OPTIMIZING DRINKING WATER SAFETY IN CAMBRIDGE BAY, NUNAVUT USING WATER QUALITY SAMPLING AND PARTICIPATORY SYSTEM DYNAMICS

CAROLINE DUNCAN

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Abstract

Arctic communities face unique challenges in accessing clean, safe drinking water. In Nunavut, these issues are particularly severe due to a lack of water quality data, limited operator capacity, and outdated policies. New strategies are needed to improve drinking water safety in Arctic communities. Water safety planning (WSP) is a risk management approach that considers both quantitative and qualitative hazards related to drinking water and involves stakeholder participation. Participatory systems dynamics (PSD) is a method used to address complex health issues and aligns well with Indigenous knowledge. Additionally, PSD can help evaluate strategies to improve decision-making.

The two main objectives of this study were to (1) identify water quality hazards in Cambridge Bay, Nunavut, and (2) assess whether water safety hazards could be identified, characterized, and prioritized using WSP risk matrices and PSD. The study aimed to integrate these tools by using hazard data to develop a model and simulate high-level mitigation strategies for improving drinking water safety. Water sampling identified several water safety hazards, including low chlorine residuals and microbial activity in cisterns and at taps, elevated disinfection byproducts throughout the system, and the presence of lead and copper in some buildings. Data from stakeholder groups revealed concerns about source water quality and quantity, infrastructure condition, and stakeholder-specific issues, such as limited regulatory capacity. Limited data reduced the effectiveness of standard WSP risk assessment methods, which rely on past frequency data to predict future events. Nonetheless, this approach identified potential water safety improvements, including the implementation of treatment barriers and monitoring measures. PSD modelling proved more flexible and adaptable in capturing interactions among infrastructure, operations, the natural environment, governance, and sociocultural factors, but it increased complexity, making it more difficult to implement or use across multiple communities. Despite these individual limitations, by combining WSP and PSD four potential options to improve water safety in Cambridge Bay were identified. This is the first study to collect comprehensive water quality data from source to tap in the Kitikmeot Region of Nunavut and to gather meaningful qualitative information on water safety hazards from community stakeholders. Additionally, it is the first to examine water safety from a systems dynamics perspective.

Dedication

To those who are trying to make the world a little better.

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Glossary

Auxiliary variable – an intermediate, conventional variable to facilitate the expression of functional dependency of a flow to system stocks.

Balancing loop – Combined with reinforcing loops, balancing processes from the building blocks of dynamic systems. Balancing loops try to bring things to a desired state and keep them there. They can limit and constrain change generated by reinforcing loops.

Causal link – An arrow in a causal loop diagram that describes a relationship between two variables with the direction of causality and the nature of the impact.

Causal loop diagram – A diagram that captures how variables in a system are interrelated.

Corrective action – Action taken when operational monitoring indicates that the control measure is not working as intended.

Endogenous variable – Internal, the opposite of exogenous. Endogenous variables are affected by other system variables.

Exogenous variable – External, the opposite of endogenous. An exogenous variable is an external variable that affects but is not affected by the system.

Feedback loop – When the effect of a causal impact comes back to influence the original cause of that effect. A feedback loop is a sequence of variables and causal links that created a closed risk of causal influences.

Flow – the amount of change something undergoes during a particular length of time. Example: the amount of water that flows out of a bathtub each minute.

Hazardous event – an event that can cause a hazard to enter the water system or inadequately removed from the water supply.

Leverage point – A variable where small change can yield large improvements in a system.

Lookup function – A numeric table version of a graphical function.

Participatory system dynamics – a methodology for building models in which a team of people participate actively and simultaneously.

Polarity matrix – a table to identify the influence variables have on one another.

Policy lever – see leverage point.

System – A group of interacting, interrelated or interdependent elements forming a complex whole.

Reinforcing loops – Along with balancing loops, reinforcing loops form the building blocks of dynamic systems. Reinforcing loops compound change in one direction with even more change in the same direction. As such, they generate both growth and collapse.

Risk level – the level of risk assigned based on a risk score (e.g. low, medium, high).

Risk – the product of the likelihood of occurrence of a hazardous event and its severity.

Risk driver – indirect factors that are influential to increasing the likelihood of a hazard entering the water system.

Risk matrix – a table used to calculate the risk score, made up of likelihood descriptors and severity descriptors.

Sensitivity analysis – analysis used to determine how responsive model outputs are to changes in specific parameters or structures. Behaviour that changes drastically suggests a critically important factor or high sensitivity.

Simulation – the projection of the behaviour of a system with a formal computer model.

Stock – an accumulation of quantities in specific locations or conditions in a system. A component of a system that accumulates or drains over time. They can only be changed by flows.

Stock and flow diagram – A visual depiction of the stock, flow and auxiliary variables in a system and how they are connected.

Water safety hazard – an agent that can reduce the safety of drinking water.

Water safety plan – A proactive risk assessment and risk management approach to help ensure drinking water safety from source to tap.

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1. Introduction

1.1 Background

Sustainable Development Goal (SDG) 6 Target 6.1 is to: “*achieve universal and equitable access to safe and affordable drinking water for all*” by 2030 (UN, 2025). Between 2015 and 2024, global access to safe drinking water increased from 68% to 74% (UN, 2025). However, this still leaves 2.2 billion people without access to safe drinking water (UN, 2025). People living in rural and remote areas and Indigenous Peoples are disproportionately represented in this total (UN, 2009). The Government of Canada has made a substantial effort to improve water and wastewater treatment systems within First Nations, Métis, and Inuit communities through funding, the legal recognition of UNDRIP, and land agreements that allow Aboriginal People to exercise their Treaty Rights as a means of reconciliation (Department of Justice, Canada, 2023). However, as of December 1, 2025, there are still 38 long-term drinking water advisories in First Nation communities (Government of Canada, 2025). In 2024, the most recent year for which data are available, 11 of the 25 predominantly Inuit communities in Nunavut experienced a boil-water advisory (Indigenous Watchdog, 2024).

Water management in Canada is complex, partly because responsibilities are divided between the multiple levels of government (federal, provincial, and municipal). Without a centralized system, implementing regulations involves multiple stakeholders. To fulfill this regulatory role, a multidisciplinary approach and cooperation among different levels of government are necessary (Dunn, Bakker and Harris, 2014). Key stakeholders include federal, provincial, and territorial government departments; municipal and local agencies; First Nations band councils; non-governmental organizations; and the public.

This affects water policy and data collection because Canada's current approach to gathering drinking water quality information is fragmented, largely because provinces and territories, not the federal government, are responsible for managing drinking water (Dyck, Plummer & Armitage, 2015). At the federal level, several key documents guide drinking water management. These include: *From source to tap: the multibarrier approach to safe drinking water* (CCME, 2002), developed and adopted by all provinces in Canada in 2002, and the Guidelines to Canadian Drinking Water Quality (GCDWQ), which consists of multiple technical documents updated regularly (Health Canada, 2022). These guidelines have been adopted, in whole or in part, and are legally binding in some provinces, such as Ontario (OMOE, 2013). However, since provinces and territories own and enforce regulations, there is a gap in protecting drinking water on federal and Indigenous lands.

Arctic and subarctic communities face numerous challenges due to their remoteness and unique geographies. One of the most pressing challenges is the delivery of safe, clean drinking water, which most people living in Southern Canada take for granted. In Nunavut, government departments are streamlining the delivery of drinking water by aligning with practices used in Southern Canada, such as the multibarrier approach. There are 25 municipalities in Nunavut, and 24 of them do not generate revenue, leaving the Government of Nunavut to fund and construct water supply infrastructure (Chalmers, Duncan & Gora, 2025). Under the Public Water Supply Regulations (PWSR) 1990, communities are responsible for monitoring the quality of drinking water at regulated locations. Chlorine and turbidity are monitored daily; bacteriological samples are collected monthly; and, since 2021, due to an interim directive, chemical and physical parameters are collected quarterly. The Government of Nunavut issued an interim directive through the Department of Health to increase the mandatory monitoring frequency and the list of parameters, aligning with Health Canada's GCDWQ (Government of Nunavut, 2021; Chalmers, Duncan & Gora, 2025). Increasing the frequency of data collection will help to establish a baseline for seasonal and annual changes in source water parameters and how climate change may influence source water quality. However, this interim directive applies only to the elements of drinking water infrastructure managed by municipal governments or the Government of Nunavut and doesn't cover the monitoring of cisterns within buildings. Cisterns have been identified as a regulatory gap in many parts of Northern Canada, and studies have

found that there is microbiological contamination in drinking water cisterns in Nunavik (Mahgoub, et al., 2025) and Nunavut (Gora et al., 2020; Daley et al., 2018).
Most research on the microbial and chemical characteristics of drinking water in Nunavut has focused on the Qikiqtani Region (Daley et al., 2018; Gora et al., 2020) and on two communities in the Kivalliq Region (Daley et al., 2018; Daley, Castleden, Jamieson, Furgal, & Ell, 2015). To date, there has been no research on drinking water in the Kitikmeot Region, except for an overview of source water for the territory (Elliott et al., 2022).

Water safety plans (WSPs) are a preventive framework developed by the World Health Organization (WHO) to address gaps in water safety that are often overlooked by regulatory approaches (Bartram et al., 2009; World Health Organization, 2023). Regulations tend to focus on the technical aspects of drinking water and often overlook the human factor (Kot, Castleden & Gagnon, 2015). Water provision is inherently complex and can be influenced by multiple conditions (Walters & Javernick-Will, 2015). Water safety planning allows a system to be viewed holistically, but only as a snapshot in time. Formal data on water safety risks in Nunavut is limited. Only Daley et al. (2018) gathered input from residents on water scarcity in Coral Harbour, a community in the Kivalliq Region.

