *E. coli* concentration at the point of discharge to the wetland (Bitton 2005). In modelling terms, the parameters of the uniformly distributed initial indicator *E. coli* concentration were adjusted to a minimum of 10^4 and a maximum of 10^5. Additionally, changing to a controlled decant at the conclusion of the passive treatment season dictates using the summer pathogen reduction coefficient for the wetland treatment component (Table 4.1). Exposure event frequency was also decreased to 20, to reflect the shorter time period during which human contact with pathogens could occur in the wetland. The risk reduction to wetland travel as a result of this mitigation is substantial, as median levels for all pathogens drop to 10^{-6} or lower, which is approximately 15 000 times less than base case risk. The 90th percentile risk levels are reduced to 10^{-4} or less, an approximate 500 times reduction.

Mitigation 2 – Behavioural change

Mitigation 2 involves interventions intended to inform people of wastewater hazards and change the patterns of human activity occurring in the treatment areas and receiving environments. Behavioural change mitigations should ultimately be chosen based on what is acceptable, appropriate, and culturally relevant to the local population (Nguyen-Viet et al. 2009). Options in this setting may include public health messaging or signage and fencing at the initial points of effluent discharge. It is assumed that these interventions are preventative initiatives, as opposed to enforced by-laws. As such, some people may still choose to enter these spaces to gain access to established travel routes and food harvesting locations. A portion of the exposed population, however, will likely alter their behaviour patterns and shift activity to locations further away from the effluent release source.

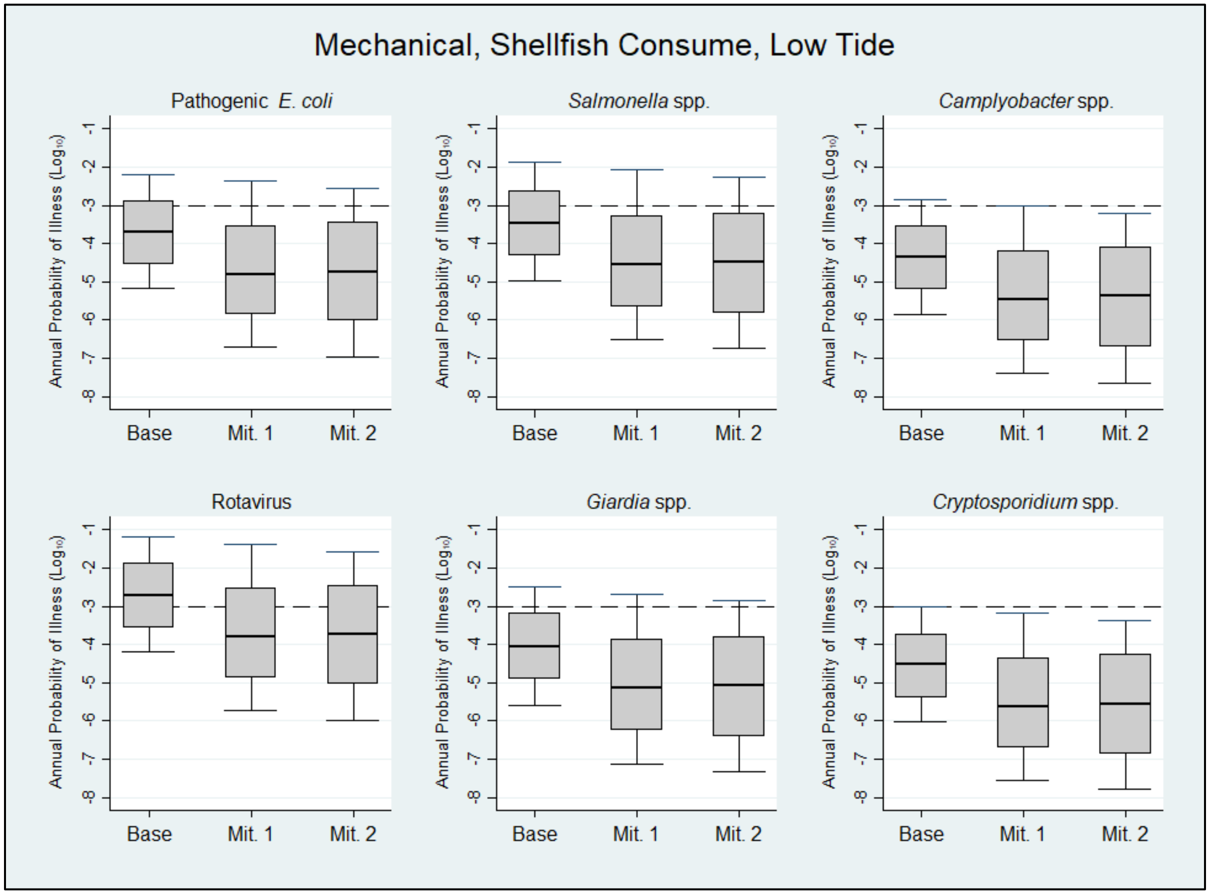
In the passive system model, the minimum parameter of the uniformly distributed distance (*dist*) variable was increased from 250 to 500 m. All other values remained the same. The result was an approximate 3 times reduction in risk at the median level and 6 times reduction at the 90th percentile for the spring-wetland travel exposure across pathogens. Even so, pathogenic *E. coli*, rotavirus and *Salmonella* median risk levels remain at or above 10^{-3}. Within the mechanical treatment model, the minimum distance (*dist*) parameter was unaltered from the base case setting of 1000 m as this original value was based on the existing level of public awareness concerning hazards in the area directly surrounding mechanical treatment facilities. Instead, the maximum parameter was increased by 1000 m for both scenarios to simulate the shoreline recreation and shellfish consumption exposure populations moving further away from the treatment facility in response to the mitigation. The result was an approximate 9 times decrease in risk at the median level across pathogens for both scenarios; dropping them all below the benchmark. A reduction of only 3.5 times was seen at the 90th percentile level, leaving several pathogen risks in both exposures higher than 10^{-3}.

Figure 4.4 Box-and-whisker graphs of individual annual probability of acute gastrointestinal illness caused by enteric pathogens associated with ‘mechanical, shore recreation, low tide’ wastewater effluent exposure scenario in Arctic Canada, under baseline conditions (Base) and mitigations (Mit. 1 – improved treatment, Mit. 2 – behavioural change).



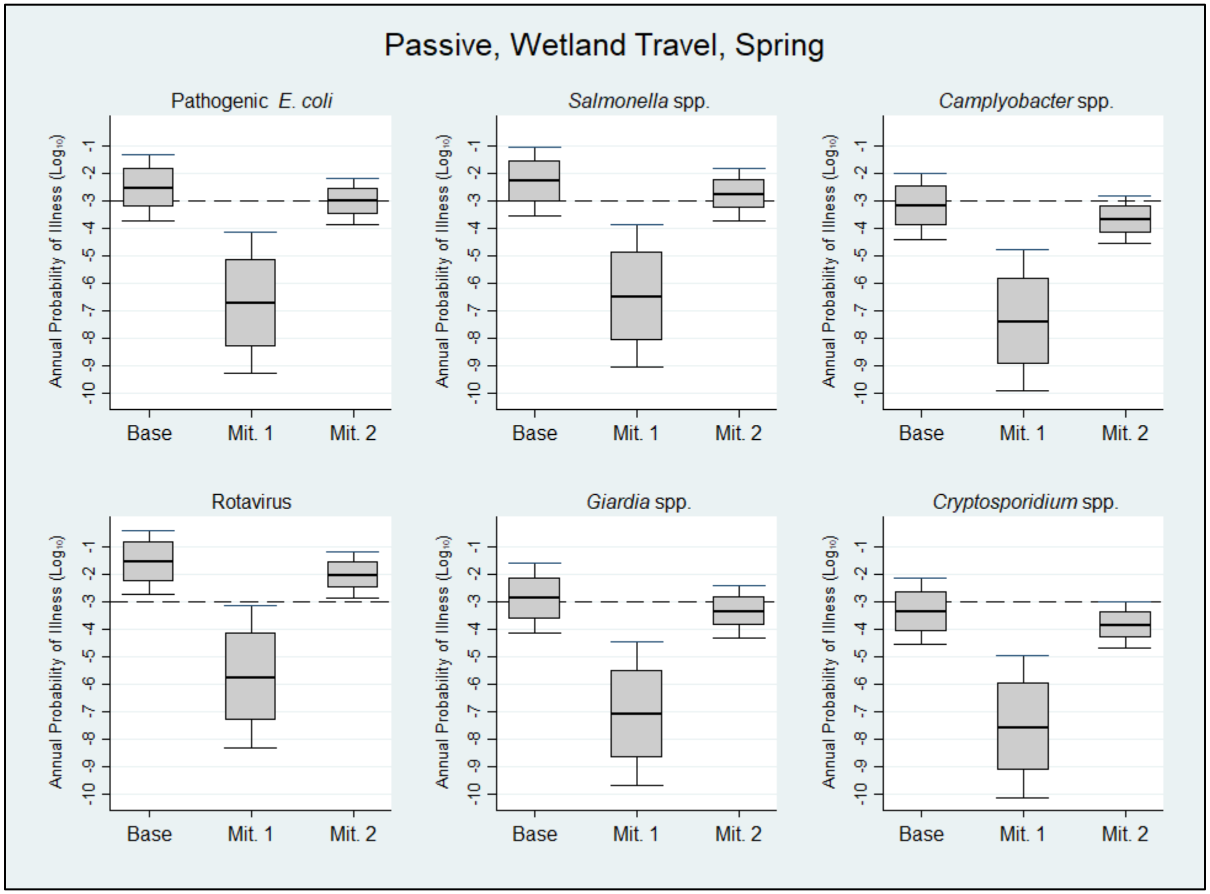
The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed lines denote a potential tolerable risk guideline (10^{-3}).

Figure 4.5 Box-and-whisker graphs of individual annual probability of acute gastrointestinal illness caused by enteric pathogens associated with ‘mechanical, shellfish consume, low tide’ wastewater effluent exposure scenario in Arctic Canada, under baseline conditions (Base) and mitigations (Mit. 1 – improved treatment, Mit. 2 – behavioural change).



The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed lines denote a potential tolerable risk guideline (10^{-3}).

Figure 4.6 Box-and-whisker graphs of individual annual probability of acute gastrointestinal illness caused by enteric pathogens associated with ‘passive, wetland travel, spring’ wastewater effluent exposure scenario in Arctic Canada, under baseline conditions (Base) and mitigations (Mit. 1 – improved treatment, Mit. 2 – behavioural change).



The probabilities were estimated using a quantitative microbial risk assessment. Boxes represent 25th and 75th percentiles, solid lines within boxes are medians, and whiskers are 10th and 90th percentiles. Large dashed lines denote a potential tolerable risk guideline (10−3).

Overall, both types of mitigations reduced the estimated AGI risk attributable to wastewater exposures. With respect to mechanical treatment specifically, the impact was similar across the two options. There is greater inherent uncertainty in the mitigation 2 results, however, as the effectiveness of improved treatment processes is more predictable than actions intended to change human behaviour. Regarding passive systems, the improved treatment mitigation was more effective, strengthening the case for well-designed stabilization pond and wetland systems in Arctic conditions (Balch et al. 2018). Infrastructure costs in the Arctic are exorbitant and decisions related to upgrading wastewater treatment should be made based on whether the investments will result in significantly improved health or environmental outcomes. Appropriate technology choices and rational allocation of resources should be part of setting priorities within an overall public health strategy and water safety plan (Murphy et al. 2009; WHO 2016). For comparative purposes, and keeping in mind that costs are highly variable, a mechanical treatment facility with disinfection capability in a medium-sized Arctic Canada community (pop. 1500) would likely cost upwards of CAD$5 – 10M. Additionally, annual operational and maintenance costs could range from CAD$300 – 800 thousand, a large portion of which get allocated to energy expenses. The initial cost of building a properly engineered passive WSP and wetland treatment system is estimated at CAD$5M, but with far less operational costs required (Johnson et al. 2014).

4.3.3 Limitations

This health risk assessment relies exclusively on *E. coli* as a fecal indicator organism and the use of pathogen inference ratios. Ideally, virus and protozoan indicator data would also be used to reduce some of the uncertainty associated with the ratios. Similarly, enterococci are considered a preferred fecal indicator in marine waters, if available (Health Canada 2012). Moreover, pathogen fate and transport models developed specifically for arctic environments would be of great benefit to future sanitation research in the region (Cho et al. 2016). However, all Arctic microbiology research – water, medical, or otherwise – is currently limited by a lack of laboratory facilities in the remote region. Therefore, for the time being, *E. coli* analysis remains the practical indicator organism given the low cost and ease of processing. More research is also recommended specifically on the human health risks associated with shellfish consumption in the Arctic as the QMRA results presented here provide only a starting estimate. Shellfish are an easily accessible, and therefore important, food source in the region (Harrison and Loring 2016), yet caution is warranted as worldwide they are commonly associated with wastewater contamination and cases of AGI (Ford 2005).

The exposure pathways assessed in this QMRA were developed using local knowledge from predominantly Inuit communities in Nunavut. As such, the findings may or may not be directly transferable to other communities and Indigenous populations in the Arctic. The model was deliberately designed to be inferential and is easily adaptable to other communities and exposure scenarios given the necessary input to define and parameterize the human-environment interactions. This type of data can be collected and inserted into the model by community members and stakeholders without the need for extensive training.

4.4. Conclusion

Building on an initial screening-level model (Daley et al. 2019), this research provides the first in-depth risk assessment of AGI attributable to wastewater treatment systems in Arctic Canada. Three exposure scenarios included in the assessment exceeded a proposed tolerable annual risk target of 10^{-3} (i.e. 1/1000). These scenarios included: shore recreation near mechanical treatment sites during low tide; consumption of shellfish harvested near mechanical treatment sites during low tide; and wetland travel near passive treatment sites during spring freshet. Lower risk probabilities were estimated in all other scenarios. These base case results suggest that human exposure to wastewater effluent via food harvesting and recreational activities may be contributing to elevated rates of AGI in some Arctic Canadian communities. Mitigations in the form of engineering controls and behavioural interventions were shown to have potential to reduce risk to varying degrees. On the whole, engineered passive systems, incorporating controlled summer discharge schedules and risk communication messaging, appear the most appropriate wastewater treatment option for Arctic communities.

This research was conducted using a modified participatory QMRA approach. Participatory epidemiology-based data collection methods including interviews, site-mapping, and public forums were used with the conventional risk assessment framework. Thereby, local knowledge of activity patterns in wastewater-impacted environments centered the exposure scenario development process. As such, the results offer an evidence base for water, sanitation, and public health policy and actions in Arctic Canada that is grounded in community knowledge. This study also lends perspective to the greater body of emerging epidemiology and microbiology research investigating various aspects of waterborne pathogens and enteric disease in the Arctic. More broadly, elements of this research may also be relevant to other locations where basic wastewater treatment practices are utilized.

Chapter 5
Conclusions

5.1 Main Findings

The three manuscript chapters of this dissertation progress as a series; initially building understanding of the issue and an appropriate assessment method, and then developing and scaling up the model. In this section, the main research findings are revisited in relation to the stated objectives of the dissertation.

Objective 1) *Review the state of knowledge on microbial health risks associated with wastewater treatment in Arctic Canada;* and

Objective 2) *Develop a conceptual model of potential human exposure pathways in Arctic Canadian communities:*

In Chapter Two, a conceptual model depicting wastewater-related exposure pathways in Inuit and Arctic communities is developed to provide basis for and guide risk assessment research. The conceptual model includes five categories of information deemed necessary to characterize the exposure pathways: pathogen source, physical environment, biological environment, human activities, and transmission routes. The state of knowledge and strength of evidence on each category are evaluated through a review of academic and grey literature.

The state of knowledge relating to enteric pathogens and wastewater treatment (pathogen source), fate and transport of pathogens in effluent discharged to lands, water, and ice near communities (physical environment), and how the population interact with the local environment (human activities, transmission routes) are all considered moderate to strong. Evidence concerning the concentrations of pathogens present in wildlife and fish that are harvested for food (biological environment) is deemed weak; therefore, the use of conservative assumptions is recommended when parameterizing this category.

Objective 3) Characterize the probability of illness associated with specific exposure scenarios, using AGI as a health outcome:

In Chapter 3, a screening-level QMRA model is developed to assess the probability of AGI associated with several worst-case exposure scenarios in five Nunavut case study sites. The resulting probabilities are compared to epidemiological estimates suggesting that the total food- and waterborne AGI incidence in Arctic communities is 2.9 – 3.9 annual cases per person (Harper et al. 2015a). The highest incidence rate predicted using the model occurs in Pangnirtung, at 5.0 annual cases of AGI per person, where a mechanical treatment system discharges directly to a marine environment during low tide. A moderate incidence rate of 1.2 annual cases of AGI per person is predicted in Naujaat, where an inadequately sized passive system is currently in use, with most of the cases predicted during spring freshet. The annual AGI incidence rates estimated for the three remaining case study locations are less than 0.1 cases per person.

In Chapter Four, a more in-depth QMRA model is used to broaden the applicability of the research across Arctic Canada and similar contexts. Moving beyond case studies, the risk of AGI is characterized for inferential wastewater exposure scenarios with full parameters ranges and compared to a global health guideline (Mara et al. 2008; WHO 2006a). The 75th percentile level for three scenarios exceeds the proposed tolerable guideline of 10^{-3} annual risk of water-related AGI (i.e. 1/1000): shore recreation near mechanical treatment sites during low tide; consumption of shellfish harvested near mechanical treatment sites during low tide; and wetland travel near passive treatment sites during spring freshet. Rotavirus and *Salmonella* spp. project the highest risk of the six enteric pathogens included in the model.

Objective 4) Evaluate mitigations and management strategies to reduce risk, if necessary:

Given that the risk of AGI for some wastewater exposure scenarios exceeds the proposed tolerable guideline, two forms of mitigation are also evaluated in Chapter Four: improved wastewater treatment and behavioural change. Both forms of mitigation are shown to potentially reduce predicted risk in all base case exposure scenarios by varying amounts and with varying financial cost. Mitigation 1 in particular reduced all median risk level estimates below the proposed guideline of 10^{-3}.

5.2 Contributions

This research has pragmatic value to the territory of Nunavut and other arctic regions where there is currently limited evidence regarding human health risks associated with wastewater treatment. The results offer a set of risk estimates that public health and public works entities can use to aid understanding of disease transmission and support changes to current wastewater operations. The inferential model can be further applied as a decision-making tool to compare relative risk between treatment system options or to forecast health risk levels under varying conditions; for example, in advance of shellfish harvesting periods or spring freshet. In more general terms, this research offers information on a localized pollution source, at a time when much Arctic environmental health research has focused on non-local or long-transport pollutants. The findings also address a priority set by ITK (2018) for more health and social science research that immediately serves Inuit communities and people.

In the last decade, significant advances have been made to characterize the performance and suitability of engineered and non-engineered passive wastewater treatment systems in an arctic climate (Balch et al. 2018). The majority of that research demonstrated effectiveness in terms of nutrient pollution abatement and related conventional environmental quality measures (CCME 2014; Greenwood 2016; Hayward et al. 2014; Ragush et al. 2015; Schmidt et al. 2016). This dissertation complements that work with a previously-absent, pathogen-based human health risk assessment and reinforces the overarching recommendation of passive treatment as the most appropriate technology for the context.

This research also contributes to a better understanding of exposure risk and AGI in Arctic communities. Links between AGI and several food- and water-related exposures have been investigated in recent years (Harper et al. 2015a; Masina et al. 2019; Mosites et al. 2018; Wright et al. 2018) as well as a growing list of specific enteric microorganisms (Daley et al. 2018b; Desai et al. 2017; Goldfarb et al. 2013; Hastings et al. 2014; Huang et al. 2018; Iqbal et al. 2015; Thivierge et al. 2016) and the prevalence of antibiotic resistant bacteria (Daloo et al. 2008; Golding et al. 2010; Hayward et al. 2018; Neudorf et al. 2017). The set of risk estimates featured in this dissertation pertain to AGI association with wastewater exposure in general, but also provide direction on other individual risk factors and pathogens to investigate with further studies. For instance, more direct methods of evaluating human behaviour patterns within the exposure scenarios that presented the highest risk (e.g. wearable sensors) may be possible. Awareness of the organisms presenting the highest risk in wastewater exposure scenarios (i.e. rotavirus and *Salmonella* spp.) may also be helpful when tailoring gastrointestinal pathogen research and outbreak investigations in remote Arctic communities, as conventional microbiology testing and analysis capacity are likely to remain limited in the region (Goldfarb et al. 2013).

The most novel contribution of the dissertation is the application of a QMRA model in an Arctic community setting. In Arctic communities, traditionally semi-nomadic Indigenous populations are striving to maintain their vital food harvesting and recreation practices while simultaneously addressing the inherent sanitation and disease prevention necessities of permanent settlements. This intertwined environmental and societal challenge represents a "complex problem" by environmental studies and ecohealth definitions (Berkes et al. 2008; Charron 2012). In this thesis research, the problem is approached by integrating participatory data collection methods into a QMRA framework. In doing so, the affected communities and populations provide their own descriptions of how they interact with the environment. These social science data are then transposed into exposure model variables (i.e. location, timing, duration, frequency, size of exposed group). Additionally, cultural nuances such as the custom of sharing harvested food amongst community members, as well as the preference of some Inuit to consume shellfish raw, are important exposure considerations that would not have been accounted for in an assessment based on standard population values. Furthermore, community knowledge also informs the mitigation designs. Wastewater operators in Pond Inlet explained to the academic research team that the practice of deferring the controlled discharge of stabilization ponds until late summer not only extends the treatment period, but also allows for the char fishing season to end; thus reducing the likelihood of human exposure in receiving waters. As QMRA continues to find new applications in less industrialized settings, the inclusion of participatory methods and socio-ecological perspectives are areas to advance the science.

5.3 Recommendations and Future Research

Based on this dissertation, the recommended wastewater management strategy for Arctic communities is passive systems operating on controlled summer discharge schedules, in combination with tailored risk communication strategies to deter human activity in receiving environments. Although well-designed passive systems present a period of increased health risk during the effluent decanting period, this period is restricted to one or two predetermined weeks per year. Therefore, risk of exposure can be more easily managed in comparison to those associated with mechanical treatment, which are influenced by uncontrolled effluent discharge and daily tides. This recommendation includes a tolerable AGI risk guideline of 10^{-3} in wastewater-impacted environments. This guideline is based on global health standards and provides a reasonable degree of health protection based on the strength of evidence at the current time.

Recommending passive treatment may have secondary public health policy impacts. Arctic communities face challenges and experience inequalities in many determinants of health (Reading and Wien 2009). There are gaps between Arctic and national averages in many health indicators as well as substantial disparities between Indigenous and non-Indigenous populations within Arctic regions (Young et al. 2012). This dissertation demonstrates that effective wastewater management and public health protection are possible with passive methods of treatment; which are generally considered the more sustainable and economical option in Arctic conditions (Johnson et al. 2014; ITK and Johnson 2008). Theoretically, this finding could translate to more financial resources available for other key sectors of development and determinants of health (e.g. education, nutrition, food security, and primary health care).

Health risk assessment research in the region could be further improved with better understanding of the fate and transport of specific pathogens in arctic environments, shellfish, and other harvested food sources; thus lessening reliance on indicator *E. coli* as an index. Within the human activity components, distinguishing risk estimates by sex, gender, and age may provide new insights as behaviours and roles related to food harvesting and recreation may differ among individuals and groups. A standalone assessment focused on the occupational risk experienced by wastewater treatment operators may also be worthwhile. These types of investigations would decrease the uncertainty of wastewater QMRA estimates while also supporting a range of other health and environmental research areas. QMRA research also has a supporting role to play as remote Arctic regions, which currently rely on diesel power plants, explore less-energy intensive water treatment technologies and innovations including water reuse at both household and community scales.

The implications of rapid climate change on the results should be considered going forward. Increasing temperatures and precipitation amounts in Arctic regions are projected to increase the incidence of infectious diseases (Hennessy and Bressler 2016; Waits et al. 2018). The framework featured in this dissertation is based on data describing past and current conditions. Therefore, deliberation must be given as to how these predictions could differ as climate change alters the conditions of the physical environment and associated subsistence lifestyles in Arctic regions. Given the conservative parameter ranges and assumptions applied herein, the results will likely still be relevant for the near future. Furthermore, the inferential model featured in Chapter Four is highly adjustable, meaning it may find further application as a method of comparing the impact of future climate change adaptation scenarios on wastewater management and public health risks.

5.4 Summary

This dissertation provides the first human health risk assessment of wastewater in Arctic Canada since the implementation of community wastewater treatment systems. A participatory QMRA approach is used to predict the risk of AGI due to inadvertent exposure to effluent in local environments near treatment sites. Mitigation options to reduce risk are also investigated. Findings indicate that wastewater treatment systems may be contributing to high AGI incidence rates in some communities. The risk estimates vary substantially, however, by treatment system, environmental conditions, and exposure pathway. In some scenarios, the risks are considered low. Based on this research, passive systems with controlled discharge and accompanying risk prevention messaging are the most appropriate wastewater treatment solution in Arctic Canada. These results have immediate public health and engineering applications in the region. In addition, the research responds to calls from the global Arctic community for more information related to infectious diseases, water security, and Indigenous health (Hennessy and Bressler 2016; ITK 2018; Nilsson et al. 2013; Parkinson et al. 2014).

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APPENDICES

Appendix A

Stochastic QMRA Model Inputs and Sources of Uncertainty

This table is appended as a supplement to the stochastic QMRA model and parameter tables featured in Chapter 4. The table provides additional detail on data sources, assumptions, limitations, and sources of uncertainty associated with each model input. The purpose of including this information is to make available all information necessary to replicate the study, model, and results.

Table A-1 Stochastic QMRA model inputs and sources of uncertainty

Model Input	Parameter Data Source	References	Assumptions and Limitations	Sources of Uncertainty	Efforts to address limitations and account for uncertainty
Initial concentration of indicator *E. coli*, C_0 (concentration in effluent at treatment system discharge point)	Water sample data from 5 Nunavut communities (Dalhousie University Northern Wastewater Research Program) Wastewater operations records	Greenwood (2016); Hayward et al. (2018); Neudorf et al. (2017) Appendix F	Assumed field data is representative of all treatment systems in Nunavut Limited by timing and duration of field season	Measurement error Random sampling error (small data sets)	Samples collected during various tidal cycles and seasons Duplicate samples, when possible Use of Pareto distribution (mechanical) and uniform distribution (passive) to reflect range of treatment efficacy across systems including periods of reduced operation

Model Input	Parameter Data Source	References	Assumptions and Limitations	Sources of Uncertainty	Efforts to address limitations and account for uncertainty
First-order reduction constants, *k* (used to predict pathogen concentration at various distances)	Water sample data from 5 Nunavut communities (Dalhousie University Northern Wastewater Research Program) Linear regression analysis	Greenwood (2016); Hayward et al. (2018); Neudorf et al. (2017) Appendix F	Assumed inactivation / dilution of *E. coli* in receiving environments can be used to conservatively predict reduction rates of six pathogens included in model	Surrogate variable (exclusive use of indicator *E. coli)* Excluded variables (unknown but significant receiving environment factors may not have been considered)	Reduction constants calculated specifically to each relevant combination of system (mechanical/passive) and receiving environment conditions (high tide/low tide, spring/summer)
Distance, *dist* (used to locate exposure point relative to effluent discharge point)	Community data (42 key informant interviews, 100 public form attendees)	Appendix E	Assumed participating key informants can provide representative expert opinion Limited by timing and duration of field season Limited by key informant availability	Subjective estimates (potential for inexpert informants; difficulty adjusting single point estimate to encompass range of values that could actually occur)	Included multiple types of key informants to gain differing perspectives Validation of preliminary analysis and parameter adjustment through public forum Inclusion of several data collection techniques within key information interview sessions (questionnaires, mapping, site-visits) Used recommended probability distribution (uniform) for modelling expert opinion (Vose 2008)

Model Input	Parameter Data Source	References	Assumptions and Limitations	Sources of Uncertainty	Efforts to address limitations and account for uncertainty
Volume, V (measure of accidental ingestion amount)	Literature values	Dorevitch et al. (2011); McBride et al. (2013): Health Canada (2007); Moya (2004); Fuhrimann et al. (2016, 2017); WHO (2006b)	Limited based on absence of data (field or relevant literature) on novel exposure pathways being assessed Assumed exposure values from similar activities (water recreation, rice paddy harvesting) were reasonably applicable	Measurement error (in literature values) Degree of representativeness of literature scenarios to context is unknown	Used recommended probability distribution (triangular) when minimum, average, and/or maximum estimates are available (which was the case with referenced source literature) Conservative factors applied to maximum parameter value (3X or 5X) based on assumed differences between literature and model exposure scenarios
Shellfish tissue pathogen accumulation factor (used to predict pathogen concentration in shellfish tissue)	Literature value	CEFAS (2014)	Assumed value Limited by absence of local field data	Accumulation factors presented in literature differ based upon water columns, wastewater content, and species; all of which are either unknown or being indirectly assessed at local shellfish harvest locations	Typical value (10X) selected from among wide range (3X to 330X) presented in literature, potential for underestimation until validation with local shellfish data available

Model Input	Parameter Data Source	References	Assumptions and Limitations	Sources of Uncertainty	Efforts to address limitations and account for uncertainty
Shellfish cooking pathogen reduction factor (used to predict pathogen inactivation or die-off due to cooking)	Community data (42 key informant interviews, 100 public form attendees)	Appendix E	Assumed value Limited by absence of local field data	Percentage of population who consume undercooked or raw shellfish in Nunavut has never been studied; furthermore, such studies would likely produce only imprecise estimates at best	Used median reduction factor (0.5); no theoretical reasoning nor adequate data exist for fitting a distribution
Indicator *E. coli* to Pathogen ratios, *E. coli: Path* (used to infer specific pathogen concentration)	Literature values	Haas et al. (1999); Howard et al. (2006); Craig et al. (2003); Fuhrimann et al. (2016, 2017); WHO (2006b); Katukiza et al. (2014); Machdar et al. (2013)	Limited by absence of data; therefore, exclusive reliance on indicator *E. coli* as indexer of pathogen occurrence in effluent-receiving environments Assumed indicator *E. coli* could be used to conservatively infer levels of specific pathogens	Surrogate variable Incorrect model form (several plausible ratios are available for each pathogen)	Despite limitations, *E. coli* analysis remains the practical indicator organism in Arctic communities given the low cost and ease of processing Used recommended probability distributions (triangular, PERT, or uniform) when minimum and maximum estimates are available (which was the case with referenced source literature)

Model Input	Parameter Data Source	References	Assumptions and Limitations	Sources of Uncertainty	Efforts to address limitations and account for uncertainty
Dose-response model parameters, r, α, N_{50} (used to determine probability of infection given dose of pathogen at exposure)	Literature values	CAMRA (2015); Dupont et al. (1971); McCullough and Eisele (1951); Black et al. (1988); Ward (1986); Rendtorff (1954); Messner et al. (2001)	Did not specifically consider susceptible populations Dose-response models are mathematical functions built on the premise that measures of dose can yield the probabilities of adverse effects. For a full discussion of the assumptions and limitations underlying dose-response modelling, see: http://qmrawiki.org/content/dose-response-assessment	Incorrect model form (several plausible dose-response models may have consistent fit with data)	Dose-response models are necessary in QMRA as it is not possible or ethical to perform a direct human or animal assessment of risk to a given dose Selected the specific recommended dose-response models and parameters for each of the six pathogens (CAMRA 2015)
Morbidity ratios, $P_{ill,path}$ (probability of illness given infection)	Literature values	Fuhrimann et al. (2017); Machdar et al. (2013); Westrell (2004); WHO (2006b); Barker et al. (2014); Schoen and Ashbolt (2010)	Assumed morbidity ratios are constant and not dose dependent Did not specifically consider susceptible populations	Incorrect model form (several plausible morbidity ratios are available for most pathogens)	Used point-estimate ratios that are heavily cited and/or cited by established QMRA scholars No theoretical reasoning for fitting a distribution

Model Input	**Parameter Data Source**	**References**	**Assumptions and Limitations**	**Sources of Uncertainty**	**Efforts to address limitations and account for uncertainty**
Frequency of exposure events per year, *freq* (number of annual occurrences of a given exposure)	Community data (42 key informant interviews, 100 public form attendees)	See Appendix E	Assumed participating key informants can provide representative expert opinion Limited by timing and duration of field season Limited by availability of key informants	Subjective estimates (potential for inexpert informants; difficulty adjusting single point estimate to encompass range of values that could actually occur)	Included multiple types of key informants to gain differing perspectives Validation of preliminary analysis and parameter adjustment through public forum Use of several data collection techniques within interview sessions (questionnaires, mapping, site-visits) Revised interview question to improve accuracy: asked informants to instead provide frequency estimates month-by-month rather than one aggregated total
Exposure Group, *ExpGroup* (total individuals exposed per event) (Note: input not a component of Chapter 4 model, but used in Chapter 3 model)	Community data (42 key informant interviews, 100 public form attendees)	See Appendix E	Assumed participating key informants can provide representative expert opinion Limited by timing and duration of field season Limited by availability of key informants	Subjective estimates (potential for inexpert informants; difficulty adjusting single point estimate to encompass range of values that could actually occur)	Included multiple types of key informants to gain differing perspectives Validation of preliminary analysis and parameter adjustment through public forum Used several data collection techniques within interview sessions (questionnaires, mapping, site-visits)

Appendix B

Ethical Approval Letter

Social Sciences & Humanities Research Ethics Board
Letter of Approval

July 31, 2013

Mr Kiley Daley
Management\Resource & Environmental Studies

Dear Kiley,

REB #: 2013-3021
Project Title: Assessing Contaminant Exposure and Human Health Risks Associated with Wastewater Management Practices in Arctic Canada Using a Modeling Approach

Effective Date: July 31, 2013
Expiry Date: July 31, 2014

The Social Sciences & Humanities Research Ethics Board has reviewed your application for research involving humans and found the proposed research to be in accordance with the Tri-Council Policy Statement on *Ethical Conduct for Research Involving Humans.* This approval will be in effect for 12 months as indicated above. This approval is subject to the conditions listed below which constitute your on-going responsibilities with respect to the ethical conduct of this research.

Sincerely,

Dr. Sophie Jacques, Chair

Post REB Approval: On-going Responsibilities of Researchers

After receiving ethical approval for the conduct of research involving humans, there are several ongoing responsibilities that researchers must meet to remain in compliance with University and Tri-Council policies.

1. Additional Research Ethics approval
Prior to conducting any research, researchers must ensure that all required research ethics approvals are secured (in addition to this one). This includes, but is not limited to, securing appropriate research ethics approvals from: other institutions with whom the PI is affiliated; the research institutions of research team members; the institution at which participants may be recruited or from which data may be collected; organizations or groups (e.g. school boards, Aboriginal communities, correctional services, long-term care facilities, service agencies and community groups) and from any other responsible review body or bodies at the research site

2. Reporting adverse events
Any significant adverse events experienced by research participants must be reported **in writing** to Research Ethics **within 24 hours** of their occurrence. Examples of what might be considered "significant" include: an emotional breakdown of a participant during an interview, a negative physical reaction by a participant (e.g. fainting, nausea, unexpected pain, allergic reaction), report by a participant of some sort of negative repercussion from their participation (e.g. reaction of spouse or employer) or complaint by a participant with respect to their participation. The above list is indicative but not all-inclusive. The written report must include details of the adverse event and actions taken by the researcher in response to the incident.

3. Seeking approval for protocol / consent form changes

Prior to implementing any changes to your research plan, whether to the protocol or consent form, researchers must submit them to the Research Ethics Board for review and approval. This is done by completing a Request for Ethics Approval of Amendment to an Approved Project form (available on the website) and submitting three copies of the form and any documents related to the change.