System dynamics (SD) is a holistic approach to investigating factors and interactions that could contribute to a possible outcome. SD theory has been applied to the study of challenges such as global warming (Naill, Belanger, Klinger & Petersen, 1992), health (Atkinson et al., 2015; Thompson et al., 2015; Homer & Hirsch, 2006), water resources (Madani & Marino, 2009; Frenandez & Selma, 2004), supply chain management (Campuzano & Mula, 2011), and many other complex systems. It is a tool for examining the interrelationships in complex systems, thereby reducing partial or inaccurate understanding of the problem under analysis (Jonassen & Strobel, 2006). Previous research has suggested that SD may align well with Inuit Quajimajatuqangit (IQ) principles in Nunavut that guide Inuit toward a brighter future (Karetak, Tester & Tagalik, 2017).

Inuit Societal Values were developed by the Government of Nunavut, based on the guiding knowledge of IQ, to incorporate Inuit beliefs, laws, principles, and values that align with the traditional knowledge, skills, and attitudes of Inuit (Government of Nunavut, 1999). Valcourt et al. (2020) note that an SD approach suggests that low service sustainability is not due to a deficiency in any single factor, but rather to a collective, weak effect of multiple factors. An enhanced understanding of how these interactions affect the delivery of safe drinking water is arguably as important as, if not more important than, assessing the factors themselves (Valcourt et al., 2020).

The perspectives of local stakeholders are particularly important for understanding complex systems with factors and interactions for which objective quantitative data is not available or, in some cases, not possible to collect (Valcourt et al., 2020). Encompassing local and community-based knowledge is important for developing future water management strategies and ensuring that source water protection, infrastructure design and operation, and ongoing water safety management activities (e.g., water quality sampling) align with the values of the IQ principle (Nunavut Impact Review Board, 2025).

To develop a more informed understanding of how quantitative and qualitative factors in complex systems interact, it is critical to include the perspectives of those with the most intimate contextual knowledge of the systems' structure and dynamics (Beall & Ford, 2010). In the context of drinking water safety in Nunavut, this means engaging meaningfully with community members and local leadership, local and external technical experts (e.g., water system operators and system designers), and government stakeholders at multiple levels.

1.2 Research Questions

This thesis addresses the four objectives specified in Section 1.2, with Chapters 4-7 dedicated to achieving each task. Chapters 4-6 have been adapted from peer-reviewed papers published during the study period. From these objectives, three overarching research questions were synthesized.

1. What are the water safety hazards in Cambridge Bay?
2. Can water safety planning be used to characterize water safety risk in Cambridge Bay?
3. Can system dynamics be used to characterize water safety risk in Cambridge Bay?

1.3 Research Objectives

This research aimed to develop a system dynamics model to identify key leverage points to optimize drinking water safety in Cambridge Bay, Nunavut. The specific objectives of this research were to:

1. Conduct an in-depth desktop review of water safety policy regulations and frameworks in Nunavut, and water quality and operational records in Cambridge Bay.
2. Identify technical water safety problems throughout the water system in Cambridge Bay from source to tap by assessing existing infrastructure and in-situ operational procedures, and by collecting water quality samples from multiple points within the system. (Chapters 4 & 5)
3. Gather qualitative data related to water access, policy, governance, and cultural considerations via participatory stakeholder engagement activities like public forums and focus groups. (Chapter 6)
4. Use participatory system dynamics modelling to identify key technical, policy, and cultural leverage points, assess the risks posed by different water safety hazards, and improve water treatment and policy in Cambridge Bay. (Chapter 7)

1.4 Thesis Structure

The thesis consists of eight chapters, each structured to address the research objectives and answer the overarching research questions.

The first three chapters provide an introduction to the concepts, literature, and methods used in this project. Chapter 1 presents the research inspiration and outlines the study's research questions and objectives. Chapter 2 reviews the relevant literature and identifies the key knowledge gaps this research aims to address. Chapter 3 describes the overarching methods applied throughout the research. For detailed methodologies, refer to Chapters 4 through 7.

Chapter 4 addresses Objective 1 and provides insight into the historical data and establishes a baseline understanding of water safety in Cambridge Bay, Nunavut. It identifies knowledge gaps that are not addressed through standard regulatory sampling and provides an initial list of water safety hazards, refined from (Chalmers, Duncan & Gora, 2025).

Chapter 5 addresses Objective 2 and fills several of the gaps identified in Chapter 4 through the analysis of extensive water sampling data that was collected from source to tap for key water quality parameters. This work addressed including data gaps on trihalomethanes (THMs) in building cisterns and taps in the community. Information collected through sampling was used to update previously identified water safety hazards and to add new hazards supported by scientific evidence.

Chapter 6 addresses Objective 3 and outlines stakeholder engagement methods for discussing water safety hazards from source to tap. This process enabled the development of a comprehensive list of community hazards, categorized into six groups to improve understanding of which hazards were predominant.

Chapter 7 examines water safety hazards through the lens of participatory system dynamics to fulfil Objective 4. The study evaluates whether this approach could be an effective tool for communicating high-priority hazards and supporting water safety planning. Chapter 8 concludes the thesis by summarizing the key findings, revisiting the research questions, and determining whether the study objectives were achieved.

1.5 Impact of Research

This research project has substantially increased the amount of drinking water quality data available for Cambridge Bay, NU. The Municipality of Cambridge Bay can use the results of this study, along with those from the wider Kitikmeot Region and the Territory of Nunavut, to address existing water safety risks and improve local drinking water policies. Many of the methods and findings described in this thesis will also be of interest to people living and working in other circumpolar regions, particularly communities served by decentralized drinking water systems. Additionally, the research undertaken aligns with Engineers Canada's new Guideline on Indigenous Consultation and Engagement (Engineers Canada, 2023).

The wider engineering community in Canada's drinking water sector has shifted toward developing more sustainable solutions for remote communities to reduce health and environmental disparities relative to urban communities. This means including the socio-economic, cultural, and political context along with scientific and engineering knowledge. Participatory SD has the potential to provide this holistic oversight and move communities, utilities, and governments towards more dynamic and responsive drinking water management that emphasizes community needs and long-term resilience. This study looked at the application of water safety planning and participatory SD modelling to address water safety concerns in a decentralized drinking water system in Cambridge Bay. Hazards identified through the WSP risk assessment were leveraged as intervention points within the SD model to assess their viability for characterizing water safety risk in remote communities.

1.6 Research Contributions

This thesis contributes to the advancement of knowledge on drinking water quality and water safety risk management in Arctic settings, with a focus on Nunavut, Canada.The following peer-reviewed papers and conference proceedings are associated with this project:

Duncan, C., Chalmers, E., & Gora, S. (2025). Application of water safety planning to improve drinking water safety in an Arctic community – a case study in Cambridge Bay, Nunavut. *International Journal of Circumpolar Health*, *84*(1). https://doi.org/10.1080/22423982.2025.2494889

Duncan, C., Slowey, G., Gora, S. (2025, May 28-30). Assessing water infrastructure, operations, and water safety in Cambridge Bay, NU, using water safety planning and participatory system dynamics. Canadian Society of Civil Engineers, Winnipeg.

Duncan, C., Ibraheem, M., Tam, A., Egotak, C., Maniyogina, K., Klengenberg, F., Gora, S. (2026). Identifying drinking water safety hazards throughout an Arctic community's water supply system, *Water Research*, Volume 288, Part B. https://doi.org/10.1016/j.watres.2025.124689

This research has also been presented at multiple conferences across Canada, including the Northern Territories Water and Waste Association Annual Conference (2023, 2025) and the American Water Works Association's Annual Conference and Exposition in Toronto (2023), among others. Interim and final results were presented to Cambridge Bay community members and local leadership in person in Cambridge Bay and over video calls multiple times in 2024 and 2025. Many of the results were also presented to other Nunavut stakeholders at events hosted by the Nunavut Association of Municipalities.

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2. Literature Review

This chapter reviews the most important literature that informed the research described in this thesis. The main goal of this review is to provide context and highlight the research gaps that motivate the contributions in the following chapters. The literature review is structured to establish the background for water safety planning risk assessments and participatory system dynamics tools, and their implementation in Nunavut, Canada.

2.1 What is Water Safety?

Water safety involves ensuring that water is clean and safe for human consumption by eliminating harmful contaminants such as microbial or chemical agents. In Canada, this is achieved by adhering to quality standards recommended by Health Canada and regulated by provincial and territorial authorities. The Health Canada *Guidelines for Canadian Drinking Water Quality* set limits on various contaminants that should be present in drinking water for it to be considered safe (Health Canada, 2022).

Many contaminants can threaten the safety of drinking water; these are called water safety hazards. Hazards to water safety include microbial pathogens, chemical contaminants, and physical and radiological hazards, as described in the water safety planning framework (WHO,2023). They can impact water quality or damage the infrastructure that supplies water. A hazardous event is an incident that introduces a hazard into the water supply system. Risk drivers are factors or conditions that increase the chance that a hazard enters or stays in the water system. Examples of risk drivers include environmental factors, weak policy and governance, and aging infrastructure.

To assess the level of risk associated with hazards, a risk matrix is often used in risk assessments. Typically, this assessment considers two factors: the likelihood of a hazardous event and the severity of its consequences if it occurs (WHO, 2023). In Canada and the Territory of Nunavut, water safety risks are managed through a regulatory approach (Government of Nunavut, 1990). The World Health Organization advocates an alternative method for achieving safe drinking water through water safety planning (WSP) (WHO, 2023). This approach involves comprehensive risk management from source to tap. Participatory system dynamics is a technique for understanding complex systems, such as those related to drinking water safety (Forrester, 1994). It combines system dynamics modelling with participatory methods, enabling stakeholders affected by the water system to share their knowledge and viewpoints (Vennix, 1999; Stave, 2010).