4. Submitting annual reports

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8. Legal Counsel

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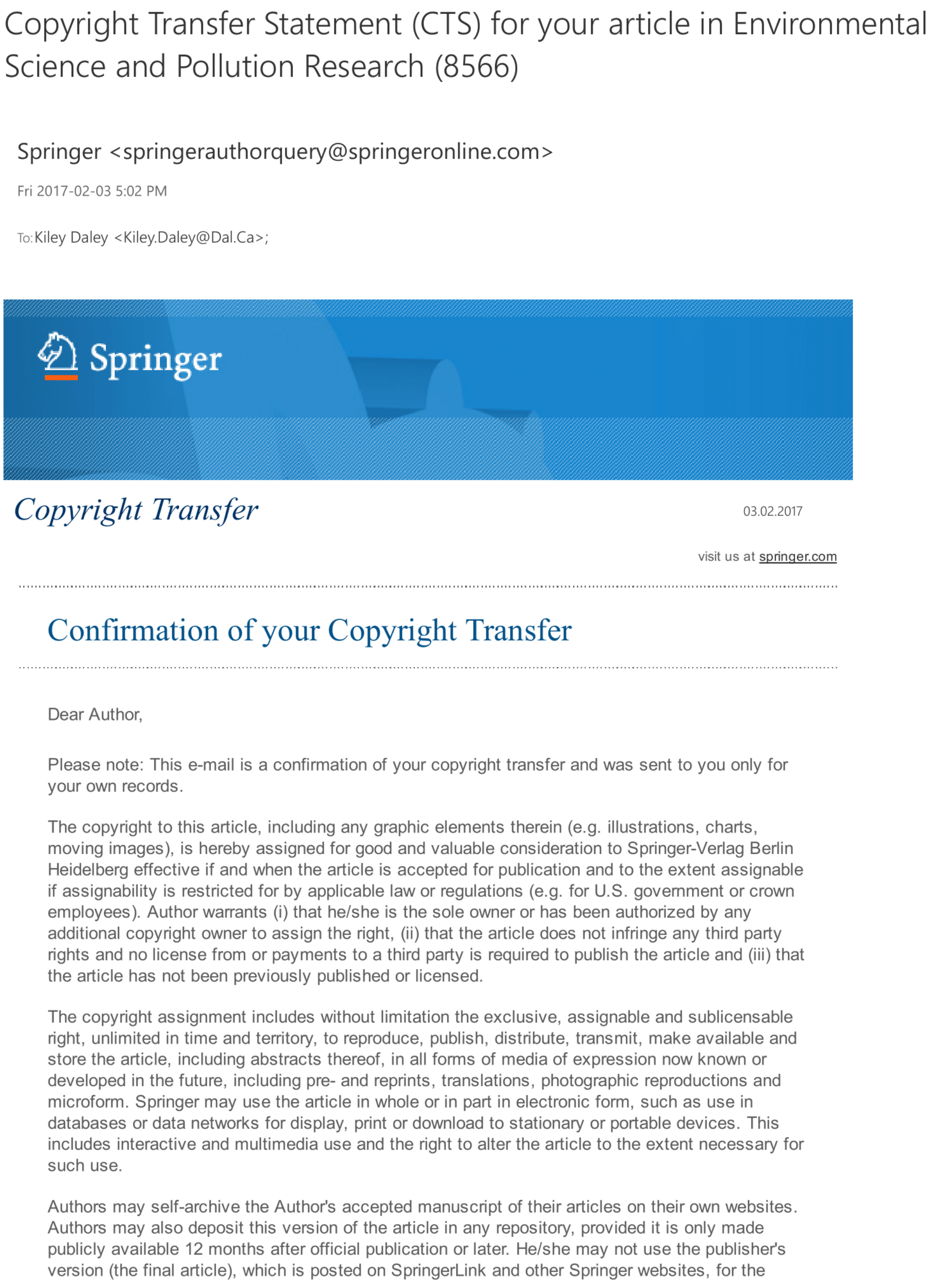

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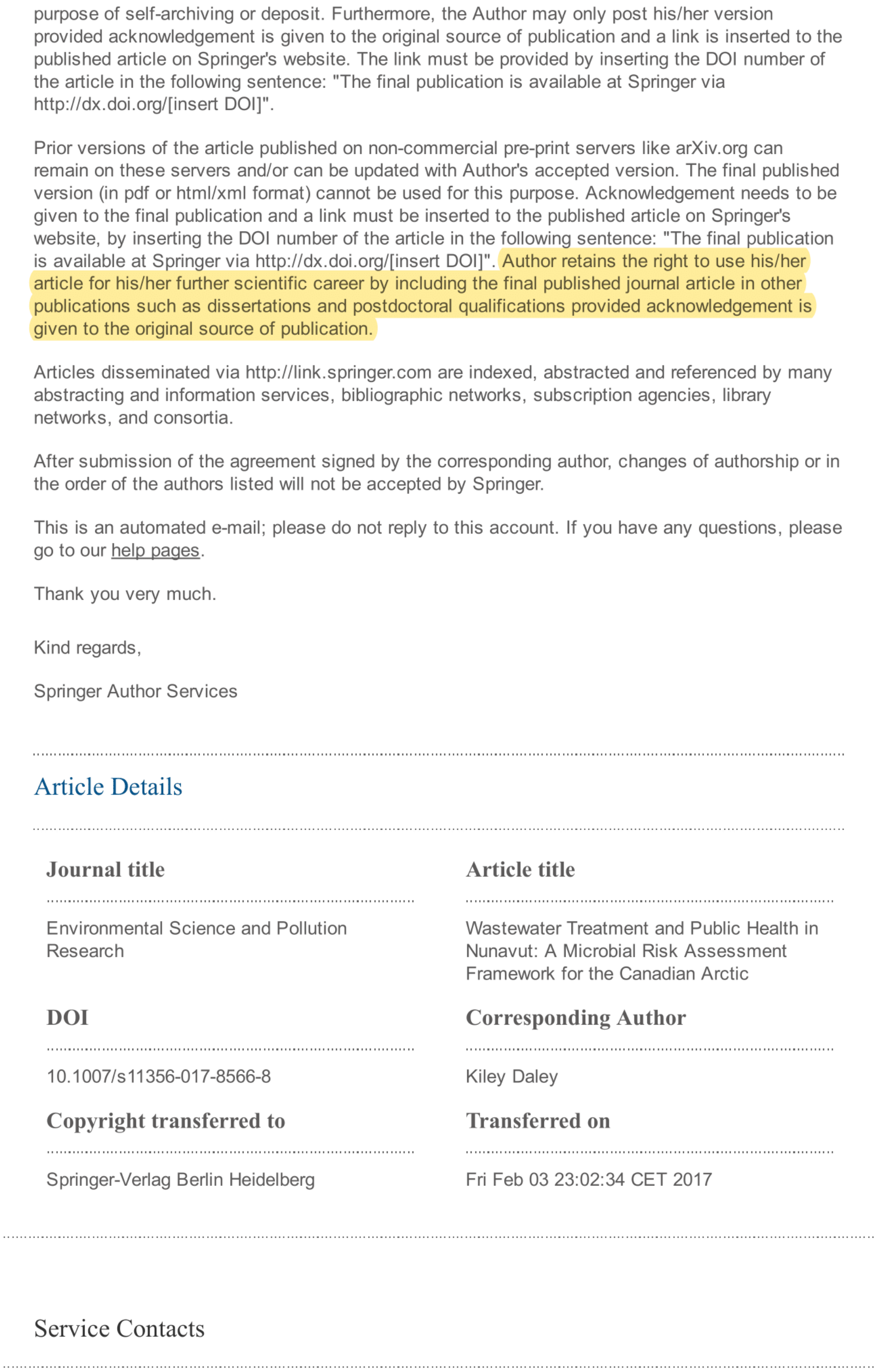

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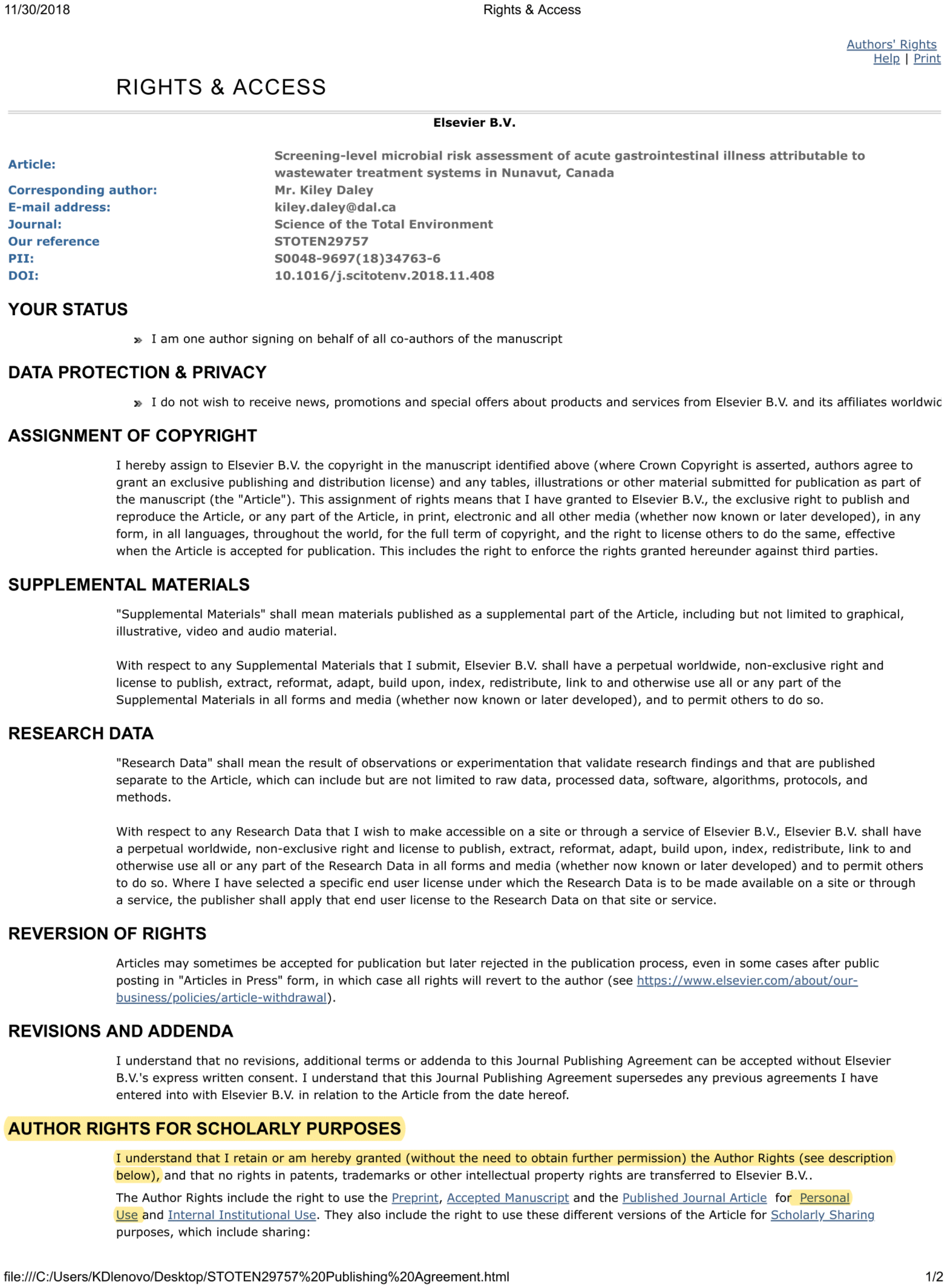

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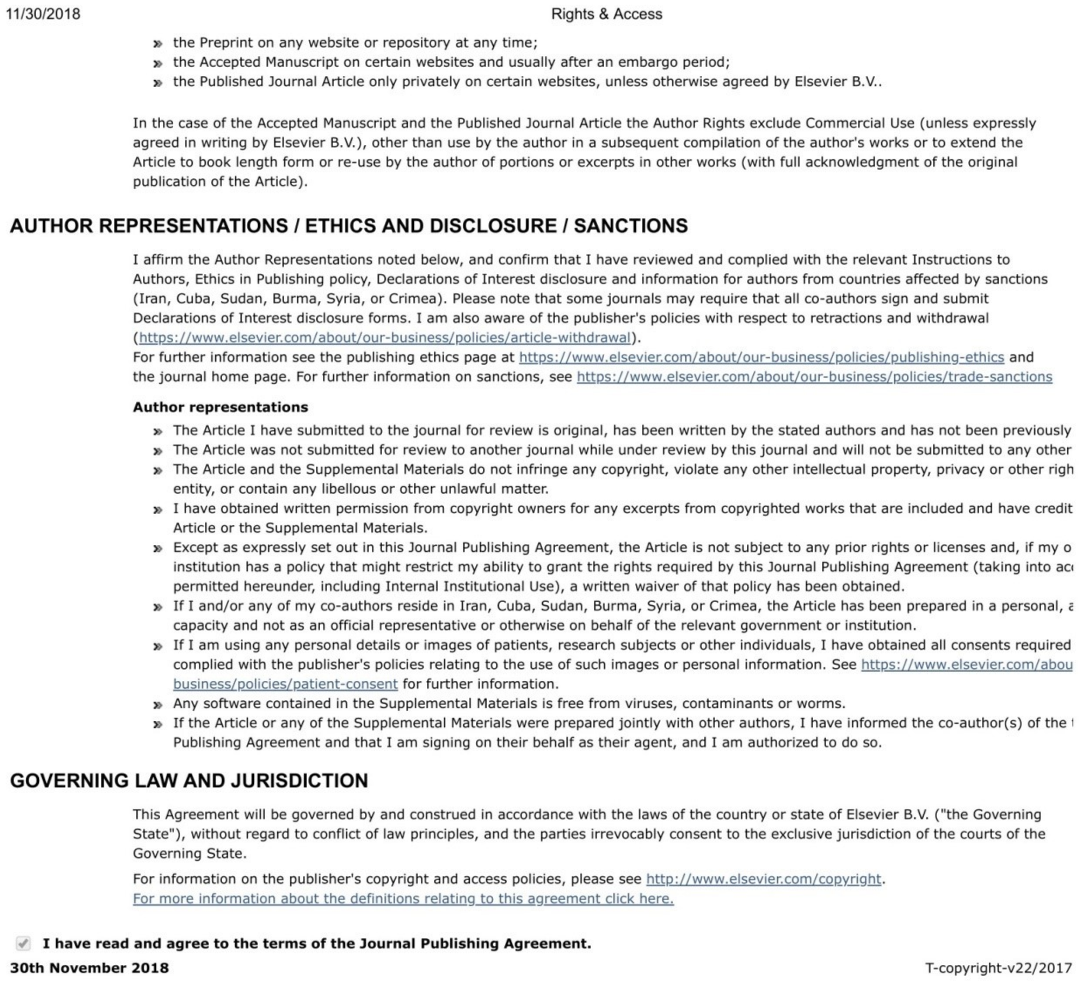

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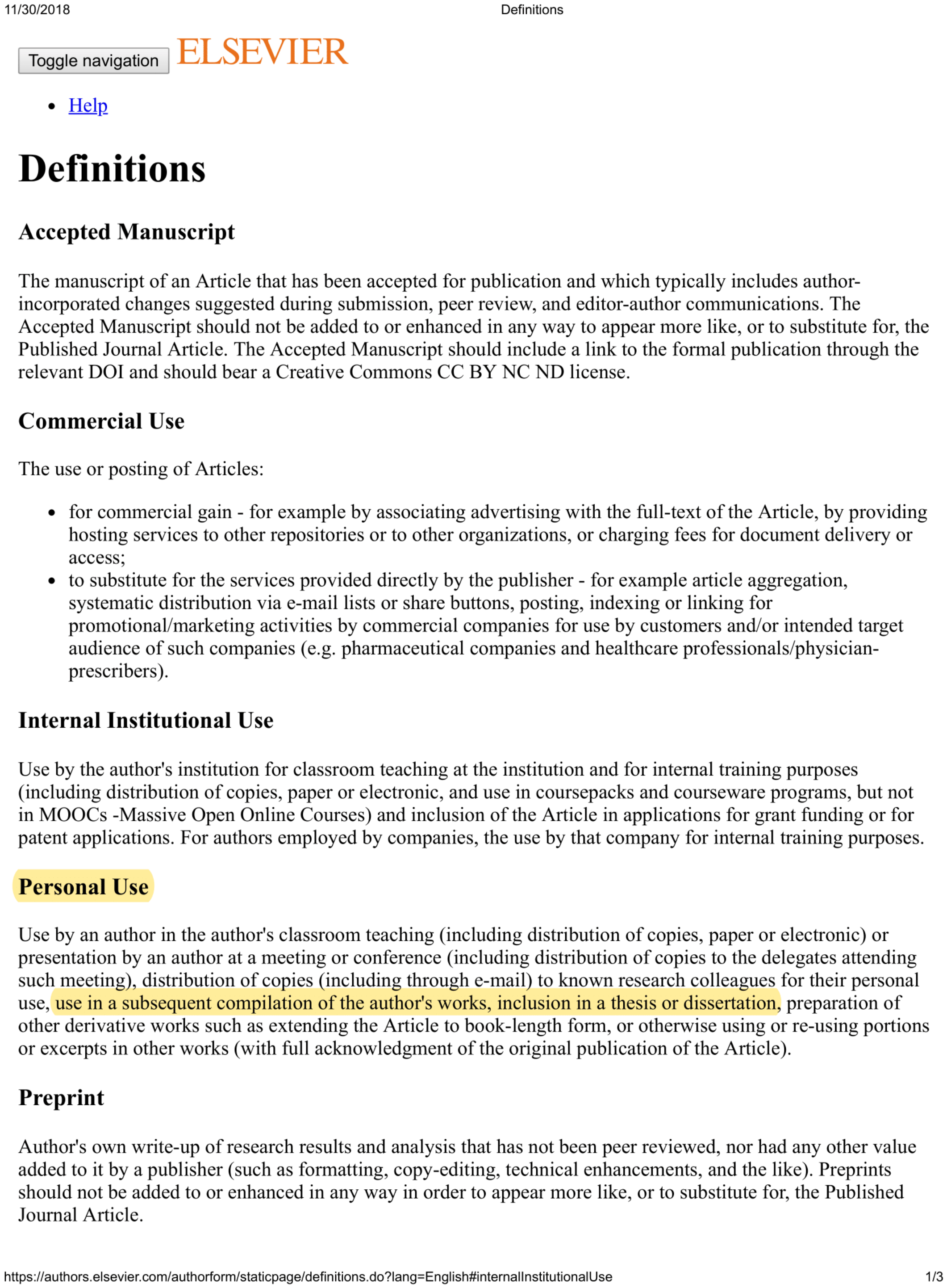

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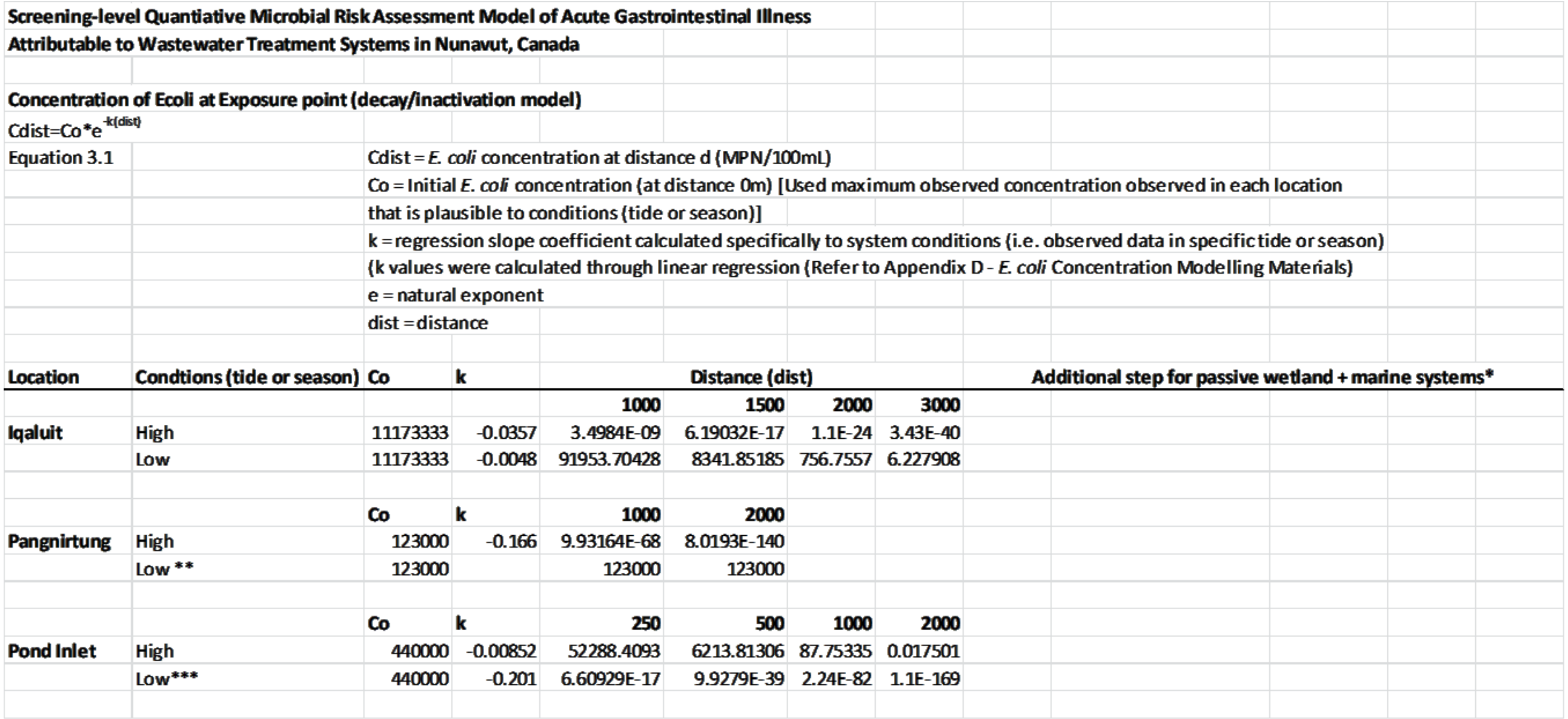
Appendix D

Chapter 3 Screening-level QMRA Model



Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness
Attributable to Wastewater Treatment Systems in Nunavut, Canada

Concentration of Ecoli at Exposure point (decay/inactivation model)

$Cdist=Co*e^{-k(dist)}$

Equation 3.1

Cdist = *E. coli* concentration at distance d (MPN/100mL)
Co = Initial *E. coli* concentration (at distance 0m) [Used maximum observed concentration observed in each location that is plausible to conditions (tide or season)]
k = regression slope coefficient calculated specifically to system conditions (i.e. observed data in specific tide or season)
(k values were calculated through linear regression (Refer to Appendix D - *E. coli* Concentration Modelling Materials)
e = natural exponent
dist = distance

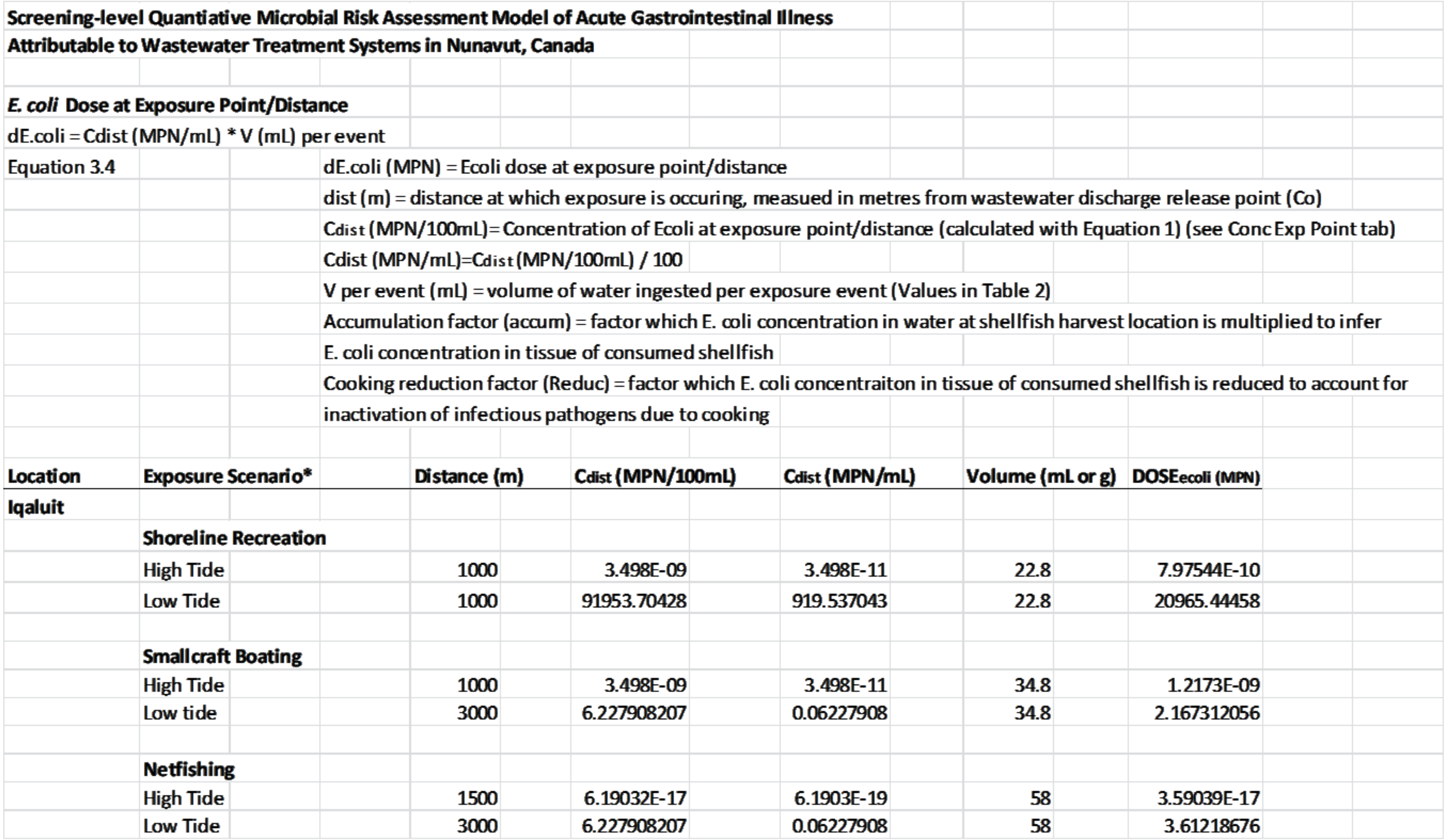
Location	**Condtions (tide or season)**	**Co**	**k**	**Distance (dist)**				**Additional step for passive wetland + marine systems***
				1000	**1500**	**2000**	**3000**	
Iqaluit	High	11173333	-0.0357	3.4984E-09	6.19032E-17	1.1E-24	3.43E-40	
	Low	11173333	-0.0048	91953.70428	8341.85185	756.7557	6.227908	
		Co	**k**	**1000**	**2000**			
Pangnirtung	High	123000	-0.166	9.93164E-68	8.0193E-140			
	Low **	123000		123000	123000			
		Co	**k**	**250**	**500**	**1000**	**2000**	
Pond Inlet	High	440000	-0.00852	52288.4093	6213.81306	87.75335	0.017501	
	Low***	440000	-0.201	6.60929E-17	9.9279E-39	2.24E-82	1.1E-169	

		Co	**k**	**500**	**1000**	**C_{1000}**	**k *(Pond Inlet, High Tide)***	**500**	**1500 (Total distance)**
Sanikiluaq	Spring Freshet	60000	-0.00898	673.2386286	7.55417085	7.554171	-0.00852	0.106682285	0.106682
	Late Summer	23000	-0.0198	1.154017687	5.79025E-05	5.79E-05	-0.00852	8.17716E-07	8.18E-07
		Co	**k**	**250**	**1300**	**C_{1300}**	**k *(Pond Inlet, High Tide)***	**250**	**1550 (Total distance)**
Naujaat	Spring Freshet	1730000	-0.00282	854807.8335	44250.94324	44250.94	-0.00852	5258.662346	5258.662
	Late Summer	1100000	-0.0133	39569.77063	0.03407541	0.034075	-0.00852	0.00404943	0.004049

*Sanikiluaq and Naujaat receiving environments are comprised of a wetland followed by a marine body. No *E.coli* concentrations data in the marine water are available. Therefore, for marine exposure scenarios in these communities (shore recreation, small craft boating, net fishing) there are two steps involved in modelling the concentration. First, the concentration is modelled to the end of the wetland using site-specific data (1000 metres in Sanikiluaq and 1300 metres in Naujaat). Second, a regression coefficient from one of the marine receiving environment communities is applied to predict the remainder of the distance. For both Sanikiluaq and Naujaat, the "Pond Inlet, High Tide" coefficient was used as it was assumed that this is the best available representative/most comparable of the conditions in these communities (minimal tides and a low-energy effluent plume from the outfall that may cling to the shoreline).

**System discharges efflunt onto a tidal flat at low tide (no marine water to mix with, so no sample taken). It is conservatively assumed that no dilution is occuring. Use Co (123000 MPN/100mL) as a conservative concentration at all distances.

***In effort to make the model clearer, 2 tide cycles with titles of "Low" and "High" are being used consistently in the 3 marine discharge communities (Iqaluit, Pang, Pond). These do not refer to absolute lowest and highest tides levels but when the tide was at relatively higher or lower levels. As such, for Pond Inlet, the tide sampled at and originally labeled "Outgoing Tide" has been changed to "Low" in this model. Due to this label change, the Pond Inlet Low tide "k" value used in this model corresponds to the Outgoing Tide "k" value in the original Ecoli sampling data and regression analysis results (Refer to Appendix D - E. coli Concentration Modelling Materials).



Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

***E. coli* Dose at Exposure Point/Distance**

dE.coli = Cdist (MPN/mL) * V (mL) per event

Equation 3.4

dE.coli (MPN) = Ecoli dose at exposure point/distance

dist (m) = distance at which exposure is occuring, measued in metres from wastewater discharge release point (Co)

C_{dist} (MPN/100mL)= Concentration of Ecoli at exposure point/distance (calculated with Equation 1) (see Conc Exp Point tab)

Cdist (MPN/mL)=C_{dist} (MPN/100mL) / 100

V per event (mL) = volume of water ingested per exposure event (Values in Table 2)

Accumulation factor (accum) = factor which E. coli concentration in water at shellfish harvest location is multiplied to infer E. coli concentration in tissue of consumed shellfish

Cooking reduction factor (Reduc) = factor which E. coli concentraiton in tissue of consumed shellfish is reduced to account for inactivation of infectious pathogens due to cooking

Location	**Exposure Scenario***	**Distance (m)**	**C_{dist} (MPN/100mL)**	**C_{dist} (MPN/mL)**	**Volume (mL or g)**	**$DOSE_{ecoli}$ (MPN)**
Iqaluit						
	Shoreline Recreation					
	High Tide	1000	3.498E-09	3.498E-11	22.8	7.97544E-10
	Low Tide	1000	91953.70428	919.537043	22.8	20965.44458
	Smallcraft Boating					
	High Tide	1000	3.498E-09	3.498E-11	34.8	1.2173E-09
	Low tide	3000	6.227908207	0.06227908	34.8	2.167312056
	Netfishing					
	High Tide	1500	6.19032E-17	6.1903E-19	58	3.59039E-17
	Low Tide	3000	6.227908207	0.06227908	58	3.61218676

	Shellfish Harvesting								
	High Tide		NA						
	Low Tide		2000	756.7557	7.567557		50	378.37785	
	Shellfish Consumption**								
	High Tide		NA						
	Low Tide		2000	756.7557	7.567557	75.676	75	5675.66775	2837.834
		Accumulation Factor (Accum)				*Accum*			*Reduc*
		10							
		Cooking Reducton Factor (Reduc)							
		0.5							
Pangnirtung									
	Shore Recreation								
	High Tide		1000	9.93164E-68	9.9316E-70		22.8	2.26441E-68	
	Low Tide (Co at distance)		1000	123000	1230		22.8	28044	
	Smallcraft Boating								
	High Tide		1000	9.9316E-68	9.9316E-70		34.8	3.45621E-68	
	Low Tide (Co at distance)		2000	123000	1230		34.8	42804	
	Netfishing								
	High Tide		2000	8.02E-140	8.019E-142		58	4.6512E-140	
	Low Tide (Co at distance)		2000	123000	1230		58	71340	
	Shellfish Harvesting								
	High Tide		NA						
	Low Tide (Co at distance)		1000	123000	1230		50	61500	

	Shellfish Consumption**								
	High Tide		NA						
	Low Tide (Co at distance)		1000	123000	1230	12300	75	922500	461250
		Accumulation Factor (Accum)				*Accum*			*Reduc*
		10							
		Cooking Reducton Factor (Reduc)							
		0.5							
Pond Inlet									
	Shoreline Recreation								
	High Tide		500	6213.81306	62.1381		22.8	1416.749378	
	Low Tide		500	9.93E-39	9.93E-41		22.8	2.26356E-39	
	Smallcraft Boating								
	High Tide		250	52288.4093	522.884093		34.8	18196.36643	
	Low tide		250	6.60929E-17	6.6093E-19		34.8	2.30003E-17	
	Netfishing								
	High Tide		1000	87.75334716	0.87753347		58	50.89694135	
	Low Tide		1000	2.24007E-82	2.2401E-84		58	1.29924E-82	
Sanikiluaq									
	Wetland Travel								
	Spring Freshet		500	673.2386286	6.73238629		50	336.6193143	
	Late Summer		500	1.154017687	0.01154018		50	0.577008844	

	Shore Recreation					
	Spring Freshet	1500	0.106682285	0.00106682	22.8	0.024323561
	Late Summer	1500	8.17716E-07	8.1772E-09	22.8	1.86439E-07
	Smallcraft Boating					
	Spring Freshet	1500	0.106682285	0.00106682	34.8	0.037125435
	Late Summer	1500	8.17716E-07	8.1772E-09	34.8	2.84565E-07
	Net Fishing					
	Spring Freshet	1500	0.106682285	0.00106682	58	0.061875725
	Late Summer	1500	8.17716E-07	8.1772E-09	58	4.74275E-07
Naujaat						
	Wetland Travel					
	Spring Freshet	250	854807.8335	8548.07833	50	427403.9167
	Late Summer	250	39569.77063	395.697706	50	19784.88531
	Shore Recreation					
	Spring Freshet	1550	5258.662346	52.5866235	22.8	1198.975015
	Late Summer	1550	0.00404943	4.0494E-05	22.8	0.00092327
	Smallcraft Boating					
	Spring Freshet	1550	5258.662346	52.5866235	34.8	1830.014496
	Late Summer	1550	0.00404943	4.0494E-05	34.8	0.001409201
	Net Fishing					
	Spring Freshet	1550	5258.662346	52.5866235	58	3050.02416
	Late Summer	1550	0.00404943	4.0494E-05	58	0.002348669

*The shellfish harvesting and shellfish consumption scenarios only apply to Iqaluit and Pangnirtung, and only in low tide conditions

The wetland travel scenario only applies to Naujaat and Sanikiluaq

Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

Pathogen-specific dose at exposure point

dpath=dE.coli * (E.coli:Pathogen ratio)

Equation 3.5

dpath (MPN) = dose of pathogen ingested during exposure event
dE.coli (MPN) = dose of E.coli ingested during exposure event(See Dose E.coli tab)
(Ecoli:Pathogen ratio) = Literature ratios between E. coli and specific pathogens

PathE.coli	Salmonella	Campylobacter	Rotavirus	Giardia	Cryptosporidium
0.08	0.01	0.00001	0.00001	0.00001	0.000001