2.2 Common Drinking Water Contaminants

Microbiological Contaminants

Waterborne diseases present a challenge to public health worldwide. Despite advances in water treatment technology and management, communities remain vulnerable due to aging or faulty infrastructure and human errors. Several waterborne infectious agents pose major health concerns, including *Campylobacter*, *Escherichia coli* (*E. coli*), total coliforms, enterococci, enteric protozoa (*Giardia* and *Cryptosporidium* (oo) cysts), enteric viruses, and other waterborne pathogens such as *Legionella* and *Mycobacteria*.

A study analyzing *Campylobacter* cases in Canada found that about 5% may be linked to water from small, contaminated drinking water systems (Murphy, Thomas, and Schmidt, 2016). In Europe, a review of the past fifteen years (2010–2024) noted *Campylobacter* outbreaks reported in over 30 cases, mainly in Ireland and the Nordic countries (Pace, Pepe and Fabbricino, 2025). As with *Campylobacter,* pathogenic *E. coli* outbreaks and illnesses are often linked to contaminated water. It is a leading cause of bacterial gastrointestinal illness in Canada through various exposure routes (food, travel, and water). Both *Campylobacter* and pathogenic *E. coli* can contaminate drinking water sources through fecal contamination, which may occur via surface runoff, sewage inputs, and, in Arctic regions, through migratory animals (Martin et al., 2007). In Canada, a major outbreak of *Campylobacter* and pathogenic *E. coli* (2,300 cases with 7 deaths) in Walkerton, ON, in 2000, prompted significant reforms in drinking water regulation and the release of the *Multibarrier approach to safe drinking water: From source to tap* (CCME, 2004).

Cryptosporidium and *Giardia* are protozoa commonly found in water sources and can be transmitted through direct consumption of contaminated water, causing severe diarrhea (Dunn & Juergens, 2020; Gerace, Presti, & Biondo, 2019; Ryan, Fayer & Xiao, 2014). Although the prevalence of illness caused by these parasites is higher in developing countries, research in Nunavut has detected both *Giardia* and *Cryptosporidium* in traditional, untreated water sources. Furthermore, most communities in Nunavut lack ultraviolet treatment to deactivate Cryptosporidium (Dillon Consulting, 2023).

Metals

Many naturally occurring metals are present in drinking water supplies worldwide. Iron and manganese are present in rocks, soils, sediments, and both surface and groundwater and are often found together. Manganese has been linked to neurotoxicity (Dobson et al., 2004; Erikson and Aschner, 2019), and Health Canada has set a maximum allowable concentration (MAC) of 0.12 mg/L in the GCDWQ (Health Canada, 2019). It has been detected in tap water in several communities in Nunavut (Gora et al., 2020; Daley et al., 2018). The aesthetic objective for manganese was set at 0.1 mg/L to reduce metallic taste and prevent discoloration of the water, which can cause staining of clothes. Although iron is not associated with adverse health effects, it can negatively impact the aesthetic quality of water. Health Canada has set an aesthetic objective for iron at 0.1 mg/L to minimize this impact (Health Canada, 2024). Iron has been found in several drinking water studies conducted in Nunavut (Gora et al., 2020; Daley et al., 2018).

Copper pipes are commonly used in plumbing systems in Canada and elsewhere in the world (Health Canada, 2019), which can lead to copper leaching into tap water. At high levels, acute exposure may cause gastrointestinal symptoms, while long-term exposure could be linked to liver and kidney failure (Health Canada, 2019). Health Canada has set a MAC limit of 2 mg/L and an AO of 1 mg/L for copper exposure. Studies have detected copper in Nunavut communities in the Kivalliq and Qikiqtani Regions (Gora et al., 2020; Daley et al., 2018).

Lead, which can occur alongside elevated copper levels, is usually present due to corrosion of distribution system components, especially lead service lines in buried piped systems, and premise plumbing (Health Canada, 2025). Historically, lead has been used in pipes, fittings, solder, or service connections. Factors such as the age of plumbing fixtures, water stagnation time, and water quality parameters like pH and temperature can cause corrosion and the release of lead particles (Wang et al., 2014). This issue has been well documented in non-Arctic communities (Health Canada, 2019; Chowdhury et al., 2016; Schwartz et al., 2021). Lead exposure is linked to renal dysfunction in adults and adverse cognitive and behavioral effects in children. Due to these chronic health risks, the MAC for lead is set at 0.005 mg/L (Health Canada, 2019). In Nunavut, some studies have conducted sampling campaigns on trucked-to-cistern distribution systems, including random day sampling and sequential stagnation sampling to test for lead and its potential sources within premise plumbing. Both studies revealed exceedances of the MAC for lead in several buildings (Daley et al, 2018; Gora et al, 2020).

Organics and Disinfection By-products

Natural organic matter (NOM), usually measured as total organic carbon (TOC) and dissolved organic carbon (DOC), naturally exists in all surface water sources and serves as a food source for microorganisms. During chemical disinfection in water treatment plants, NOM can react with disinfectants like chlorine, forming disinfection by-products (DBPs) (Beauchamp et al., 2020; Beauchamp et al., 2018). Two commonly regulated DBPs are trihalomethanes (THMs) (Health Canada, 2006) and haloacetic acids (HAAs) (Health Canada, 2008; Guilherme & Rodriguez, 2014). Health Canada recommends that THMs in drinking water should not exceed 0.1 mg/L and that HAAs should not exceed 0.08 mg/L. While THMs are not considered carcinogenic, they serve as indicators for the possible presence of more harmful DBPs (Mian et al., 2018; Diana, Felipe-Sotelo & Bond, 2019).

Anthropogenic Contaminants

Anthropogenic contaminants are directly linked to human activities. Drinking water supplies can be polluted by industrial discharges, pesticides and fertilizers from agricultural runoff, and poor sewage management. Contaminants include petroleum products, such as those in Iqaluit (American Society of Civil Engineer, 2023); pharmaceuticals (Coderre et al, 2025); emerging contaminants such as per–and polyfluoroalkyl substances (PFAS) (Health Canada, 2024), which are now often detected in water sources (Kosuth, Mason and Wattenberg, 2018); and microplastics (Kosuth, Mason, Wattenberg, 2018; Candra & Walsh, 2024).

2.3 Drinking Water Treatment Processes

The main aim of drinking water treatment is to lower the level of disease causing microorganisms (pathogens) and other contaminants to a tolerable or acceptable degree. Tolerable usually refers to aesthetic quality, while acceptable refers to the maximum allowable concentration of contaminants in water before it is considered unsafe for drinking. The following provides an overview of the treatment processes. Health Canada recommends a multi-barrier source-to-tap approach to drinking water safety (CCME, 2002). The WHO recommends a similar approach as well as water safety planning (discussed in Section 2.7) (WHO, 2012).

Multi-barrier Approach

For decades, water treatment systems have helped reduce contamination and the incidence of waterborne diseases. After waterborne outbreaks in Walkerton, Ontario, and North Battleford, Saskatchewan, public concern for drinking water supplies grew. The Canadian Council of Ministers of the Environment published "*From Source to Tap: The multibarrier approach to safe drinking water*" in 2002 (CCME, 2002). This approach has been incorporated into the Guidelines for Canadian Drinking Water. As part of this multibarrier approach, approved treatment technologies are recommended in order to meet the GCDWQ. The three most commonly used water treatment processes in Nunavut are filtration, chlorination, and UV treatment.

Filtration

Filtration is a common method for removing particles from water. Nearly all surface water treatment plants in Canada rely on filtration because surface water often contains algae, sediment, clay, and other organic or inorganic matter. Microorganisms that can cause illnesses are also found in surface waters, and combining filtration with disinfection helps improve the safety of drinking water. The GCDWQ provides a baseline recommendation for treating surface water sources to eliminate microbial contaminants. Both filtration and disinfection are recommended. The guidelines also set a minimum treatment standard for bacteria, enteric protozoa, and viruses. Various filtration options are outlined in the Health Canada Guidelines, including “conventional” chemically assisted gravity media filtration (coagulation-flocculation-sedimentation-media filtration), direct filtration (coagulation-flocculation-media filtration), slow sand filtration, microfiltration, ultrafiltration, and nanofiltration. Conventional, direct, and slow sand filtration are granular filtration technologies, while micro-, ultra-, and nanofiltration are membrane technologies. Conventional filtration is the most commonly used system in southern Canada and can be applied to any surface water, especially high turbidity waters (Crittenden et al., 2012). Direct filtration is typically used for low turbidity raw water and includes coagulation, flocculation, and filtration (Crittenden et al., 2012). Slow sand filtration features a biological layer that operates through biological activity on the bed surface (Maiyo, Dasika, & Jafvert, 2023). It is considered the least complex type of granular media filter (Sizirici Yildiz, 2012) and is common in smaller treatment facilities (Haig et al., 2011). Micro-, ultra-, and nanofiltration are pressure-driven membrane systems that remove contaminants such as bacteria, viruses, and suspended solids from the water (Madaeni, 1999).

Disinfection

Disinfection is the process of killing, removing, or inactivating pathogenic microorganisms. There are two objectives of disinfection and two methods. Primary disinfection occurs within the water treatment plant. The goal of primary disinfection is to inactivate microorganisms before water enters the distribution system. Primary disinfectants include chlorine, ozone, chlorine oxide, and ultraviolet (UV) treatment. In Arctic communities, chlorine use is common due to its low price and ease of implementation, and some more advanced systems incorporate UV treatment to inactivate *Cryptosporidium*. In Nunavut, chlorine and UV treatment are the only primary disinfectant technologies used.