Location	**Exposure Scenario**	**dE.coli**	**dpathE.coli**	**dSalm**	**dCampy**	**dRotav**	**dGiard**	**dCrypto**
Iqaluit								
	Shoreline Recreation							
	High Tide	7.9754E-10	6.38035E-11	7.97544E-12	7.97544E-15	7.97544E-15	7.97544E-15	7.97544E-16
	Low Tide	20965.4446	1677.235566	209.6544458	0.209654446	0.209654446	0.209654446	0.020965445
	Smallcraft Boating							
	High Tide	1.2173E-09	9.73843E-11	1.2173E-11	1.2173E-14	1.2173E-14	1.2173E-14	1.2173E-15
	Low tide	2.16731206	0.173384964	0.021673121	2.16731E-05	2.16731E-05	2.16731E-05	2.16731E-06
	Netfishing							
	High Tide	3.5904E-17	2.87231E-18	3.59039E-19	3.59039E-22	3.59039E-22	3.59039E-22	3.59039E-23
	Low Tide	3.61218676	0.288974941	0.036121868	3.61219E-05	3.61219E-05	3.61219E-05	3.61219E-06
	Shellfish Harvesting							
	High Tide	NA						
	Low Tide	378.37785	30.270228	3.7837785	0.003783779	0.003783779	0.003783779	0.000378378
	Shellfish Consumption							
	High Tide	NA						
	Low Tide	2837.83388	227.02671	28.37833875	0.028378339	0.028378339	0.028378339	0.002837834

Pangnirtung								
	Shore Recreation							
	High Tide	2.2644E-68	1.81153E-69	2.26441E-70	2.26441E-73	2.26441E-73	2.26441E-73	2.26441E-74
	Low Tide	28044	2243.52	280.44	0.28044	0.28044	0.28044	0.028044
	Smallcraft Boating							
	High Tide	3.4562E-68	2.76497E-69	3.45621E-70	3.45621E-73	3.45621E-73	3.45621E-73	3.45621E-74
	Low Tide	42804	3424.32	428.04	0.42804	0.42804	0.42804	0.042804
	Netfishing							
	High Tide	4.651E-140	3.721E-141	4.6512E-142	4.6512E-145	4.6512E-145	4.6512E-145	4.6512E-146
	Low Tide	71340	5707.2	713.4	0.7134	0.7134	0.7134	0.07134
	Shellfish Harvesting							
	High Tide	NA						
	Low Tide	61500	4920	615	0.615	0.615	0.615	0.0615
	Shellfish Consumption							
	High Tide	NA						
	Low Tide	461250	36900	4612.5	4.6125	4.6125	4.6125	0.46125
Pond Inlet								
	Shoreline Recreation							
	High Tide	1416.74938	113.3399502	14.16749378	0.014167494	0.014167494	0.014167494	0.001416749
	Low Tide	2.2636E-39	1.81085E-40	2.26356E-41	2.26356E-44	2.26356E-44	2.26356E-44	2.26356E-45
	Smallcraft Boating							
	High Tide	18196.3664	1455.709315	181.9636643	0.181963664	0.181963664	0.181963664	0.018196366
	Low tide	2.3E-17	1.84003E-18	2.30003E-19	2.30003E-22	2.30003E-22	2.30003E-22	2.30003E-23
	Netfishing							
	High Tide	50.8969414	4.071755308	0.508969414	0.000508969	0.000508969	0.000508969	5.08969E-05
	Low Tide	1.2992E-82	1.03939E-83	1.29924E-84	1.29924E-87	1.29924E-87	1.29924E-87	1.29924E-88

Sanikiluaq								
	Wetland Travel							
	Spring Freshet	336.619314	26.92954514	3.366193143	0.003366193	0.003366193	0.003366193	0.000336619
	Late Summer	0.57700884	0.046160707	0.005770088	5.77009E-06	5.77009E-06	5.77009E-06	5.77009E-07
	Shore Recreation							
	Spring Freshet	0.02432356	0.001945885	0.000243236	2.43236E-07	2.43236E-07	2.43236E-07	2.43236E-08
	Late Summer	1.8644E-07	1.49151E-08	1.86439E-09	1.86439E-12	1.86439E-12	1.86439E-12	1.86439E-13
	Smallcraft Boating							
	Spring Freshet	0.03712544	0.002970035	0.000371254	3.71254E-07	3.71254E-07	3.71254E-07	3.71254E-08
	Late Summer	2.8457E-07	2.27652E-08	2.84565E-09	2.84565E-12	2.84565E-12	2.84565E-12	2.84565E-13
	Net Fishing							
	Spring Freshet	0.06187573	0.004950058	0.000618757	6.18757E-07	6.18757E-07	6.18757E-07	6.18757E-08
	Late Summer	4.7428E-07	3.7942E-08	4.74275E-09	4.74275E-12	4.74275E-12	4.74275E-12	4.74275E-13
Naujaat								
	Wetland Travel							
	Spring Freshet	427403.917	34192.31334	4274.039167	4.274039167	4.274039167	4.274039167	0.427403917
	Late Summer	19784.8853	1582.790825	197.8488531	0.197848853	0.197848853	0.197848853	0.019784885
	Shore Recreation							
	Spring Freshet	1198.97501	95.91800118	11.98975015	0.01198975	0.01198975	0.01198975	0.001198975
	Late Summer	0.00092327	7.38616E-05	9.2327E-06	9.2327E-09	9.2327E-09	9.2327E-09	9.2327E-10
	Smallcraft Boating							
	Spring Freshet	1830.0145	146.4011597	18.30014496	0.018300145	0.018300145	0.018300145	0.001830014
	Late Summer	0.0014092	0.000112736	1.4092E-05	1.4092E-08	1.4092E-08	1.4092E-08	1.4092E-09
	Net Fishing							
	Spring Freshet	3050.02416	244.0019328	30.5002416	0.030500242	0.030500242	0.030500242	0.003050024
	Late Summer	0.00234867	0.000187894	2.34867E-05	2.34867E-08	2.34867E-08	2.34867E-08	2.34867E-09

Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

Dose-Response Models

Single parameter exponential function (Equation 3.2, applicable to *Giardia* and *Cryptosporidium*)

$P(d)=1-e^{-kd}$

Two-parameter beta-Poisson function (Equation 3.3, applicable to *E.coli*, *Salmonella*, *Campylobacter*, Rotavirus)

$P(d)=1-[1+(d/N_{50})*(2^{1/\alpha}-1)]^{-\alpha}$

P(d) = Pinf(dpath) = probablily of infection for dose, d

e = natural exponent

r, N_{50}, α = literature dose-response model parameters

Pathogen	**Model**	**α**	**N_{50}**	**r**
Pathogenic *E.coli*	**beta-Poisson**	0.16	2110000	
Salmonella	**beta-Poisson**	0.389	16800	
Complyobacter	**beta-Poisson**	0.14	890.38	
Rotavirus	**beta-Poisson**	0.253	6.17	
Giardia	**Exponential**			0.02
Cryptosporidium	**Exponential**			0.057

Although absolute "0" risk is not possible, formula returns a "0" result when probability is extremely low (≤ 1.00E-16)

Location	**Exposure Scenario**	**dpath*e.coli***	**Pinf(dpath*e.coli*)**	**d*solm***	**Pinf(d*solm*)**	**d*compy***	**Pinf(d*compy*)**	**drotav**	**Pinf(drotav)**	**d*giord***	**Pinf(d*giord*)**	**d*crypto***	**Pinf(d*crypto*)**
Iqaluit													
	Shoreline Recreation												
	High Tide	6.3804E-11	0	7.97544E-12	0	7.9754E-15	0	7.97544E-15	4.66294E-15	7.97544E-15	0	7.97544E-16	0
	Low Tide	1677.23557	0.009235	209.6544458	0.02300663	0.20965445	0.00454068	0.209654446	0.09629165	0.209654446	0.004184	0.020965445	0.00119432
	Smallcraft Boating												
	High Tide	9.7384E-11	0	1.2173E-11	0	1.2173E-14	0	1.2173E-14	7.32747E-15	1.2173E-14	0	1.2173E-15	0
	Low tide	0.17338496	9.88E-07	0.021673121	2.4795E-06	2.1673E-05	4.7819E-07	2.16731E-05	1.28703E-05	2.16731E-05	4.33E-07	2.16731E-06	1.2354E-07
	Netfishing												
	High Tide	2.8723E-18	0	3.59039E-19	0	3.5904E-22	0	3.59039E-22	0	3.59039E-22	0	3.59039E-23	0
	Low Tide	0.28897494	1.65E-06	0.036121868	4.1325E-06	3.6122E-05	7.9699E-07	3.61219E-05	2.145E-05	3.61219E-05	7.22E-07	3.61219E-06	2.0589E-07
	Shellfish Harvesting												
	High Tide	NA		NA		NA		NA		NA		NA	
	Low Tide	30.270228	0.000172	3.7837785	0.00043255	0.00378378	8.3457E-05	0.003783779	0.002234592	0.003783779	7.57E-05	0.000378378	2.1567E-05
	Shellfish Consumption												
	High Tide	NA		NA		NA		NA		NA		NA	
	Low Tide	227.02671	0.001287	28.37833875	0.00322797	0.02837834	0.00062455	0.028378339	0.016182681	0.028378339	0.000567	0.002837834	0.00016174

Pangnirtung													
	Shore Recreation												
	High Tide	1.8115E-69	0	2.26441E-70	0	2.2644E-73	0	2.26441E-73	0	2.26441E-73	0	2.26441E-74	0
	Low Tide	2243.52	0.012218	280.44	0.03035919	0.28044	0.00603648	0.28044	0.120111353	0.28044	0.005593	0.028044	0.00159723
	Smallcraft Boating												
	High Tide	2.765E-69	0	3.45621E-70	0	3.4562E-73	0	3.45621E-73	0	3.45621E-73	0	3.45621E-74	0
	Low Tide	3424.32	0.018235	428.04	0.04507709	0.42804	0.0090977	0.42804	0.161350302	0.42804	0.008524	0.042804	0.00243685
	Netfishing												
	High Tide	3.721E-141	0	4.6512E-142	0	4.651E-145	0	4.6512E-145	0	4.6512E-145	0	4.6512E-146	0
	Low Tide	5707.2	0.029158	713.4	0.07141329	0.7134	0.01480604	0.7134	0.220337788	0.7134	0.014167	0.07134	0.00405812
	Shellfish Harvesting												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	4920	0.025491	615	0.06262623	0.615	0.01286784	0.615	0.202317151	0.615	0.012225	0.0615	0.00349936
	Shellfish Consumption												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	36900	0.125588	4612.5	0.28355319	4.6125	0.07363611	4.6125	0.464738963	4.6125	0.088123	0.46125	0.02594864
Pond Inlet													
	Shoreline Recreation												
	High Tide	113.33995	0.000644	14.16749378	0.00161618	0.01416749	0.00031219	0.014167494	0.008242401	0.014167494	0.000283	0.001416749	8.0751E-05
	Low Tide	1.8108E-40	0	2.26356E-41	0	2.2636E-44	0	2.26356E-44	0	2.26356E-44	0	2.26356E-45	0
	Smallcraft Boating												
	High Tide	1455.70931	0.008051	181.9636643	0.02007565	0.18196366	0.00395052	0.181963664	0.086051024	0.181963664	0.003633	0.018196366	0.00103666
	Low tide	1.84E-18	0	2.30003E-19	0	2.3E-22	0	2.30003E-22	0	2.30003E-22	0	2.30003E-23	0
	Netfishing												
	High Tide	4.07175531	2.32E-05	0.508969414	5.8223E-05	0.00050897	1.1229E-05	0.000508969	0.000302028	0.000508969	1.02E-05	5.08969E-05	2.9011E-06
	Low Tide	1.0394E-83	0	1.29924E-84	0	1.2992E-87	0	1.29924E-87	0	1.29924E-87	0	1.29924E-88	0

Sanikiluaq													
	Wetland Travel												
	Spring Freshet	26.9295451	0.000153	3.366193143	0.00038485	0.00336619	7.4249E-05	0.003366193	0.00198919	0.003366193	6.73E-05	0.000336619	1.9187E-05
	Late Summer	0.04616071	2.63E-07	0.005770088	6.6014E-07	5.7701E-06	1.2731E-07	5.77009E-06	3.42656E-06	5.77009E-06	1.15E-07	5.77009E-07	3.289E-08
	Shore Recreation												
	Spring Freshet	0.00194588	1.11E-08	0.000243236	2.7828E-08	2.4324E-07	5.3667E-09	2.43236E-07	1.44446E-07	2.43236E-07	4.86E-09	2.43236E-08	1.3864E-09
	Late Summer	1.4915E-08	8.5E-14	1.86439E-09	2.1316E-13	1.8644E-12	4.1078E-14	1.86439E-12	1.10711E-12	1.86439E-12	3.73E-14	1.86439E-13	1.0658E-14
	Smallcraft Boating												
	Spring Freshet	0.00297003	1.69E-08	0.000371254	4.2474E-08	3.7125E-07	8.1913E-09	3.71254E-07	2.20471E-07	3.71254E-07	7.43E-09	3.71254E-08	2.1161E-09
	Late Summer	2.2765E-08	1.3E-13	2.84565E-09	3.2552E-13	2.8457E-12	6.2839E-14	2.84565E-12	1.68998E-12	2.84565E-12	5.7E-14	2.84565E-13	1.6209E-14
	Net Fishing												
	Spring Freshet	0.00495006	2.82E-08	0.000618757	7.079E-08	6.1876E-07	1.3652E-08	6.18757E-07	3.67451E-07	6.18757E-07	1.24E-08	6.18757E-08	3.5269E-09
	Late Summer	3.7942E-08	2.16E-13	4.74275E-09	5.4268E-13	4.7428E-12	1.0458E-13	4.74275E-12	2.81641E-12	4.74275E-12	9.48E-14	4.74275E-13	2.6978E-14
Naujaat													
	Wetland Travel												
	Spring Freshet	34192.3133	0.119614	4274.039167	0.27142337	4.27403917	0.06955811	4.274039167	0.455238849	4.274039167	0.081929	0.427403917	0.02406766
	Late Summer	1582.79083	0.008732	197.8488531	0.02176088	0.19784885	0.00428942	0.197848853	0.091995403	0.197848853	0.003949	0.019784885	0.0011271
	Shore Recreation												
	Spring Freshet	95.9180012	0.000545	11.98975015	0.00136836	0.01198975	0.00026426	0.01198975	0.006997217	0.01198975	0.00024	0.001198975	6.8339E-05
	Late Summer	7.3862E-05	4.21E-10	9.2327E-06	1.0563E-09	9.2327E-09	2.0371E-10	9.2327E-09	5.48288E-09	9.2327E-09	1.85E-10	9.2327E-10	5.2626E-11
	Smallcraft Boating												
	Spring Freshet	146.40116	0.000831	18.30014496	0.00208586	0.01830014	0.00040311	0.018300145	0.01058427	0.018300145	0.000366	0.001830014	0.00010431
	Late Summer	0.00011274	6.42E-10	1.4092E-05	1.6122E-09	1.4092E-08	3.1093E-10	1.4092E-08	8.3686E-09	1.4092E-08	2.82E-10	1.4092E-09	8.0325E-11
	Net Fishing												
	Spring Freshet	244.001933	0.001383	30.5002416	0.00346784	0.03050024	0.00067112	0.030500242	0.01734158	0.030500242	0.00061	0.003050024	0.00017384
	Late Summer	0.00018789	1.07E-09	2.34867E-05	2.687E-09	2.3487E-08	5.1821E-10	2.34867E-08	1.39477E-08	2.34867E-08	4.7E-10	2.34867E-09	1.3387E-10

Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

Individual Probability of Illness per pathogen per exposure event

Pill, path = Pinf,path*Pill I inf

Equation 3.6

Pill, path = Probability of illness per pathogen per exposure event
Pinf,path = probability of infection for dose, d, of specific pathogen (See Dose-Response Models tab)
Pill I inf = Morbidity ratios (probability of illness conditional upon infection)

Pathogen	**Probabilty (Pill | inf)**
Pathogenic Ecoli	0.35
Salmonella	0.8
Campylobacter	0.3
Rotavirus	0.5
Giardia	0.9
Cryptosporidium	0.79

Location	**Exposure Scenario**	**Pinf(pathe.*coli*)**	**Pill, *e.coli***	**Pinf(*salm*)**	**Pill,*salm***	**Pinf(*campy*)**	**Pill,*campy***	**Pinf(rotav)**	**Pill,rotav**	**Pinf(*giard*)**	**Pill,*giard***	**Pinf(*crypto*)**	**Pill,*crypto***
Iqaluit													
	Shoreline Recreation												
	High Tide	0	0	0	0	0	0	4.66294E-15	2.33E-15	0	0	0	0
	Low Tide	0.009235462	0.0032324	0.023006633	0.018405	0.004540682	0.0013622	0.09629165	0.048146	0.00418431	0.0037659	0.001194317	0.0009435
	Smallcraft Boating												
	High Tide	0	0	0	0	0	0	7.32747E-15	3.66E-15	0	0	0	0
	Low tide	9.87509E-07	3.456E-07	2.47954E-06	1.98E-06	4.78193E-07	1.435E-07	1.28703E-05	6.44E-06	4.33462E-07	3.901E-07	1.23537E-07	9.759E-08
	Netfishing												
	High Tide	0	0	0	0	0	0	0	0	0	0	0	0
	Low Tide	1.64584E-06	5.76E-07	4.13255E-06	3.31E-06	7.96988E-07	2.391E-07	2.145E-05	1.07E-05	7.22437E-07	6.502E-07	2.05895E-07	1.627E-07
	Shellfish Harvesting												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	0.000172296	6.03E-05	0.000432555	0.000346	8.34567E-05	2.504E-05	0.002234592	0.001117	7.56727E-05	6.811E-05	2.15673E-05	1.704E-05
	Shellfish Consumption												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	0.001287002	0.0004505	0.003227973	0.002582	0.000624547	0.0001874	0.016182681	0.008091	0.000567406	0.0005107	0.000161743	0.0001278