Secondary disinfection serves the purpose of maintaining a residual within the distribution system to inhibit microbial growth after primary treatment. This residual reduces the risk of microbial regrowth and protects water from potential contamination after treatment. Chlorine is a common disinfectant used for secondary disinfection; it is recommended that a free residual of 0.2 mg/L is maintained throughout the distribution system to prevent regrowth (Health Canada, 2016).

Chlorine

Chlorine is widely used for primary and secondary disinfection. It can eliminate pathogenic microorganisms, including bacteria, viruses, and parasites (Kerwick et al., 2005). Chlorine kills these organisms by oxidizing the cell membrane, which can destroy or weaken the cell wall, leading to the microorganism's death. The effectiveness of chlorine disinfectant is often described using the CT concept, where C stands for the chlorine residual at the outlet of the chlorine contact reactor and time is the time that the chlorine spends in contact with the target microorganisms.

Several studies in Northern Canada have shown that secondary disinfection free chlorine residual levels are often below regulated concentrations at the tap, risking recontamination (O'Keeffe, 2024; Mahgoub et al., 2025; Gora et al., 2020; Wright et al., 2018; Daley et al., 2018; Martin et al., 2007). In 2018, Daley et al. found that, compared with utilidor water delivery, water trucked to cisterns contained significantly less free chlorine residual. The lack of residual chlorine could result from various factors related to chlorine reactivity, such as depletion by biofilms in cisterns, absence of routine cleaning and disinfection, high water temperatures, and residence time in cisterns and secondary storage containers (Rossman et al., 1994; Niquette et al., 2011).

UV Disinfection

UV water treatment is a physical disinfection treatment process that uses UV light to inactivate microorganisms (Kerwick, Reddy, Holt, & Chamberlain, 2005). The benefits of using UV treatment include inactivating many pathogenic microbes, the absence of chemical additives, no taste or odour issues, and minimal or no effect on DBP formation (Chatterley & Linden, 2010; Guo, Yuan & Yang, 2013; Reckhow et al., 2010). UV disinfection reliably inactivates *Giardia* and *Cryptosporidium* when the required ultraviolet transmission (UVT) is met (Clancy et al., 1998). Viruses are less vulnerable to UV inactivation than bacteria and protozoa, requiring a much higher UV dose to achieve a meaningful degree of inactivation. As a result, it is not considered practical in Nunavut to achieve virus inactivation using UV disinfection (Dillon Consulting, 2023). Additionally, UV absorbance is impacted when water has high turbidity or high levels of dissolved and suspended solids, making UV treatment less effective in achieving 4-log virus inactivation (Lanrewaju et al., 2022). UV treatment is not widespread in Nunavut, and currently, many communities still lack protection from *Giardia* and *Cryptosporidium* (Dillon Consulting, 2023).

2.4 Water Governance in Canada

Canada's governance is characterized as decentralized, and water quality responsibilities require multilevel governance and collaboration (Hurlbert, 2009). There are numerous water organizations at the federal, provincial, territorial, and municipal levels, which can create interagency coordination challenges. Key stakeholders include federal, provincial, and territorial government departments; municipal and local governments; First Nations band councils; non-governmental organizations; and the public.

Canada still lacks a unified policy to address water safety hazards and issues (de Loe, 2010). Nor is there a standardized approach to collecting drinking water quality data (Christensen, Goucher, & Phare, 2010). The federal government is responsible for water quality and quantity on federal land and other areas of federal jurisdiction, such as First Nation lands (ECCC, 2024). Provincial and territorial governments have been granted the power through the Constitution Act of 1867 to manage natural resources within their boundaries (as of 2025, through devolution, the Territory of Nunavut also holds this power). Furthermore, management is delegated to municipalities by provincial and territorial governments to enact by-laws affecting water resources. This decentralized multi-level governance system can pose challenges, and with limited information sharing, it can generate governance gaps and overlaps (Bakker & Cook, 2011; Dunn, Bakker, & Harris, 2014).

In Canada, Indigenous Peoples have often been denied a voice in source water protection (Ivey et al, 2006) and water resource planning (Irvine et al, 2020), which are vital parts of water governance and management. In Ontario, multi-stakeholder committees develop and oversee source water protection plans, safeguarding nearly 450 municipal drinking water systems (OMOE, 2019). Indigenous representatives are often not meaningfully involved as partners or decision-makers in these committees, and Indigenous Knowledge is undervalued or excluded throughout planning processes, despite jurisdictional and historical contexts (Collins et al, 2022). Multiple studies have shown that strained relationships between their communities and different levels of government affect their ability to engage in formal conversations about local water security and stewardship (Black & McBean, 2016; Lucier, et al., 2022). Building relationships and enhancing social capital and knowledge sharing among stakeholders has been found to be very beneficial (Lucier, et al., 2022), leading to better technical and financial solutions. Indigenous Knowledge remains underutilized in formal water resource planning, highlighting a gap in current water governance in Canada that hinders the development of more sustainable water management practices.

In 2016, the Minister of Indigenous and Northern Affairs announced full support for the United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP) (Government of Canada, 2016). The United Nations adopted UNDRIP in 2007 to reaffirm the continued recognition of Indigenous Peoples' cultures and ways of life. The declaration outlines specific minimum standards for the well-being of Indigenous Peoples, including the right to self-determination and self-government, the right to participate in decision-making processes, and the right to conserve and protect their lands and waters without discrimination (UN General Assembly, 2007). In 2022, the Government of Canada's budget plan proposed to allocate $65.8 million over the next five years and $11 million ongoing to Justice Canada and Natural Resources Canada to accelerate efforts to meet legislated requirements, including the co-development of an action plan with Indigenous partners. Additionally, the budget proposed $9.5 million over five years for the Department of National Defence to align its operations and engagement with Indigenous Peoples with the Act. This is part of the United Nations Declaration on the Rights of Indigenous Peoples Act Action Plan (Department of Justice, 2023), which details priorities for First Nations, Inuit, and Métis from 2023 to 2028. The plan emphasises collaboration and aims to further advance reconciliation across federal law and policy (Department of Justice Canada, 2023).

2.5 Overall Governance in Nunavut

Much of Northern Canada is part of Inuit Nunangat, which covers about 40% of Canada's landmass and includes 51 communities across four regions: Inuvialuit (Northwest Territories), Nunavik (Quebec), Nunatsiavut (Labrador), and Nunavut. In 1999, Nunavut became Canada's newest territory following the 1993 Nunavut Act and the Nunavut Land Claims Agreement (NLCA). The territory, which has 25 communities, has an 85% Inuit population (Statistics Canada, 2023). The NLCA provides a framework for managing land, wildlife, marine areas, and mineral resources. It designates "Designated Inuit Organizations," which represent the interests of all Inuit, including Regional Inuit Organizations such as the Qikiqtani Inuit Association (QIA) (QIA, 2025), Kivalliq Inuit Association (KIA), and Kitikmeot Inuit Association (KitIA) (KitIA, 2025) (Le Teno & Frison, 2021). Among all Inuit organizations, Nunavut Tunngavik Incorporated (NTI) plays the most important role. NTI oversees NLCA implementation, helps develop cultural and social programs, and manages the Inuit compensation fund, with support from regional Inuit organizations such as QIA. Several organizations created under the agreement work to protect Inuit rights and facilitate co-management with the government over land, water, and wildlife decisions. Additionally, Inuit Qaujimajatuqangit (IQ) is integrated into policy and acknowledges certain Inuit land rights (Levesque, 2014). IQ is seen as an ethical framework for living well and a way of thinking that connects all parts of life (Karetak, Tester, & Tagalik, 2017). Unlike "Western science," which tends to focus on particular variables though experimentation, IQ is considered a holistic approach to thinking and living, linking social, environmental and spiritual elements (Nowosad et al, 2025). In governance, IQ is incorporated throughout. For example, NTI and the various boards are involved in decisions related to cultural issues and Inuit livelihoods, including water and natural resources.

In 2024, the Government of Canada, Government of Nunavut, and Nunavut Tunngavik Incorporated signed the Nunavut Lands and Resources Devolution Agreement. This marked the beginning of the transfer of greater authority over Crown lands, resource management, and water-related decision making to Nunavummiut. Regarding resource management and water sources, there are six co-managed institutions (Nunavut Wildlife Management Board, Nunavut Impact Review Board, Nunavut Planning Commission, Nunavut Water Board, Surface Rights Tribunal, and Nunavut Marine Council), all of which have advisory roles to governments. Nunavut is a multi-level system of governance that involves multiple actors with different mandates, located at various levels, including Inuit (Alcantara & Nelles, 2014).

Within Nunavut municipalities, there are two key leadership roles in the governance structure. First, the mayor is an elected official chosen by the community. As mayor, they serve on the municipal council, represent residents politically, set local priorities and policies, and make final decisions on the budget, bylaws, and community direction. By contrast, the Senior Administrative Officer (SAO) is hired by the mayor to run day-to-day operations, manage the municipal staff, and implement the decisions made by the mayor and council (Iqaluit News, 2025).

2.6 Water Governance in Nunavut

The water governance structure in Nunavut is intricate, involving stakeholders across federal, territorial, and municipal levels, as well as Inuit organizations and arms-length government agencies (e.g., public housing, Nunavut Water Board), alongside engineers, operators, and users who directly interact with water infrastructure (Figure 2-1). (Government of Nunavut, 2023). The Government of Nunavut is responsible for initiating, financing, and overseeing planning studies that identify problems, objectives, scope, procedures, methodology, and the study (Chalmers, Duncan & Gora, 2024). It also bears ultimate responsibility for selecting and installing water treatment systems. In eight communities, the Department of Transport and Infrastructure Nunavut (GN-TIN) owns and operates the systems. In the remaining communities, ownership of the infrastructure is transferred to the municipality after commissioning. Operational funding for all communities is mainly provided by the GN Department of Community Services (GN-CS).

Figure 2-1: Organizational chart of stakeholders that contribute to safe drinking water in Nunavut (adapted from the Government of Nunavut Drinking Water Strategic Framework, 2023).

Nunavut's drinking water quality is currently governed by the *Public Water Supply Regulations* (PWSR) (1990*),* which do not fully align with the standards outlined in the GCDWQ (Health Canada, 2022). Additionally, Nunavut has not yet fully adopted the Multi-barrier approach to safe drinking water, especially regarding source water protection and water treatment. Under the 1990 regulations, only chlorine disinfection was required, with a minimum free chlorine residual of 0.2 mg/L after 20 minutes of contact time. In 2015, design documentation indicated an intent to meet the GCDWQ standards, and since then, the territory has made efforts to improve drinking water quality through upgrades to water treatment infrastructure.

Water infrastructure in Nunavut includes treatment facilities and distribution systems, such as truck-to-cistern and utilidor/water mains. Across Nunavut's 24 municipalities and the capital city, Iqaluit, water treatment systems vary significantly, from basic pumphouses with chlorine injection at truck fill points to various filtration methods and UV disinfection systems. Recently, more advanced systems have been introduced, including membrane treatment with full automation (as in the Municipality of Whale Cove). This diversity of systems can make it challenging to manage them and ensure regulatory compliance. Most Nunavut municipalities rely on truck-to-cistern distribution, with few national guidelines in place. Globally, there is limited evidence supporting the use of risk management frameworks to optimize trucked water supply (Lane & Kumpel, 2023).

Collecting baseline data has traditionally been a lower priority in Nunavut, resulting in limited understanding of source water quality, treatment effectiveness, and how climate change affects water supplies (Bakaic and Medeiros, 2017). In general, baseline data for drinking water systems include not only water quality and quantity data but also information on the physical state of the systems, serving as indicators of management, operations, and the effectiveness of oversight and regulation (Van Derslice, 2011). From a public health perspective, data on the occurrence of waterborne and water-washed diseases are very limited because such cases are not usually reported or monitored (Hennessy and Bressler, 2016). However, to meet the GCDWQ, community water quality monitoring has increased to quarterly sampling to support the design of new water treatment infrastructure.

In March 2023, the Government of Nunavut, Department of Community and Government Services (now GN-TIN), published their drinking water strategic framework (Government of Nunavut, 2023). This framework sets out six overarching goals (Table 2-1) aimed at achieving the vision "*to have healthy Nunavummiut with a low incidence of water-related disease through a sufficient supply of safe drinking water now and into the future"* (Government of Nunavut, 2023). The framework includes activities to enhance their multi-barrier approach to safe drinking water, standardize water treatment across the territory, and improve oversight of cistern hygiene. In addition, the Government of Nunavut has developed a risk prioritization tool to collect data on the physical condition of infrastructure for funding purposes.

Table 2-1: Goals of Drinking Water Strategic Framework (Government of Nunavut, 2023)

Goal 1	To strengthen the organizational capacity to deliver drinking water programs
Goal 2	To ensure adequate and up to date physical infrastructure for the delivery of drinking water programs
Goal 3	To develop a sufficient and skilled workforce
Goal 4	To institute information management systems for drinking water
Goal 5	To implement effective operations and maintenance of all drinking water systems
Goal 6	To increase public involvement, awareness, and education about drinking water

2.7 Water Safety Planning

Regulatory interventions like those currently embraced in Canada, including in Nunavut, primarily focus on the technical aspects of drinking water and often overlook other factors (Kot, Castleden & Gagnon, 2015). To address these gaps and promote a preventative approach, the WHO developed water safety planning (WSP) guidelines. For small, decentralized communities, WSPs were comprehensive given limited capacity, leading to the creation of a dedicated WSP for small communities to adopt, ensuring a consistent and safe water supply (WHO, 2012).

There are six stages to WSP that move away from the traditional "end of pipe" water quality requirements (WHO, 2012): 1. Engage the community and assemble a WSP team; 2. Describe the community water supply; 3. Conduct a comprehensive assessment of present and potential risks by identifying and evaluating hazards, hazardous events, risks, and existing control measures throughout a water supply from the water source to residential taps; 4. Develop and implement a plan that reduces identified risks to an acceptable level; 5. Monitor measures and verify the WSP; and 6. Document, review, and improve WSP implementation (WHO, 2012) (Figure 2-2). This has been updated into ten modules in the new iteration published in 2023 (WHO, 2023).

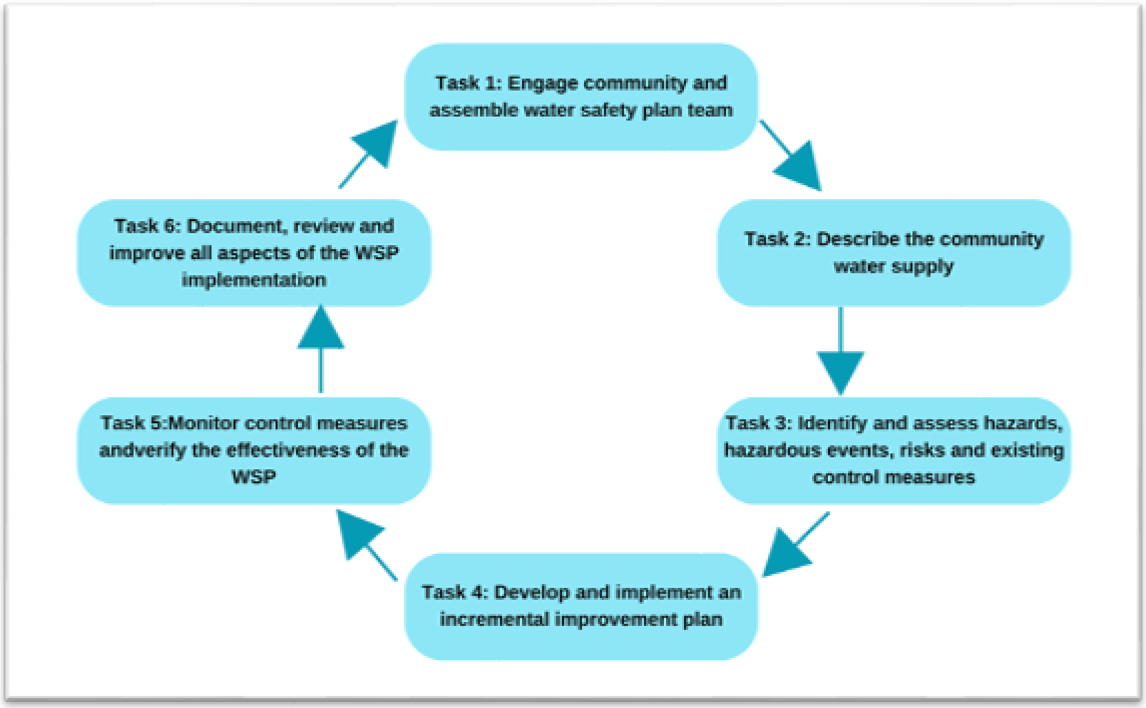

Figure 2-2: Water Safety Planning process as presented in WSP for small communities. Adapted from (WHO, 2023).

WSP has been adopted in over 40 countries since the framework was first released (WHO, 2017) over 20 years ago. However, in Canada, adoption has been limited at the provincial and regional levels (Lane, Fuller, Dyment & Gagnon, 2022; Chalmers, Duncan & Gora, 2024). Alberta is the only province to have successfully implemented WSP through regulation (AESRD, 2013). However, although not formally adopted, in Ontario, a risk based approach has been adopted that aligns with WSP. Under the *Drinking Water Quality Management Standard* and *Safe Drinking Water Act, 2002*, the focus on proactive hazard identification and risk management is similar to the WHO framework (Fuller et al, 2023). WSPs have also been explored for water safety management in predominantly Indigenous communities in Canada. Lane et al. examined the possibility of applying the WSP framework in Nunavut (Lane, Stoddart & Gagnon, 2018) and Hasan et al. and Lane et al. examined interest in WSP use among First Nations communities (Hasan, Hicking & David, 2011; Lane, Fuller, Dyment & Gagnon, 2022).

WSP is a bottom-up management approach that focuses on operational competency and capacity. It has been developed to improve the overall approach to compliance in endpoint testing (Gunnarsdottir et al, 2012). Canadian and United Nations experts have emphasized the importance of building water safety in First Nation communities from the ground up through meaningful community engagement and co-development (Swain, Louttit & Hrudey, 2006; McGregor, 2012; Anaya, 2013). However, to date, this approach has not been formally adopted in Nunavut outside of academic research studies (Lane, Fuller, Dyment & Gagnon, 2022; Lane, Stoddart & Gagnon, 2018; Chalmers, Duncan & Gora, 2024), partly because the WSP framework does not account for the complex socio-economic and political structures that small communities in Nunavut must navigate.

Step 3 in a WSP is to identify hazards and assess risk using a risk matrix approach (Bartram, et al, 2009). Risks are calculated by multiplying a likelihood score by a consequence or severity score (Figure 2-3) (Bartram et al, 2009; WHO, 2012; WHO, 2016; WHO 2023).