Pangnirtung													
	Shore Recreation												
	High Tide	0	0	0	0	0	0	0	0	0	0	0	0
	Low Tide	0.012218087	0.0042763	0.030359193	0.024287	0.006036478	0.0018109	0.120111353	0.060056	0.0055931	0.0050338	0.001597231	0.0012618
	Smallcraft Boating												
	High Tide	0	0	0	0	0	0	0	0	0	0	0	0
	Low Tide	0.018234751	0.0063822	0.045077092	0.036062	0.009097698	0.0027293	0.161350302	0.080675	0.008524261	0.0076718	0.002436854	0.0019251
	Netfishing												
	High Tide	0	0	0	0	0	0	0	0	0	0	0	0
	Low Tide	0.029158418	0.0102054	0.07141329	0.057131	0.014806038	0.0044418	0.220337788	0.110169	0.014166694	0.01275	0.004058123	0.0032059
	Shellfish Harvesting												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	0.025490936	0.0089218	0.062626231	0.050101	0.01286784	0.0038604	0.202317151	0.101159	0.012224664	0.0110022	0.003499363	0.0027645
	Shellfish Consumption												
	High Tide	**NA**				**NA**		**NA**		**NA**		**NA**	
	Low Tide	0.125587782	0.0439557	0.283553192	0.226843	0.073636114	0.0220908	0.464738963	0.232369	0.088122848	0.0793106	0.025948644	0.0204994
Pond Inlet													
	Shoreline Recreation												
	High Tide	0.00064402	0.0002254	0.001616179	0.001293	0.000312193	9.366E-05	0.008242401	0.004121	0.00028331	0.000255	8.07515E-05	6.379E-05
	Low Tide	0	0	0	0	0	0	0	0	0	0	0	0
	Smallcraft Boating												
	High Tide	0.008050724	0.0028178	0.020075646	0.016061	0.00395052	0.0011852	0.086051024	0.043026	0.003632659	0.0032694	0.001036655	0.000819
	Low tide	0	0	0	0	0	0	0	0	0	0	0	0
	Netfishing												
	High Tide	2.31887E-05	8.116E-06	5.82234E-05	4.66E-05	1.12294E-05	3.369E-06	0.000302028	0.000151	1.01793E-05	9.161E-06	2.90112E-06	2.292E-06
	Low Tide	0	0	0	0	0	0	0	0	0	0	0	0

Sanikiluaq													
	Wetland Travel												
	Spring Freshet	0.000153292	5.365E-05	0.00038485	0.000308	7.4249E-05	2.227E-05	0.00198919	0.000995	6.73216E-05	6.059E-05	1.91871E-05	1.516E-05
	Late Summer	2.62908E-07	9.202E-08	6.60135E-07	5.28E-07	1.27311E-07	3.819E-08	3.42656E-06	1.71E-06	1.15402E-07	1.039E-07	3.28895E-08	2.598E-08
	Shore Recreation												
	Spring Freshet	1.10828E-08	3.879E-09	2.78277E-08	2.23E-08	5.36673E-09	1.61E-09	1.44446E-07	7.22E-08	4.86471E-09	4.378E-09	1.38644E-09	1.095E-09
	Late Summer	8.50431E-14	2.977E-14	2.13163E-13	1.71E-13	4.10783E-14	1.232E-14	1.10711E-12	5.54E-13	3.73035E-14	3.357E-14	1.06581E-14	8.42E-15
	Smallcraft Boating												
	Spring Freshet	1.69158E-08	5.921E-09	4.24739E-08	3.4E-08	8.19133E-09	2.457E-09	2.20471E-07	1.1E-07	7.42509E-09	6.683E-09	2.11615E-09	1.672E-09
	Late Summer	1.29674E-13	4.539E-14	3.25517E-13	2.6E-13	6.28386E-14	1.885E-14	1.68998E-12	8.45E-13	5.69544E-14	5.126E-14	1.62093E-14	1.281E-14
	Net Fishing												
	Spring Freshet	2.8193E-08	9.868E-09	7.07899E-08	5.66E-08	1.36522E-08	4.096E-09	3.67451E-07	1.84E-07	1.23751E-08	1.114E-08	3.52692E-09	2.786E-09
	Late Summer	2.16049E-13	7.562E-14	5.42677E-13	4.34E-13	1.04583E-13	3.137E-14	2.81641E-12	1.41E-12	9.4813E-14	8.533E-14	2.69784E-14	2.131E-14
Naujaat													
	Wetland Travel												
	Spring Freshet	0.119613867	0.0418649	0.271423371	0.217139	0.069558106	0.0208674	0.455238849	0.227619	0.081929215	0.0737363	0.024067664	0.0190135
	Late Summer	0.00873162	0.0030561	0.021760878	0.017409	0.004289423	0.0012868	0.091995403	0.045998	0.003949159	0.0035542	0.001127103	0.0008904
	Shore Recreation												
	Spring Freshet	0.000545221	0.0001908	0.001368356	0.001095	0.000264256	7.928E-05	0.006997217	0.003499	0.000239766	0.0002158	6.83392E-05	5.399E-05
	Late Summer	4.20678E-10	1.472E-10	1.05628E-09	8.45E-10	2.0371E-10	6.111E-11	5.48288E-09	2.74E-09	1.84654E-10	1.662E-10	5.26263E-11	4.157E-11
	Smallcraft Boating												
	Spring Freshet	0.000831315	0.000291	0.002085864	0.001669	0.000403111	0.0001209	0.01058427	0.005292	0.000365936	0.0003293	0.000104305	8.24E-05
	Late Summer	6.42087E-10	2.247E-10	1.61222E-09	1.29E-09	3.10925E-10	9.328E-11	8.3686E-09	4.18E-09	2.8184E-10	2.537E-10	8.03245E-11	6.346E-11
	Net Fishing												
	Spring Freshet	0.001382753	0.000484	0.003467843	0.002774	0.000671118	0.0002013	0.01734158	0.008671	0.000609819	0.0005488	0.000173836	0.0001373
	Late Summer	1.07015E-09	3.746E-10	2.68703E-09	2.15E-09	5.18209E-10	1.555E-10	1.39477E-08	6.97E-09	4.69734E-10	4.228E-10	1.33874E-10	1.058E-10

Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness
Attributable to Wastewater Treatment Systems in Nunavut, Canada

Total Expected Annual Cases (Incidence)

Pill,path,total = ∑Probill,path
Equation 3.7
Pill,path,total = Total probability of illness caused by any pathogen per person per single exposure event
Pill, pathogen = Probability of illness per pathogen per given exposure event

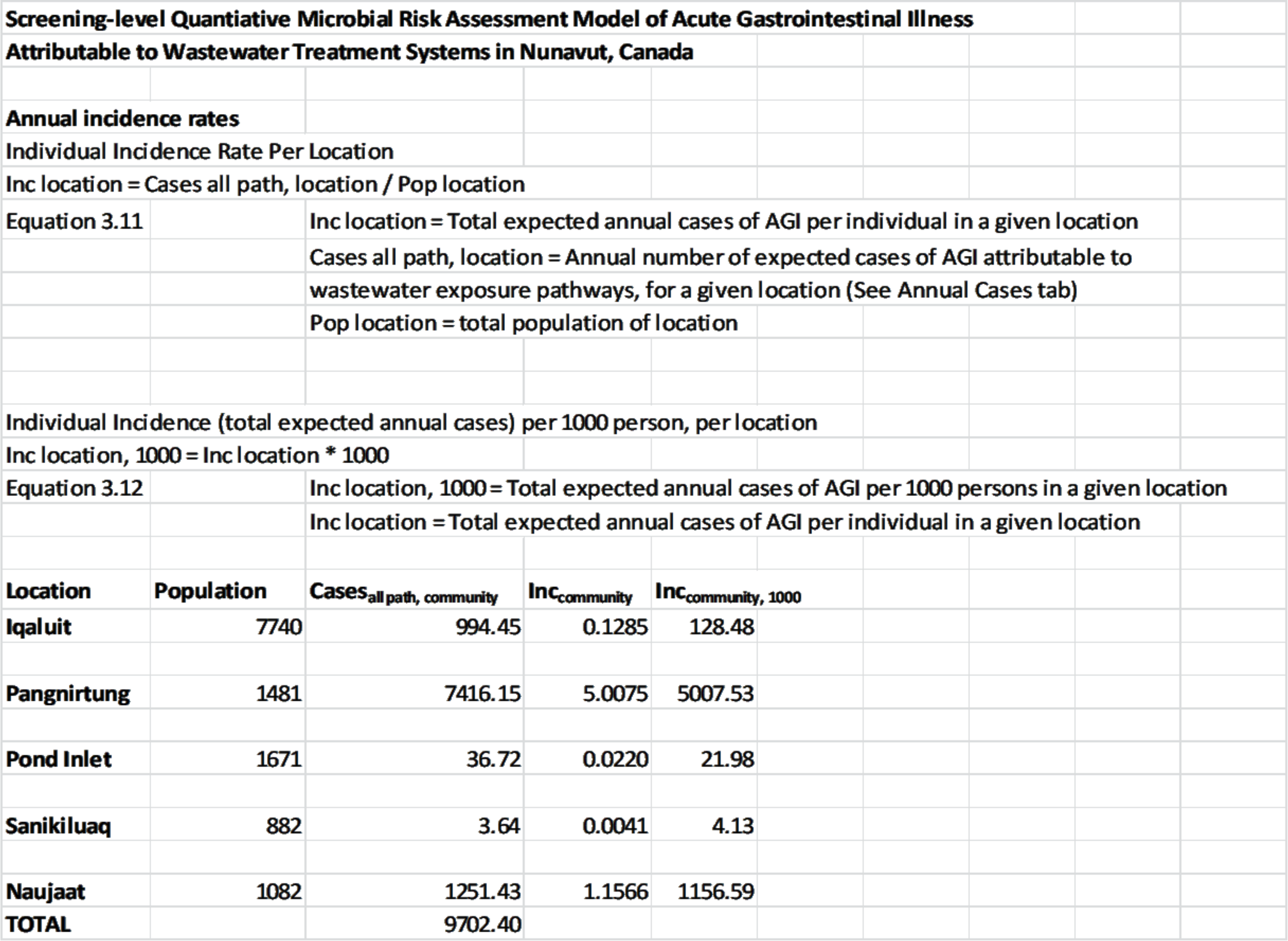
Casespathi…j = ∑(Freq)(ExpGroup) Pill I path
Equation 3.8
Casespathi…j = Annual number of expected cases of AGI per pathogen per exposure scenario
(encompassing frequency of events per year and population exposed per event)
Freq = Frequency of exposure event per year
ExpGroup = Exposed population per single event
Pill I path = Individual proability of illness per pathogen per exposure event (Calculated with Equation 6)(See Cond Prob Illness tab)

Casesall path = ∑Casespath i…j
Equation 3.9
Casesall path = Annual number of expected cases of AGI per exposure scenario (i.e. summing all cases of illness atrributable to each pathogen for a given exposure scenario)
Casespath i…j = Annual number of expected cases of AGI per pathogen per exposure scenario

Casesall path, location = ∑ Casesall path
Equation 3.10
Case sall path, location = Annual number of expected cases of AGI attributable to wastewater exposure pathways, for a given location
Cases all path = Annual number of expected cases of AGI per exposure scenario

Location	Exposure Scenario	Frequency	Population	Pill, pathe.*coli*	Cases pathe.coli	Pill, *salm*	Cases *salm*	Pill ,*campy*	Cases *campy*	Pill, rotav	Cases rotav	Pill ,*giard*	Cases *giard*	Pill ,*crypto*	Cases *crypto*	Cases all path, per exp	Cases all path, location	P ind illness any path single exp
Iqaluit																		
	Shoreline Recreation																	
	High Tide	105	100	0	0	0	0	0	0	2.33147E-15	2.448E-11	0	0	0	0	2.44804E-11		2.33147E-15
	Low Tide	105	100	0.003232412	33.94032459	0.018405306	193.2557154	0.001362205	14.3031498	0.048145825	505.531163	0.003765879	39.54173132	0.00094351	9.906856001	796.4789399		0.075855137
	Smallcraft Boating																	
	High Tide	105	100	0	0	0	0	0	0	3.66374E-15	3.8469E-11	0	0	0	0	3.84692E-11		3.66374E-15
	Low tide	105	100	3.45628E-07	0.003629094	1.98363E-06	0.020828105	1.43458E-07	0.00150631	6.43513E-06	0.06756887	3.90116E-07	0.004096219	9.75941E-08	0.001024738	0.09865333		9.39556E-06
	Netfishing																	
	High Tide	85	100	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Low Tide	85	100	5.76045E-07	0.004896385	3.30604E-06	0.028101328	2.39096E-07	0.00203232	1.0725E-05	0.09116241	6.50193E-07	0.005526644	1.62657E-07	0.001382582	0.133101668		1.5659E-05
	Shellfish Harvesting																	
	High Tide	NA	NA															0
	Low Tide	40	100	6.03036E-05	0.241214505	0.000346044	1.384175448	2.5037E-05	0.100148	0.001117296	4.46918431	6.81054E-05	0.272421744	1.70382E-05	0.068152683	6.535296692		0.001633824
	Shellfish Consumption																	
	High Tide	NA	NA															0
	Low Tide	40	400	0.000450451	7.207213189	0.002582379	41.31805841	0.000187364	2.99782379	0.00809134	129.461448	0.000510665	8.170642648	0.000127777	2.044437195	191.1996232		0.011949976
	TOTALS			0.003744088	41.39727776	0.021339018	236.0068786	0.001574988	17.4046602	0.057371622	639.620526	0.00434569	47.99441857	0.001088586	12.0218532	994.4456148	994.45	
	Percent of total cases				0.041628498		0.237325074		0.01750187		0.64319307		0.048262487		0.012089	1		
Pangnirtung																		
	Shore Recreation																	
	High Tide	105	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Low Tide	105	50	0.004276331	22.45073528	0.024287354	127.5086106	0.001810944	9.50745351	0.060055677	315.292303	0.00503379	26.42739773	0.001261813	6.624515849	507.8110157		0.096725908
	Smallcraft Boating																	
	High Tide	105	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Low Tide	105	50	0.006382163	33.50635505	0.036061674	189.3237868	0.002729309	14.3288741	0.080675151	423.544543	0.007671835	40.27713178	0.001925115	10.10685213	711.0875432		0.135445246
	Netfishing																	
	High Tide	85	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Low Tide	85	50	0.010205446	43.37314614	0.057130632	242.8051856	0.004441812	18.8776989	0.110168894	468.2178	0.012750025	54.18760635	0.003205918	13.62514956	841.0865868		0.197902726
	Shellfish Harvesting																	
	High Tide	NA	NA															0
	Low Tide	40	50	0.008921828	17.84365519	0.050100984	100.2019689	0.003860352	7.72070408	0.101158575	202.317151	0.011002198	22.00439555	0.002764497	5.528993395	355.6168677		0.177808434
	Shellfish Consumption																	
	High Tide	NA	NA															0
	Low Tide	40	200	0.043955724	351.6457905	0.226842554	1814.74043	0.022090834	176.726675	0.232369482	1858.95585	0.079310563	634.4845073	0.020499429	163.9954311	5000.548687		0.625068586
	TOTALS			0.073741491	468.8196821	0.394423198	2474.579982	0.034933251	227.161405	0.584427779	3268.32765	0.115768411	777.3810387	0.02965677	199.8809421	7416.1507	7416.15	
	Percent of total cases				0.06321604		0.333674447		0.03063063		0.44070405		0.104822713		0.026952114	1		
Pond Inlet																		
	Shoreline Recreation																	
	High Tide	10	50	0.000225407	0.112703537	0.001292943	0.646471747	9.3658E-05	0.04682901	0.0041212	2.06060021	0.000254979	0.127489381	6.37936E-05	0.031896824	3.025990715		0.006051981
	Low Tide	10	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Smallcraft Boating																	
	High Tide	10	50	0.002817753	1.408876743	0.016060517	8.030258259	0.001185156	0.59257801	0.043025512	21.5127559	0.003269393	1.634696621	0.000818958	0.409478799	33.5886443		0.067177289
	Low tide	10	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	Netfishing																	
	High Tide	10	50	8.11604E-06	0.00405802	4.65787E-05	0.023289355	3.36881E-06	0.0016844	0.000151014	0.07550688	9.1614E-06	0.004580701	2.29189E-06	0.001145943	0.110265307		0.000220531
	Low Tide	10	50	0	0	0	0	0	0	0	0	0	0	0	0	0		0
	TOTALS			0.003051277	1.5256383	0.017400039	8.700019361	0.001282183	0.64109142	0.047297726	23.648863	0.003533533	1.766766704	0.000885043	0.442521567	36.72490033	36.72	
	Percent of total cases				0.04154234		0.236897018		0.01745659		0.64394628		0.048108142		0.012049633	1		