System readiness		Consequence				
		1	2	3	4	5
	1	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Figure 2-3: Risk matrix developed for Nunavut WSP framework (Chalmers, Duncan, & Gora, 2024).

This approach was used by Lane et al. to co-develop a risk assessment web application with First Nation stakeholders from six communities to build capacity within Atlantic First Nation communities. This application identified not only risks to individual systems but also risks common across the participating communities. Although increased communication and data ownership were significant benefits, the fragmented governance structure in Canada means that adopting proactive strategies in First Nation communities requires co-developing risk assessments across all levels of governance (Lane, Fuller &

Gagnon, 2022). Lane et al. (2022) examined the current opportunities and barriers faced by operators in Canada's Atlantic region and found that risk assessment was seen as ‘strictly diagnostic’ and that operators were unlikely to incorporate it into operational practice unless mandated by regulation. Their findings indicated that, to adopt a risk-based approach, operators' understanding of risk, along with effective communication and a dedication to improvement (Lane, Fuller & Gagnon, 2022).

Although risk matrices have generally performed well in situations where data are limited or unavailable, as described above, Lane and Gagnon (2022) point out limitations in the accuracy of probability and impact estimates (Lane & Gagnon, 2022). Their study examines the suitability of the risk matrix method for capturing risk levels associated with system-specific hazardous events. It shows that larger datasets, combined with simpler approaches, may better align with WSP results (Lane & Gagnon, 2022). Most risk matrices used in other jurisdictions rely either on a past frequency score or a system readiness score under the ‘likelihood’ of an event. However, Cox found that many WSP risk matrices developed for these jurisdictions were ambiguous regarding their inputs and outputs, and their scoring definitions were often poorly defined (Cox, 2008). Lane and Hrudey further studied the design of risk matrices and proposed possible improvements Lane & Hrudey, 2023). Building on this, Chalmers et al. developed a new risk scoring approach specifically for Nunavut (Chalmers, Duncan & Gora, 2024).

Risk assessments within the WSP framework rarely includes social and cultural factors that can influence hazards and risks to a system. Typically, interventions aimed at reducing risks in drinking water focus on technology and infrastructure, such as water treatment methods and stricter water quality regulations (Sobsey, 2006). Unfortunately, these measures often overlook the human element involved in ensuring water safety.

2.8 Participatory System Dynamics

Systems dynamics modelling (SD modelling) is a powerful tool for simulating complex, nonlinear, and uncertain water resources problems (Nozari, Moradi & Godarzi, 2021; Chen & Wei, 2014). SD modelling has been applied to a wide range of sectors, such as health policy, project management and economic systems and water. Zarghami et al., reviewed research that adopted the framework for water supply and distribution networks framework (Zarghami, Gunawan & Schultmann, 2018). SD offers many assets in helping to understand the dynamic behaviour of complex systems (Sterman, 2000) and testing assumptions about how different actions and policies will contribute to sustainable solutions (Forrester, 1994; Sterman, 2000).

Social relationships and processes (such as cooperation and conflict) often drive behaviour related to drinking water and sanitation, but this knowledge remains on the periphery of decision-making that affects drinking water delivery. Research over the past decade has demonstrated that interventions that neglect social and political contexts are unlikely to succeed (Black & McBean, 2016; Black & McBean, 2017abcd; McGregor, 2012).

Participatory system dynamics (PSD), also known as community-based system dynamics (CBSD), is a modelling method that combines the principles of system dynamics modelling with participatory decision-making. PSD encourages stakeholder engagement and combines research and knowledge to solve complex problems through multidisciplinary collaboration (Rieder, Larson, Sas-Rolfes & Kopainsky, 2021). PSD provides a structured and collaborative approach to understanding and managing complex systems like drinking water treatment. It promotes transparency, inclusiveness (Stave; Rouwette, Bleijenbergh & Vennix, 2016), and collective learning (Sedlacko et al, 2014), empowering stakeholders to actively contribute to problem-solving (Vennix, 1999) and decision-making processes. Additionally, PSD can enhance social learning and community development (Stave, 2010; Davies et al, 2015). Interventions to water safety often occur after a problem arises (e.g., treatment failure, poor quality of source water) without addressing the root cause of problems, such as inequitable social relationships and processes (Kot, Castleden & Gagnon, 2015). The relationship between water services and objectives such as health, environmental protection, socio-economic development, fire protection, convenience and aesthetics, and equity are complex. This has been seen in Southern Canada, where an increasing influx of financial and human capital was required prior to implementing the First Nations National Water Strategy (Government of Canada, 2022). Considering the perceptions and knowledge of the users and the decision-makers is important in achieving objectives, selecting alternatives, and designing systems. PSD can promote the devolution of resources, responsibility, and authority to the community level.

As recognition of water challenges grow, the key ingredients for change are already present; however, leveraging them requires a shift toward systems-level thinking and adaptation (Rieder, Larson, Sas-Rolfes & Kopainsky, 2021). Phan et al. showed that out of 169 articles related to SD and water resources only 18 were related to water quality and none identified risk management (Phan, Bertone & Stewart, 2021). These articles range from the bioavailability of metals in wetlands (Wood & Shelly, 1999) to degraded water quality following sudden pollution events (Zhang et al, 2011) to antibiotic pollution in the Volga River (Sverdrup, Frolova & Sverdrup, 2020).

Systems dynamics modelling was originally developed for business and industrial use (Sterman, 2000; Forrester, 1994). There are four key steps in developing a model: 1) problem identification and system conceptualization; 2) model formulation and analysis; 3) model validation; and 4) policy analysis and implementation (Forrester, 1994). Mathematically, SD models are systems of coupled, nonlinear, first-order differential equations solved numerically. SD is a useful modelling approach for guiding complex systems modelling when data is limited, as it still allows response simulations (Sterman, 2000). It involves illustrating a problem with a diagram that displays variables (e.g. stocks and flows), relationships (e.g. causal links), time delays, and feedback loops, auxiliary variables, parameters, constants, and causal links between variables (Forrester, 1994). The model helps users understand complex causal factors thought to influence system behaviour and to simulate and evaluate how external interventions at various points might change the system's development (Meadows, 2008).

Variables

Variables are elements that represent the factors within a system and describe how it changes over time (Meadows, 2008). There are various variables in a system dynamics model that interact through relationships and feedback loops. These variables include stocks, flows, auxiliaries, and constants. For example, in Table 2-2, the stock variable is the water stored in a reservoir. The water in the reservoir can be increased by rain (inflow) and decreased by evaporation (outflow). Additionally, an auxiliary variable can influence the outflow due to daily water demand, and a constant variable provides a maximum boundary representing the reservoir's capacity.

Table 2-2: Example of different types of variables within a system dynamics stock and flow model.

Stock	Water stored in a reservoir
Flow	Rain (inflow), Evaporation (outflow)
Auxiliary	Daily water demand
Constant	Reservoir maximum capacity

Feedback Loops

Feedback loops occur when there are two or more causal links between connected variables (Figure 1-4). Therefore, a connection starting at any variable in the loop, when traced back along the causal chain, will eventually return the original starting variable (Pruyt, 2013).

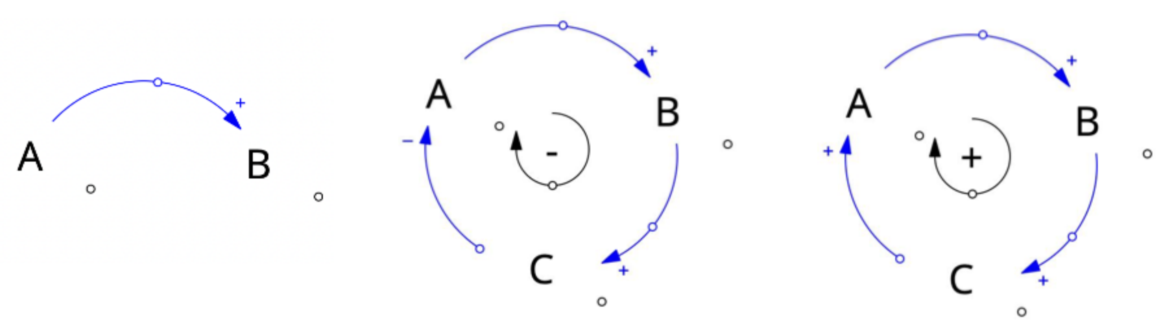

Figure 2-4: Example of causal links (left), a negative feedback loop (middle), and a positive feedback loop (right).

There are two types of feedback loops: positive (reinforcing) and negative (balancing). In a positive loop, an increase in A will lead to a further increase in A over time, or a decrease in A will lead to a further decrease in A. These loops are known to produce exponential growth behaviour, which can be either beneficial or harmful. In negative loops, instead of A increasing after an increase, A will decrease after some time, and vice versa — if there is an initial decrease in A, then A will increase after a period of time. These balancing loops help maintain stability or resist change (Pruyt, 2013; Forrester, 1994). For example, Figure 2-5 shows a reinforcing loop on the left and a balancing loop on the right. Both are drawn from a study by Daniel et al. 2021 that explored a system dynamics approach to assess influencing sustainability factors to a community based rural drinking water supply program in Mageland Regency, Indonesia. The reinforcing loop shows that accidental and deliberate damage influence pipe network functionality. Accidental damage includes damage caused by flooding, landslides, animals, or theft. Meanwhile, the balancing loop shows that an increase in the pipe network will increase the number of beneficiaries and thus decrease the number of beneficiaries without access to the piped network.