Sanikiluaq																		
	Wetland Travel																	
	Spring Freshet	50	50	5.36521E-05	0.134130236	0.00030788	0.769700011	2.22747E-05	0.05568676	0.000994595	2.48648794	6.05894E-05	0.151473592	1.51578E-05	0.037894556	3.635373086		0.001454149
	Late Summer	50	50	9.20176E-08	0.000230044	5.28108E-07	0.00132027	3.81932E-08	9.5483E-05	1.71328E-06	0.0042832	1.03862E-07	0.000259654	2.59827E-08	6.49568E-05	0.00625361		2.50144E-06
	Shore Recreation																	
	Spring Freshet	55	50	3.87897E-09	1.06672E-05	2.22622E-08	6.1221E-05	1.61002E-09	4.4276E-06	7.22232E-08	0.00019861	4.37824E-09	1.20402E-05	1.09529E-09	3.01205E-06	0.000289982		1.05448E-07
	Late Summer	65	50	2.97651E-14	9.67365E-11	1.7053E-13	5.54223E-10	1.23235E-14	4.0051E-11	5.53557E-13	1.7991E-09	3.35731E-14	1.09113E-10	8.41993E-15	2.73648E-11	2.62655E-09		8.08169E-13
	Smallcraft Boating																	
	Spring Freshet	40	50	5.92053E-09	1.18411E-05	3.39791E-08	6.79583E-05	2.4574E-09	4.9148E-06	1.10235E-07	0.00022047	6.68258E-09	1.33652E-05	1.67176E-09	3.34352E-06	0.000321894		1.60947E-07
	Late Summer	65	50	4.53859E-14	1.47504E-10	2.60414E-13	8.46345E-10	1.88516E-14	6.1268E-11	8.44991E-13	2.7462E-09	5.1259E-14	1.66592E-10	1.28053E-14	4.16173E-11	4.00955E-09		1.23371E-12
	Net Fishing																	
	Spring Freshet	35	50	9.86755E-09	1.72682E-05	5.66319E-08	9.91058E-05	4.09567E-09	7.1674E-06	1.83726E-07	0.00032152	1.11376E-08	1.94909E-05	2.78626E-09	4.87596E-06	0.000469428		2.68245E-07
	Late Summer	50	50	7.56173E-14	1.89043E-10	4.34142E-13	1.08535E-09	3.13749E-14	7.8437E-11	1.40821E-12	3.5205E-09	8.53317E-14	2.13329E-10	2.1313E-14	5.32824E-11	5.13996E-09		2.05599E-12
	TOTALS			5.37638E-05	0.134400057	0.000308521	0.771248569	2.23211E-05	0.05579875	0.000996675	2.49151175	6.07155E-05	0.151778143	1.51894E-05	0.037970744	3.642708012	3.64	
	Percent of total cases				0.036895644		0.211723961		0.01531793		0.6839724		0.041666294		0.010423768	1		
Naujaat																		
	Wetland Travel																	
	Spring Freshet	35	50	0.041864853	73.26349344	0.217138696	379.9927188	0.020867432	36.5180055	0.227619425	398.333993	0.073736293	129.0385134	0.019013455	33.27354604	1050.42027		0.600240154
	Late Summer	45	50	0.003056067	6.876150753	0.017408702	39.16957995	0.001286827	2.89536043	0.045997702	103.494829	0.003554243	7.997046054	0.000890411	2.003425236	162.4363913		0.072193952
	Shore Recreation																	
	Spring Freshet	25	50	0.000190827	0.238534044	0.001094685	1.36835624	7.92769E-05	0.09909618	0.003498608	4.37326032	0.00021579	0.269737036	5.3988E-05	0.067485	6.416468826		0.005133175
	Late Summer	40	50	1.47237E-10	2.94475E-07	8.45025E-10	1.69005E-06	6.11129E-11	1.2223E-07	2.74144E-09	5.4829E-06	1.66189E-10	3.32377E-07	4.15748E-11	8.31496E-08	8.00515E-06		4.00258E-09
	Smallcraft Boating																	
	Spring Freshet	25	50	0.00029096	0.363700404	0.001668691	2.085864187	0.000120933	0.15116653	0.005292135	6.61516906	0.000329342	0.411677919	8.24013E-05	0.103001569	9.730579667		0.007784464
	Late Summer	40	50	2.24731E-10	4.49461E-07	1.28978E-09	2.57955E-06	9.32776E-11	1.8656E-07	4.1843E-09	8.3686E-06	2.53656E-10	5.07313E-07	6.34564E-11	1.26913E-07	1.22184E-05		6.1092E-09
	Net Fishing																	
	Spring Freshet	35	50	0.000483963	0.846936064	0.002774275	4.854980686	0.000201335	0.35233682	0.00867079	15.1738827	0.000548837	0.960464637	0.000137331	0.240328638	22.42892958		0.012816531
	Late Summer	50	50	3.74551E-10	9.36377E-07	2.14963E-09	5.37406E-06	1.55463E-10	3.8866E-07	6.97383E-09	1.7435E-05	4.2276E-10	1.0569E-06	1.05761E-10	2.64401E-07	2.5455E-05		1.0182E-08
	TOTALS			0.045886672	81.58881639	0.240085054	427.4715095	0.022555804	40.0159662	0.291078674	527.991165	0.078384506	138.677441	0.020177586	35.68778695	1251.432685	1251.43	
	Percent of total cases				0.065196328		0.3415857		0.03197612		0.42190936		0.110814942		0.028517544	1		
Totals					593.4658146		3147.529638		285.278922		4462.07972		965.9714431		248.0710745		9702.40	
Percent of total cases					0.06116693		0.324407439		0.0294029		0.45989459		0.099560086		0.02556802		1	



Screening-level Quantiative Microbial Risk Assessment Model of Acute Gastrointestinal Illness Attributable to Wastewater Treatment Systems in Nunavut, Canada

Annual incidence rates

Individual Incidence Rate Per Location

Inc location = Cases all path, location / Pop location

Equation 3.11 Inc location = Total expected annual cases of AGI per individual in a given location

Cases all path, location = Annual number of expected cases of AGI attributable to wastewater exposure pathways, for a given location (See Annual Cases tab)

Pop location = total population of location

Individual Incidence (total expected annual cases) per 1000 person, per location

Inc location, 1000 = Inc location * 1000

Equation 3.12 Inc location, 1000 = Total expected annual cases of AGI per 1000 persons in a given location

Inc location = Total expected annual cases of AGI per individual in a given location

Location	**Population**	**Cases**$_{\text{all path, community}}$	**Inc**$_{\text{community}}$	**Inc**$_{\text{community, 1000}}$
Iqaluit	7740	994.45	0.1285	128.48
Pangnirtung	1481	7416.15	5.0075	5007.53
Pond Inlet	1671	36.72	0.0220	21.98
Sanikiluaq	882	3.64	0.0041	4.13
Naujaat	1082	1251.43	1.1566	1156.59
TOTAL		9702.40		

Appendix E

Key Informant and Community Research Materials

Summary of Key Informant Interviews, Community Forums, and Council Presentations

Preamble

Each key informant was assigned to a project category based upon their primary area of expertise, experience, and perspective in relation to the research topic. Many informants, however, provided information relevant to multiple categories. Likewise, some key informants were able to provide information relevant to multiple communities (e.g. Environmental Health Officers are responsible for multiple communities within a region). Key informants were asked to provide their preferred title.

Research updates were delivered to communities and stakeholders via council meetings and community forums. During these sessions, community members also provided feedback and validation of preliminary exposure scenarios.

In several communities, a significant amount of wastewater operations information had already been gathered during earlier components of the Dalhousie University Nunavut Wastewater Research Program. As such, that information was incorporated into this project and duplicate meetings with wastewater operators were not requested.

Legend for Categories
E=Environmental Management, H=Public Health, T=Traditional Land Users, WW=Wastewater Management

Community Summaries

Pond Inlet

Title	Category	Year
Conservation / Wildlife Officer, Government of Nunavut, Environment	E	2014
Nurse in Charge, Government of Nunavut, Health	H	2014
Local Hunter and Fisher	T	2014
Local Hunter and Fisher	T	2014
Local Hunter and Fisher / Member of Hunters & Trappers Association	T	2014
Community Member	T	2014
Community Forums (50-75 people)		2015
Council Meeting (5 members in attendance)		2015

Pangnirtung

Title	Category	Year
Conservation / Wildlife Officer, Government of Nunavut, Environment	E	2014
Manager of Fisheries, Government of Nunavut, Environment	E	2014
Environmental Health Specialist, Government of Nunavut, Health	H	2015
Environmental Health Officer, Government of Nunavut, Health	H	2015
Local Shellfish Harvester	T	2015
Community Health Committee	T	2015
Community-hired Researcher, Hamlet of Pangnirtung	WW	2015

*A community forum was not held in Pangnirtung as the entire trip to the community was cancelled due to weather in 2014. The 2015 trip was also shortened by several days due to weather. Also, during the 2015 trip, the wastewater treatment plant malfunctioned and untreated wastewater was continuously released into receiving waters near the community for several days. As a result, the Government of Nunavut Department of Health issued a public advisory recommending that people refrain from harvesting shellfish in the area. Given the circumstances, a community forum was deemed inappropriate.

*Additionally, a presentation was not made directly to the Pangnirtung Hamlet Council. The preferred protocol in this community is to have research presented to the Hamlet Senior Administrative Officer, who in turn relays the information to Council. Pangnirtung also maintains a directory of research that has been conducted in the community, including information on the Dalhousie University Wastewater Research Program. The directory is available to the public at the hamlet office and community library.

Iqaluit

Title	Category	Year
Pollution Prevention Program Manager, Government of Nunavut, Environment	E	2014
Research Manager, Nunavut Research Institute	E	2014
Environmental Health Officer, Government of Nunavut, Health	H	2014
Environmental Health Officer, Government of Nunavut, Health	H	2014
Environmental Health Officer, Government of Nunavut, Health	H	2015
Manager Iqaluit Public Health, Government of Nunavut, Health	H	2015
Iqaluit Hunters and Trappers Organization (7 members in attendance)	T x 7	2015

Director of Sustainability, City of Iqaluit	WW	2014
Director Community Infrastructure, Government of Nunavut, Community and Government Services	WW	2014
Wastewater Facility Operator, City of Iqaluit	WW	2015

*A community forum was not held in Iqaluit. Due to legal issues surrounding the wastewater treatment facility in Iqaluit, a public event featuring preliminary and incomplete research was deemed inappropriate and inadvisable. For the same reason, a presentation was not made directly to City Council. Research updates were provided to the Government of Nunavut Department of Health, Department of Community & Government Services, and Nunavut Research Institute for review and dissemination at their discretion. Preliminary results were also presented to the Northern Territories Water & Waste Association.

Naujaat

Title	Category	Year
Conservation / Wildlife Officer, Government of Nunavut, Environment	E	2016
Acting Head Nurse, Health Centre, Government of Nunavut, Health	H	2016
Environmental Health Officer, Government of Nunavut, Health	H	2016
Hunters and Trappers Organization (7 Members)	T × 7	2016
Senior Administration Officer, Hamlet of Naujaat	WW	2016
Community Forums (50 people)		2016
Council Meeting (11 members in attendance)		2016

Sanikiluaq

Title	Category	Year
Conservation / Wildlife Officer, Government of Nunavut, Environment	E	2016
Wastewater Foreman, Hamlet of Sanikiluaq	WW	2016
Community Forums (30 people)		2016
Council Meeting (7 members in attendance)		2016

Key Informant Totals

	WW	E	T	H	**TOTAL**
Pond Inlet		1	4	1	6
Pangnirtung	1	2	2	2	7
Iqaluit	3	2	7	4	16
Naujaat	1	1	7	2	11
Sanikiluaq	1	1			2
TOTAL	6	7	20	9	**42**

Key Informant Recruitment Script

Dear [name of potential key informant]

My name is Kiley Daley. I am a graduate student from Dalhousie University, Nova Scotia. I am working on a research project titled "Assessing Exposures and Human Health Risk associated with Wastewater Treatment in Remote Arctic Communities". Our work is a sub-project of a large wastewater management project between the Government of Nunavut and Dalhousie University. Your community ________ has been involved for several years.

It is important to note that this research is not a reactionary response to a current wastewater related health emergency in the community, but rather an opportunity to proactively plan for upcoming regulations that assure wastewater treatment areas are operated in a safe manner.

The purpose of our project is to investigate community activities and features of the local environment and how they relate to wastewater management practices and protecting health in the community. As a member of [participants' organization if applicable] your insight is very valuable and we would like to invite you to be part of the research. Your participation would involve taking part in an interview that would take approximately 30 minutes. You will be asked questions about your areas of insight (wastewater, environment, and/or health). You may also be asked if you know of any existing data sets (for example, logbooks, inventories, government data available to the public) related to the research topic. With your permission, the interview may be audio recorded. You will have the opportunity to review the transcription for verification.

I will be in [insert community name] until [insert date that we will depart from community]. If you are interested in participating in the research, we can schedule the interview at a time that is convenient for you. If you have any questions or would like some more detailed information about the research before deciding if you would like to participate, we can continue discussing the project now or you can contact us at [insert address and telephone number of accommodations while in community].

Thank you for your time.

Kiley Daley

Participant Information and Informed Consent Form

Participant Information and Informed Consent Form (Page 1 of 3)

Project Title

Assessing Exposures and Human Health Risks associated with Wastewater Treatment in Arctic Communities

Principal Investigator

Kiley Daley, PhD Student
Dalhousie University
Centre for Water Resources Studies
1360 Barrington St. D514
Halifax, Nova Scotia, B3H 4R2
Telephone in Halifax: 902-826-1898 or 902-494-6070
Local Contact: ______________________________
Email: kiley.daley@dal.ca

Primary Supervisor

Dr. Rob Jamieson, Tel: 902-494-6791, Email: jamiesrc@dal.ca

Description of Project

Introduction

We invite you to take part in a research study being conducted by Dalhousie University. Your participation is voluntary and you may withdraw from the study at any time. You should discuss any questions you have about this study with the researchers listed above or the Community Research Liaison.

Purpose and Objectives

The purpose of this study is to learn about exposure pathways and human health risks associated with current wastewater (sewage) treatment techniques in Nunavut communities. By understanding more about the activities that residents participate in, risk management strategies related to wastewater treatment and public health protection can be improved if needed

There is minimal risk to participating in this study. This research is not a reactionary response to a current water related emergency in the community.

Participant Information and Informed Consent Form (Page 2 of 3)

Description of What Will Happen (In-Person Interview and/or Request for Existing Data)
You will be asked to participate in one in-person interview with the research team. This will take approximately 30 minutes. You will be asked questions about your areas of insight (wastewater, environment, and/or health). You may also be asked if you know of any existing data sets (for example, logbooks, inventories, government data available to the public) related to the research topic. If you give permission, the interview will be audio recorded.

The interview will take place at a time and location that is convenient for you.

Conditions for Release of Recorded Information
With your permission, direct quotes may be included but no names will be directly linked to those quotes. The names of government departments that provide public data may be included if applicable. You will be given the option to review and approve your transcribed interview for inclusion in final results before they are published.

If a Community Liaison is required to assist for translation or other research-related purposes, they will be required to sign a confidentiality agreement.

Questions
If you have any questions about this study, please contact the research team in person while they are in the community. When not in the community they can be reached by collect call (902-494-6070) or email (kiley.daley@dal.ca; jamiesrc@dal.ca).

Problems or Concerns
If you have any difficulties with, or wish to voice concern about, any aspect of your participation in this study, you may contact Catherine Connors, Director, Research Ethics, Dalhousie University at (902) 494-1462, ethics@dal.ca.

This project is also registered with the Nunavut Research Institute under the following technical title: "Northern Municipal Wastewater Effluent Discharge Quality Objectives in the Context of Canadian Council of Ministers of the Environment Strategy and Environment Canada's Wastewater Systems Effluent".

Participant Information and Informed Consent Form (Page 3 of 3)

DALHOUSIE
UNIVERSITY
Inspiring Minds

Project Title
Assessing Exposures and Human Health Risks associated with Wastewater Treatment in Remote Arctic Communities

Research Team
Principal Investigator:
Kiley Daley (Phone: 902-494-6070, Email: kiley.daley@dal.ca)

Supervisor:
Dr. Rob Jamieson (Phone: 902-494-6791, Email: jamiesrc@dal.ca)

To be completed by the research participant:

"I have been fully informed of the objectives of the project being conducted. I understand these objectives and consent to being interviewed for the project. I understand that steps will be undertaken to ensure that this interview will remain confidential unless I consent to being identified. I also understand that, if I wish to withdraw from the study, I may do so without any repercussions."

Signature of Research Participant: ______________________________

Printed Name: ____

I believe that the person signing this form understands what is involved in the study and voluntarily agrees to participate.

Signature of Researcher or Designee:
____

Date: _____________________________

THE INFORMATION SHEET IS ATTACHED TO THIS CONSENT FORM. A COPY OF THE INFORMATION SHEET IS GIVEN TO THE RESEARCH PARTICIPANT.

Key Informant Research Questionnaires

FIELD COPY
Questionnaire – Environment Informants
(Conservation Officers and Environmental Departments and Organizations)
Assessing Exposures and Human Health Risks Associated with Wastewater Treatment in Arctic Communities

PREAMBLE

The purpose of this study is to learn about exposure pathways and human health risks associated with current wastewater (sewage) treatment techniques in Nunavut communities. By understanding more about the activities that residents participate in, risk management strategies related to wastewater treatment and public health protection can be improved if needed There is minimal risk to participating in this study. This research is not a reactionary response to a current water related emergency in the community. There are not right or wrong answers to each question. All opinions are meaningful and valuable. Do you have any questions before we begin?

COMMUNITY SPECIFIC EVENTS AND DATA

Do you have information on the wildlife present in the area (land and water) near the community and wastewater treatment area (species, temporal and spatial variation, numbers)? Do you have data on the marine receiving waters near the community and the wastewater treatment area (tides and currents, sunlight, temperature, humidity, composition of water)

HARVESTING INFORMATION

Do you have data on harvested food in this community (amounts per season, etc.)
What are the hunting seasons? Are there any quotas or conservation programs for certain species
Have there ever been any “events” resulting in high big kills (unanticipated biological growth in the water, etc.)
Have there been public health advisories issues related to food harvesting in this community
Do you have any specific environmental or wildlife concerns related to wastewater treatment in this community?

CONCLUSION

Do you have any other comments that you would like to include? They can be related to any of the topics we discussed or general comments?

CONTACT AND FOLLOW-UP INFORMATION

Thank you for talking with me today.
I will be in (insert community) until (insert date) if you think of anything else you would like to add to your discussion. You can reach me anytime by email or collect by telephone. My information is on your contact sheet.

FIELD COPY
Questionnaire – Public Health Informants
(Environmental Health Officers and Health Centres)
Assessing Exposures and Human Health Risks Associated with Wastewater Treatment in Arctic Communities

PREAMBLE

The purpose of this study is to learn about exposure pathways and human health risks associated with current wastewater (sewage) treatment techniques in Nunavut communities. By understanding more about the activities that residents participate in, risk management strategies related to wastewater treatment and public health protection can be improved if needed

There is minimal risk to participating in this study. This research is not a reactionary response to a current water related emergency in the community.

There are not right or wrong answers to each question. All opinions are meaningful and valuable. Do you have any questions before we begin?

FOOD AND WATERBORNE ILLNESS

Can you tell me, generally, about any history of food or waterborne illness in at the community level?
Can you tell me about the exposure pathways (confirmed or suspected)?
Can you tell me about the co-occurrence of illness?
Has there ever been any health outcomes related specifically to wastewater exposures in this community?

LOCALIZED EXPERTISE

When working in a setting like this, with people consuming a lot of traditional food, is there any specialized training or consideration regarding food and waterborne illness?

DATA SETS

Is there a database of food and waterborne illness in this community? In the territory?
Is it public information or can researchers' apply to access it?
Are regular reviews of health outcome data pertinent to water and foodborne illness at the community level undertaken to identify potential seasonal patterns?

CONCLUSION

Do you have any other comments that you would like to include? They can be related to any of the topics we discussed or general comments?

CONTACT AND FOLLOW-UP INFORMATION

Thank you for talking with me today.
I will be in (insert community) until (insert date) if you think of anything else you would like to add to your discussion. You can reach me anytime by email or collect by telephone. My information is on your contact sheet.

FIELD COPY
Questionnaire – Traditional Land Users (fishers, harvesters, recreation)
Assessing Exposures and Human Health Risks Associated with Wastewater Treatment in Arctic Communities

PREAMBLE

The purpose of this study is to learn about exposure pathways and human health risks associated with current wastewater (sewage) treatment techniques in Nunavut communities. By understanding more about the activities that residents participate in, risk management strategies related to wastewater treatment and public health protection can be improved if needed

There is minimal risk to participating in this study. This research is not a reactionary response to a current water related emergency in the community.

There are not right or wrong answers to each question. All opinions are meaningful and valuable. Do you have any questions before we begin?

GENERAL UNDERSTANDING OF ACTIVITIES

Can you tell me about some of the hunting and fishing activities that take place here?
Can we talk a little about some of these? By species:
    What areas of the community do these take place (use maps)
    When do they take place (season, popular time of day)
    How often do you do this activity?
    How much/many animals do you harvest each time?
    What are the steps involved (digging/collecting/fishing, handling, cleaning, Storage, preparation to eat?

UNDERSTANDING POPULATIONS

Who participates in these activities (harvesters, preparation)
Is harvested food shared among families or community-wide?
Are there foods that children or other specific people don’t eat?
Does harvested food from other communities get brought here?
Does harvested food from here get brought to other communities?
How much of your regular diet would you estimate is country food?

RECREATION AND OTHER VALUES

What other activities (recreation, boating) take place in areas near the shore close to town or the wastewater treatment plant?
Are there any other social or cultural values that these areas have in the community, besides for food and recreation?

HEALTH

What do you think about the health of your country food in regards to pollution? Do you have any concerns about wastewater (sewage) treatment and how it might impact the local environment and your food? Have you or your family ever felt ill and attributed it to traditional food? Were you diagnosed?

CONCLUSION

Do you have any other comments that you would like to include? They can be related to any of the topics we discussed or general comments?

CONTACT AND FOLLOW-UP INFORMATION

Thank you for talking with me today. I will be in (insert community) until (insert date) if you think of anything else you would like to add to your discussion. You can reach me anytime by email or collect by telephone. My information is on your contact sheet.

FIELD COPY
Questionnaire – Wastewater Operators and Forepersons
Assessing Exposures and Human Health Risks Associated with Wastewater Treatment in Arctic Communities

PREAMBLE

The purpose of this study is to learn about exposure pathways and human health risks associated with current wastewater (sewage) treatment techniques in Nunavut communities. By understanding more about the activities that residents participate in, risk management strategies related to wastewater treatment and public health protection can be improved if needed

There is minimal risk to participating in this study. This research is not a reactionary response to a current water related emergency in the community.

There are not right or wrong answers to each question. All opinions are meaningful and valuable. Do you have any questions before we begin?

GENERAL

What type of wastewater treatment system do you use in this community? (i.e. passive lagoons or mechanical plants, trucks or utilidors)

*PASSIVE SYSTEMS (LAGOONS) – USE THESE QUESTIONS

Where is the lagoon located? How far is that from town (if applicable)? Do you know when it was built? Do you know why it was located there? Have there been any major changes or repairs?

PASSIVE SYSTEMS QUESTIONS CONTINUED

Do you have any records/data on how much influent goes in (volume and variability: litres or truck-loads per day during different times per year)?
Do you have any data on the quality (treatment level) at different stages? (influent, mid-season, discharge)?
How does the system work during winter (does it freeze over, does the influent melt a whole)

PASSIVE SYSTEMS QUESTIONS CONTINUED

When do you decant/discharge?
How many times per year do you decant/discharge?
How do you decant (pump, valve)
What factors influence your decision to decant/discharge (season, informed by Hamlet)

*MECHANICAL SYSTEMS – USE THESE QUESTIONS

Do you know when the plant was built?
Do you know why it was located there?
Have there been any major changes or repairs?
Does the plant continuously discharge or do you control it manually?
If manual, what factors influence your decision?

MECHANCIAL SYSTEMS CONTINUED

Do you have any records/data on how much influent goes in (volume and variability: litres or truck-loads per day during different times per year)?
Do you have any data on the quality (treatment level) at different stages? (influent, discharge)?
How does the system work during winter (does the outflow freeze over)

PUBLIC HEALTH PROTECTION

Are the treatment or outflow areas (lagoons, wetlands, discharge run-off areas, receiving waters) marked for the public?
Are there signs or barriers to prevent entry?
Has there ever been breaks in the lagoon berm or plant break-downs?
Are there scheduled shutdowns or power outages that impact the plant?
How is treatment impacted during those times?
Is the community informed if there is a period of reduced treatment?
Have you ever seen people in the outflow areas? What were they doing?
Do you have any concerns about public health risks related to wastewater treatment in the community? Have there ever been an health advisories issued?

CONCLUSION

Do you have any other comments that you would like to include? They can be related to any of the topics we discussed or general comments?

CONTACT AND FOLLOW-UP INFORMATION

Thank you for talking with me today.
I will be in (insert community) until (insert date) if you think of anything else you would like to add to your discussion. You can reach me anytime by email or collect by telephone. My information is on your contact sheet.

Appendix F

E. coli Concentration Modelling Materials

Justification of Distributions Selected to Model Initial Indicator *E. coli* Concentrations (MPN/100mL) in Effluent Discharged from Nunavut Wastewater Treatment Systems (i.e. concentration at distance 0 m in receiving environment)

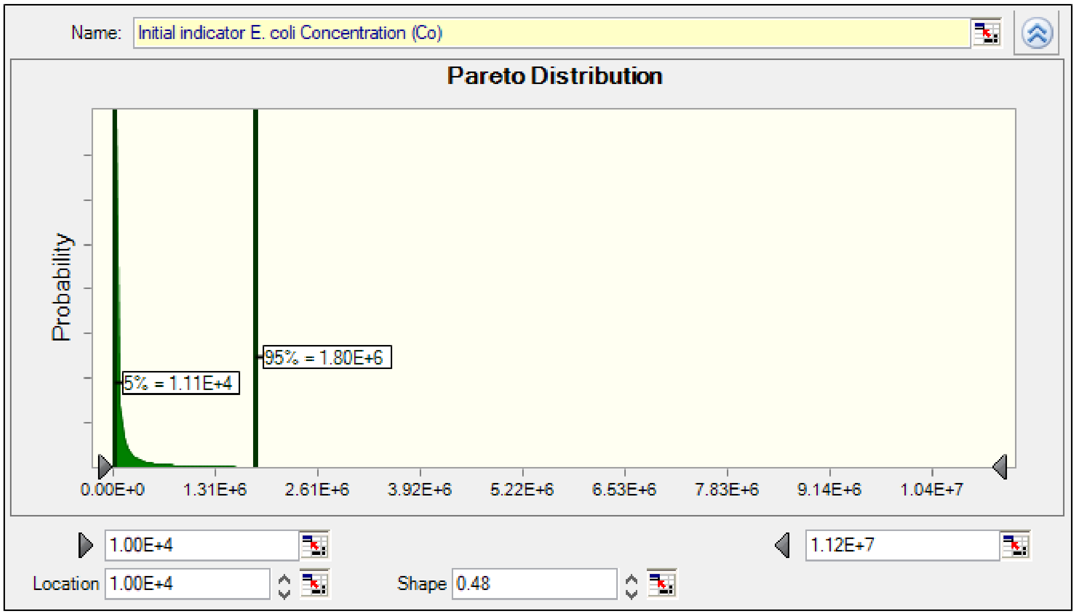
1. Mechanical Treatment System (secondary treatment with no disinfection stage)
Distribution and Parameter Values: Pareto (location = 1.0×10^4; shape = 0.48)
Information known about the variable based on site data, literature, and professional judgement:

- Typical *E. coli* concentration following secondary treatment, with no disinfection stage, when system is operating normally is 1.0×10^4;
- The treatment system in incapable of treating effluent to a concentration less than 1.0×10^4;
- The treatment system fails, partially fails, or is offline approximately 5–10% of the time, resulting in effluent concentrations typical of raw sewage, which are up to 1.0×10^6 to 1.0×10^7.

Characteristics of the Pareto distribution:

- Belongs to exponential category of distributions (general shape)
- Mode and minimum are equal (this trait distinguishes Pareto from classic exponential)
- Has a minimum lower bound (i.e. minimum is not −infinity)
- Parameters
    - Location: lower bound for the variable
    - Shape: rate of decrease. The larger the shape parameter, the smaller the variance and the quicker its tails falls away

Figure F-1 Results of characterizing initial indicator *E. coli* concentrations (MPN/100mL) in effluent discharged from mechanical wastewater treatment systems in Nunavut (i.e. concentration at distance 0 m in receiving environment) using a Pareto distribution.



Name: Initial indicator E. coli Concentration (Co)

1.00E+4

1.12E+7

Location 1.00E+4

Shape 0.48

Percentile	Pareto distribution	Percentile	Pareto distribution
0%	1.00×10^4	60%	6.07×10^5
10%	1.23×10^4	70%	1.05×10^5
20%	1.56×10^4	80%	2.19×10^5
30%	2.04×10^4	90%	6.91×10^5
40%	2.76×10^4	100%	1.12×10^7
50%	3.95×10^4		

Chi-Square Goodness of Fit test:
(0.05 significance level)
Result = 1.8

p=0.18 (smallest result at which null hypothesis should be rejected. Null hypothesis being Pareto fits the ‘dummy’ data set created based on knowledge of variable described above)

Note: With only 15 observations in the ‘dummy’ data set, the test result is not that robust, but provides a general indication that Pareto is reasonable assumption.

2. Passive Treatment Systems (stabilization pond/lagoon with uncontrolled discharge) Distribution and Parameter Values: Uniform (minimum = 1.0×10^5; maximum = 1.0×10^6)

A uniform distribution assumption was based on site data, literature, and professional judgement. The data set displayed below (Table D-1), which was collected during the Nunavut Wastewater Research Program, includes observations from a range of passive systems in Nunavut (i.e. Pond Inlet is engineered, Sanikiluaq and Naujaat are minimally engineering existing ponds). The data was used for reference only. Distribution fitting tests were not conducted as ample evidence is available in peer-reviewed literature to justify a uniform distribution.

Table F-1 Initial *E. coli* concentrations (MPN/100mL) in effluent discharged from passive wastewater treatment systems in Nunavut (i.e. concentration at distance 0 m in receiving environment)

Site	**Conditions**	***E. coli* concentration (MPN/100mL**
Naujaat	Spring	1.7×10^6
		2.6×10^5
	Summer	1.1×10^6
		4.6×10^5
Sanikiluaq	Spring	6.0×10^4
		3.1×10^4
	Summer	2.3×10^4
		2.3×10^4
Pond Inlet	Summer	4.4×10^5
	Summer	3.8×10^5
	Summer	2.6×10^5

Modelling Coefficients Derived from Nunavut Wastewater Research Program Data and Used for Predicting *E. coli* Concentrations in Wastewater Effluent-impacted Receiving Environments in Arctic Canada.

Table F-2 Complete set of modelling coefficients derived for purposes of predicting *E.coli* concentrations in effluent-impacted receiving environments in Nunavut and Arctic Canada

Study Site	Conditions	Regression Coefficient	p-value	R^2 value
Pond Inlet	Outgoing Tide	−0.20186 (-2.01×10^{-1})	0.0003	0.9756
	Low Tide	−0.04220 (-4.22×10^{-2})	0.0010	0.8670
	High Tide	−0.00852 (-8.52×10^{-3})	<0.0001	0.9912
Pangnirtung	High Tide	−0.16578 (-1.66×10^{-1})	0.0073	0.7537
	Outgoing Tide	−0.11722 (-1.17×10^{-1})	0.0165	0.12247
	Incoming Tide	−0.09048 (-9.05×10^{-2})	0.0267	0.3956
Iqaluit	High Tide	−0.03572 (-3.57×10^{-2})	<0.001	0.95136
	Low Tide	−0.0048 (-4.80×10^{-3})	<0.0001	0.91372
Sanikiluaq	Spring Freshet	−0.00898 (-8.98×10^{-3})	<0.0001	0.9899
	Late Summer	−0.01983 (-1.98×10^{-2})	0.0028	0.9831
Naujaat	Spring Freshet	−0.00282 (-2.82×10^{-3})	0.0018	0.8048
	Late Summer	−0.01332 (-1.33×10^{-2})	0.0003	0.9352

Table F-3 Selected set of modelling coefficients used for predicting *E. coli* concentrations in effluent-impacted receiving environments in Nunavut case study sites, as presented in Chapter 3

Study Site	Conditions	Regression Coefficient	p-value	R^2 value
Pond Inlet	Low Tide[a]	−0.20186 (-2.01×10^{-1})	0.0003	0.9756
	High Tide	−0.00852 (-8.52×10^{-3})	<0.0001	0.9912
Pangnirtung	High Tide	−0.16578 (-1.66×10^{-1})	0.0073	0.7537
	Low Tide[b]			
Iqaluit	High Tide	−0.03572 (-3.57×10^{-2})	<0.001	0.95136
	Low Tide	−0.0048 (-4.80×10^{-3})	<0.0001	0.91372
Sanikiluaq[c]	Spring Freshet	−0.00898 (-8.98×10^{-3})	<0.0001	0.9899
	Late Summer	−0.01983 (-1.98×10^{-2})	0.0028	0.9831
Naujaat[c]	Spring Freshet	−0.00282 (-2.82×10^{-3})	0.0018	0.8048
	Late Summer	−0.01332 (-1.33×10^{-2})	0.0003	0.9352

[a] In effort to create a more useful model, only 2 tide cycle titles (low and high) were used in the Chapter 3 case sites where effluent was discharged directly to marine receiving environments (Pond Inlet, Pangnirtung, and Iqaluit); rather than the 4 titles used in the original data (low, high, incoming, outgoing). These modified titles do not refer to absolute lowest and highest tides levels; but, rather when the tide was at relatively higher or lower levels. As such, for Pond Inlet, the tide level sampled at and originally labeled "outgoing tide" in the Nunavut Wastewater Research Program data has been changed to "low" in the Chapter 3 model. Due to this label change, the regression coefficient (labeled *k* in the chapter) used in the Pond Inlet low tide model scenarios corresponds to the outgoing tide regression coefficient value in Table F-2 (Complete set of modelling

coefficients derived for purposes of predicting E.coli concentrations in effluent-impacted receiving environments in Nunavut case study sites).

[b] System discharges effluent directly into a tidal flat at low tide (i.e. no marine water to mix with), so it was not possible to collect water quality data and derive a regression coefficient. It was conservatively assumed that no dilution is occurring; and therefore, the *E. coli* concentration at initial discharge (C_0) was used to model exposures at all distances at this site.

[c] Sanikiluaq and Naujaat receiving environments are comprised of a wetland followed by a marine body. No *E. coli* concentration data from the marine water at these sites are available. Therefore, for marine exposure scenarios in these communities (shore recreation, small craft boating, net fishing), two steps are involved in modelling the *E. coli* concentration at the exposure point. First, the concentration is modelled from the discharge point (0 m) to the end of the wetland using site-specific data (1000 m in Sanikiluaq and 1300 m in Naujaat). Second, a regression coefficient from one of the marine receiving environment communities is applied to predict the remainder of the distance to the exposure point. For both Sanikiluaq and Naujaat, the "Pond Inlet, high tide" coefficient was used as it was assumed that this is the best available comparable of conditions in these communities (i.e. minimal tides and a low-energy effluent plume from the outfall that may cling to the shoreline).

Table F-4 Selected set of modelling coefficients used for predicting *E. coli* concentrations in effluent-impacted receiving environments in Arctic Canada, as presented in Chapter 4

Treatment System	Assumed Representative Site	Conditions	Regression Coefficient	p-value	R^2 value
Mechanical	Iqaluit	High Tide	-0.03572 (-3.57×10^{-2})	<0.001	0.95136
		Low Tide	-0.0048 (-4.80×10^{-3})	<0.0001	0.91372
Passive (Wetland portions[a])	Sanikiluaq	Spring Freshet	-0.00898 (-8.98×10^{-3})	<0.0001	0.9899
		Late Summer	-0.01983 (-1.98×10^{-2})	0.0028	0.9831
Passive (Marine portions[a])	Pond Inlet	High	-0.00898 (-8.98×10^{-3})	<0.0001	0.9912

[a] Most passive treatment system receiving environments are comprised of a wetland followed by a marine body. No data of *E. coli* concentrations in the marine portion of these sites are available, including the Sanikiluaq site which was chosen as a representative example of passive treatment systems in Arctic Canada. Therefore, for exposure scenarios occurring in the marine portion of passive treatment receiving environments (e.g. shore recreation, small craft boating, netfishing), two steps are involved in modelling the *E. coli* concentration at the exposure point. First, the concentration is modelled from the discharge point (0 m) to the end of the wetland (e.g. 1000 m). Second, a regression coefficient representative of marine receiving environment conditions in passive treatment systems in Arctic Canada was applied to predict the remainder of the distance to the exposure point. The "Pond Inlet, high tide" coefficient was used as it was assumed that this is the best available comparable of conditions in these sites (i.e. minimal tides and a low-energy effluent plume from the outfall that may cling to the shoreline).