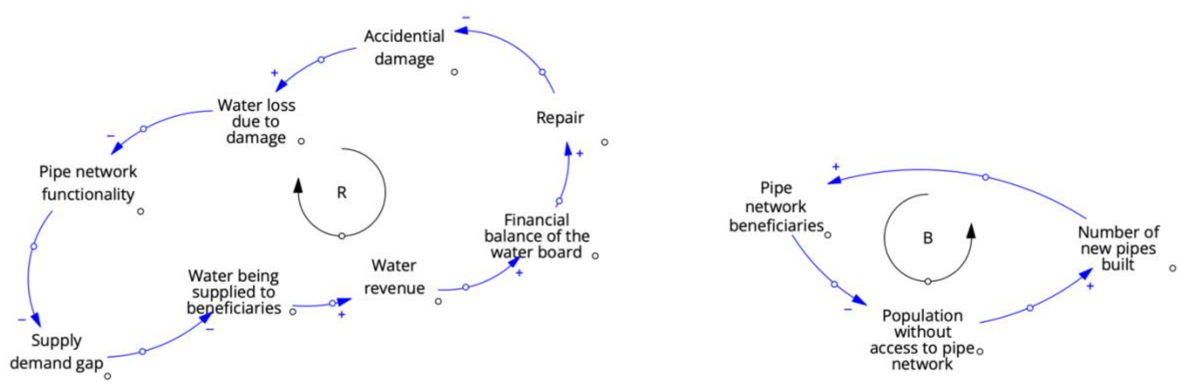

Figure 2-5: Causal loop diagrams of sub-model feedback mechanisms, with a reinforcing loop on the left and a balancing loop on the right. Adapted from (Daniel et al, 2021)

Stock and Flow

A stock variable accumulates over time. Stocks start at an initial value, and during a simulation run, they can only be increased or decreased by flow variables, specifically inflow and outflow variables (Meadows, 2008). They are ultimately defined by the initial value assigned to them and the flows that feed into them (Figure 2-6). Mathematically, stocks are integral equations:

$x = x_0 + \int_{t0}^{t}(+ax - bx)\,dt$ Equation 1

Where:

χ = the stock variable and is equal to the amount in stock χ_0 at t_0, plus the integral over the difference of the inflow $a\chi$ and outflow $b\chi$ over the time interval considered.

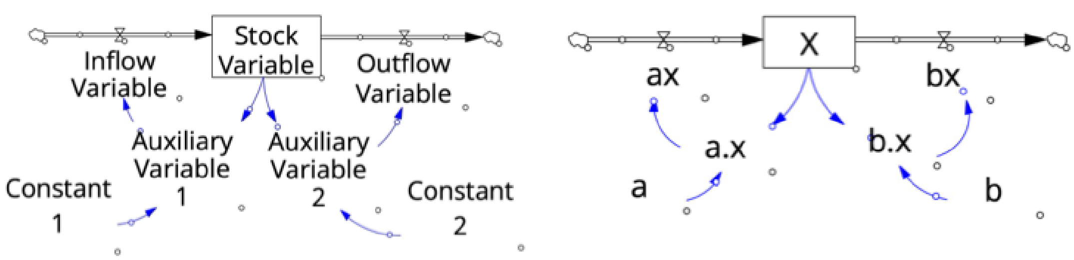

Figure 2-6: Example of a simple stock and flow model demonstrating the integral equation used in the stock variable. Adapted from (Pruyt, 2013)

Flows are variables that enter or leave a stock and can influence its accumulation over time. The sum of all flows connected to a stock indicates its rate of change over the simulation period (Meadows, 2008). Various equations can be used to represent flow variables. For example, the flow equation below is proportional to the size of the corresponding stock. In this equation, the stock multiplied by the variable determines the rate of growth, while the constant acts as a time parameter that scales over time.

$flow = \frac{stock\ x\ variable}{constant}$ Equation 2

This equation is used in Daniel et al. (2021). Where the flow of *Population growth* is an inflow to the Village Population (Figure 2-7). The equation for the stock and flow submodel is as follows.

$$Population\ growth = \frac{Village\ population\ (Persons) x\ Population\ growth\ rate(Dmnl*)}{Growth\ period\ (Month)} \quad \text{Equation 3}$$

*Dmnl - Dimensionless

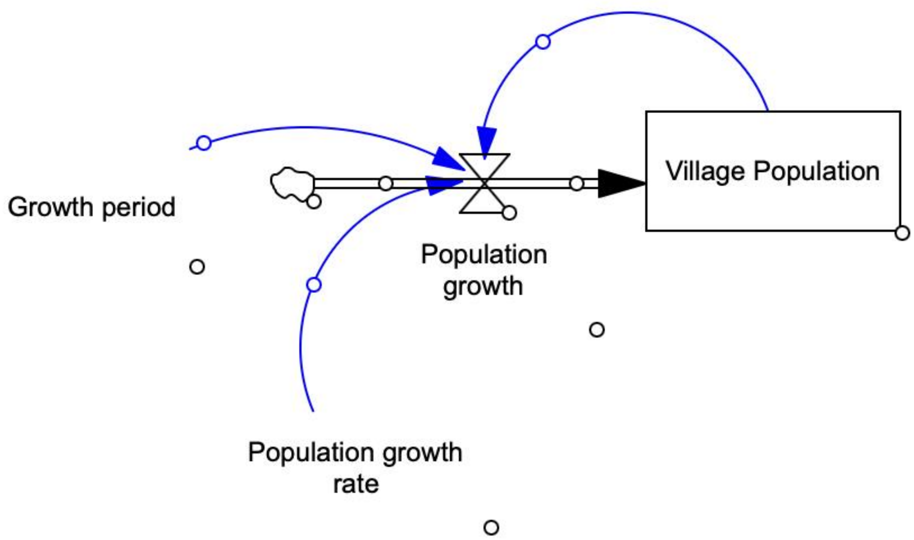

Figure 2-7: Stock and model of village population growth adapted from (Daniel et al 2021).

Another example of a stock and flow diagram is shown in Figure 2-8. A study assessing the cholera epidemic response in Al Hudaydah, Yemen, displays two stocks (Susceptible Population and Population with Clean Water) and two flows (Receiving clean water and Stop receiving clean water) (Loo, Aguiar & Kopainsky, 2023). The flows act as both inflows and outflows for the two stocks. If we consider the population susceptible to cholera, this stock decreases as more individuals receive clean water, which in turn increases the stock of population with clean water. Conversely, if individuals stop receiving clean water, the population with clean water decreases, and the population susceptible to cholera increases. This demonstrates how flows can cause stocks to accumulate or deplete over time.

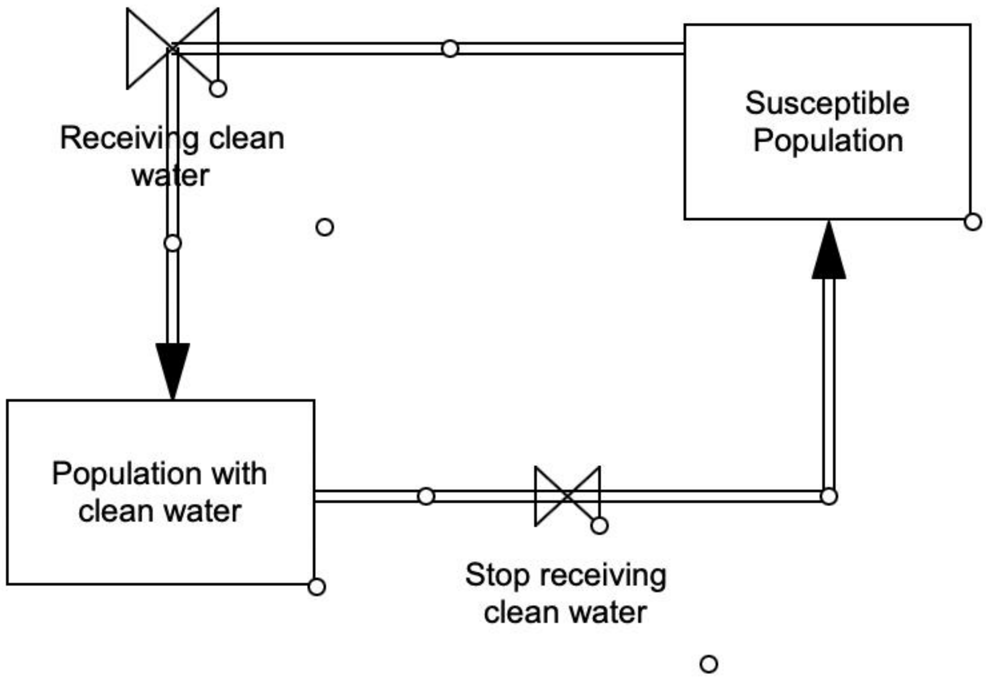

Figure 2-8:Stock and flow diagram showing clean water provision intervention. Adapted from (Loo, Aguiar & Kopainsky, 2023)

Auxiliaries

Auxiliaries are variables that can closely match real-world system elements, helping the model remain interpretable, mainly by keeping flow equations simple and clear. Sometimes, equations involving auxiliary variables need special functions (Pruyt, 2013). In Daniel et al. (2021), several types of auxiliary variables are used to assess the sustainability of a community-based drinking water program. These include exogenous inputs, such as External Contributions to the stock Water Finance Board; endogenous variables, such as Community Development and Percentage of Beneficiaries that Pay; and constants, such as Community Characteristics (Figure 2-9).

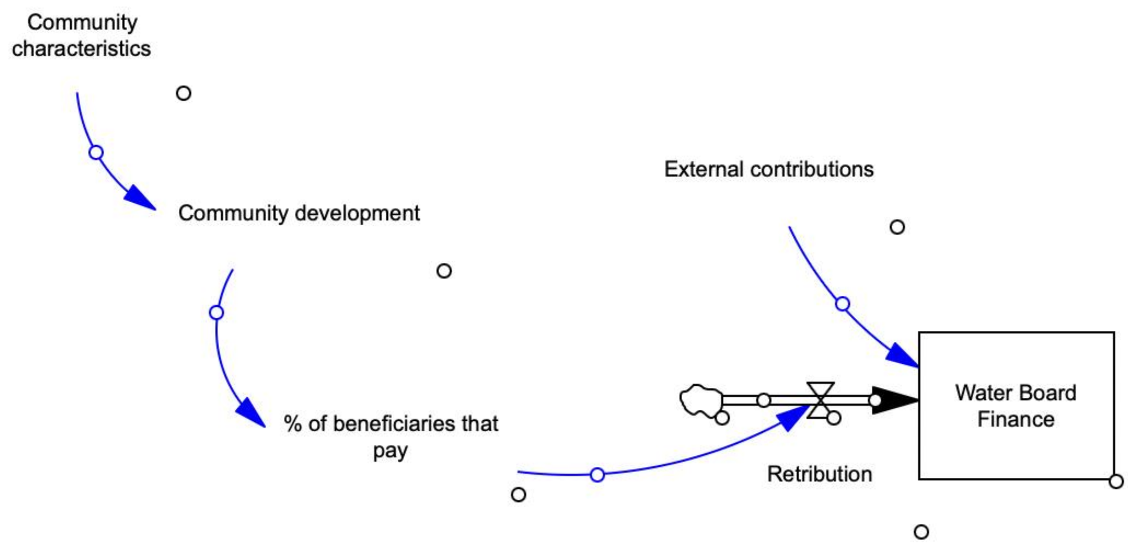

Figure 2-9: Subsection of stock and flow diagram adapted from (Daniel et al 2021).

Parameters and Constants

Although there are few constants in real life, there are variables that can be assumed constant during a simulation run (Meadows 2008). For example, there might be conversion factors, reference values (such as trucks' total water-holding capacity), adjustment times, and so on. These variables are incorporated into a model using exogenous parameters, provided they are not affected by other model variables. The values of constants can originate from actual data and/or knowledge of a system (Meadows, 2008). However, they are often assumptions and can be inaccurate, necessitating a sensitivity analysis to reduce inaccuracy (Forrester, 1994).

Functions

Functions help account for the nonlinearity of relationships in real life by representing the complex, non-proportional relationships between variables (Mohapatra, 1980). Examples of functions that can be used in stock and flow model equations are provided below.

Max () Min () – this function provides a constraint on variables to a meaningful range, ensuring the simulation remains realistic and logically consistent (Poznyak et al, 2023), i.e., 0 – 1. Within drinking water systems, many variables are bounded by physical and institutional limits. For example, you cannot have a negative water supply. Additionally, the boundary for the risk and effectiveness indices is 0 to 1. The functions Max() and Min() enforce this boundary.

WITH LOOKUP () – Specifies a nonlinear relationship between the input x and the output by passing the input through a series of x,y pairs documented as numbers. The function supports data integration with judgment, such as regulatory thresholds and response curves. For example a regulation limit for THMs is 0.1 mg/L. below the threshold the water is considered safe, however when the limit is exceeded the regulatory concern increases rapidly.

IF THEN ELSE () – Similar to the real world, certain responses only occur once a threshold has been crossed. This function supports conditional behaviour within the model. For example, repairs to water infrastructure would be triggered by damage to that infrastructure.

SMOOTH () – The "smooth" function provides a delay (e.g., in water quality monitoring, there is a delay between when the sample is taken and when the result is received). This is used to handle irregular data, such as water quality data.

EXPONENT () – This function represents tipping points or exponential decay or growth and allows the model to have a concave response. E.g. increased level of pollution in the water due to a fuel spill.

Data Collection for PSD

PSD models can integrate multiple types of data, including numeric data (e.g. water quality data, design parameters), semi-quantitative data (e.g. ranked hazards), and qualitative data (e.g. truck operators sharing reasons for not delivering, such as no access from heavy snow on steps to intake). One of the major strengths of PSD is its ability to incorporate stakeholder input. Stakeholder input is usually through methods such as workshops, interviews, and group discussions (Vennix, 1999; Stave, 2010; Walters & Javernick-Will, 2015; Valcourt et al, 2020). A starting point is problem identification, and during these workshops, stakeholders contribute to identifying key variables (hazards and risk drivers to the water system) and causal relationships through tools such as polarity matrices.

The problem this model was attempting to solve was what factors can improve water safety in Cambridge Bay. This determined that water safety was a stock and could accumulate over time. Using WSP, the multi-barrier approach to safe drinking water, current hazards identified in the community, and information collected from stakeholder workshops, risk drivers can be interpreted into quantifiable variables that influence water safety. For example, various forms of contamination can enter the water system. This would be considered an outflow of the Water Safety Level stock. Treatment plants provide a barrier to reduce contamination as long as they are effective, which would be an inflow.

Sensitivity Analysis

Sensitivity analysis in SD models can serve several purposes: identifying errors in the model; gaining insights into the connections within the model structure; testing robustness; and pinpointing highly sensitive policy levers (Pennell 1997; Tank-Nielsen 1980). Within the Vensim program, a multivariate sensitivity simulation, also known as Monte Carlo sampling, can be conducted, which performs hundreds of simulations with constants sampled over a range of values, usually 10% (Fiddamen, 2022). However, manual adjustments to parameters one at a time are necessary for visualizations. Model testing is crucial as it can offer vital insights into where small changes in the model may lead to significant shifts in behaviour (Pruyt, 2013).

2.9 Research Gaps

This in-depth review of water safety management in Nunavut and water safety management frameworks, specifically water safety planning, water safety matrices, and participatory system dynamics, identified a series of key knowledge gaps. These include a lack of baseline technical and scientific data in Arctic communities, limited previous research on the application of formal water safety management frameworks and modelling approaches in Arctic communities, and poor integration of Indigenous Knowledge and stakeholder perspectives in drinking water safety management in Arctic communities.

Research Gap 1: Drinking water quality and operational data

Research on drinking water in Nunavut has historically been limited due to the remoteness, high costs, and capacity challenges faced by many communities. A few studies have explored the use of water safety plans in the territory (Chalmers, Duncan, & Gora, 2024; Lane, Stoddart, & Gagnon, 2018). However, most research on the microbial and chemical characteristics of drinking water in Nunavut has been conducted in the Qikiqtani Region (Daley, et al, 2018; Gora, et al., 2020) and in two communities in the Kivalliq Region (Daley, et al., 2018; Daley, Castleden, Jamieson, Furgal, & Ell, 2015). To date, there has been no research on drinking water in the Kitikmeot Region, other than an overview of source water for the territory (Elliott, et al., 2022). The Kitikmeot Region is located in the western part of the territory and has unique geographical, cultural, and linguistic characteristics relative to the rest of Nunavut.

Research Gap 2: Water safety management frameworks

Water safety planning has been explored to a limited extent in Arctic regions. Lane, Stoddart & Gagnon (2018) examined the framework's application in Nunavut, and Chalmers, Duncan & Gora (2025) developed a novel risk matrix which was employed on realistic scenarios through research and authors' experiences. However, water safety planning risk matrices have not been applied to real life scenarios using community water quality data and lived experiences.

Participatory system dynamics has not been applied to drinking water management in an Arctic setting, however, there have been a couple studies that have used similar methods to develop causal loop diagrams in developing countries (Walters et al, 2015; Valcourt et al, 2020). Furthermore, there has been no stock and flow simulation model developed using participatory system dynamics methods to drinking water management, however models have been applied to rural drinking water systems using global data systems to develop the structures for modelling purposes (Daniels et al, 2020; Cannon et al, 2018). Participatory system dynamics methods have not previously been employed in a truck to cistern system in remote community settings in Canada.

Research Gap 3: Effective collection and integration of stakeholder input into water safety management

Community and stakeholder engagement is a common goal for Indigenous Peoples in Canada and has been highlighted in the Truth and Reconciliation Report as a way to create positive impacts by addressing challenges through community empowerment, collaboration, partnerships, and policy and funding changes (Trust and Reconciliation, 2015). Additionally, the UN has emphasized the importance of working with Indigenous communities to tackle issues such as water safety. However, in practice, engagement activities can be costly and logistically difficult, especially in remote communities like Nunavut, where building relationships with various stakeholders and engaging meaningfully require significant effort. It is particularly challenging to collect and incorporate stakeholder input in formats suitable for risk analysis and risk modelling, as it demands substantial time and organization to conduct activities in person, due to limited internet connectivity and a preference for face-to-face engagement. This is especially challenging in predominantly Indigenous communities, where community stakeholders have historically been excluded, and Indigenous and local knowledge have been underused in developing more sustainable water management practices (Black & McBean, 2017d; McGregor D., 2012; Lucier, et al., 2022; Christensen, Goucher, & Phare, 2010). Daley et al. (2018) gathered input on water scarcity in Coral Harbour; however, aside from this, no other formal data has been collected from stakeholders in Nunavut regarding water safety.

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3. General Methodology

3.1 Ethics and Nunavut Research License

This research was conducted under Ethics Certificate: 2024–004 from the York University Ethics Review Board and Nunavut Research License: 04 001 24N-A. Informed consent was obtained from all participants involved in the research. Copies of the research licenses and consent forms provided to participants are provided in Appendices A and B.

3.2 Community Profile

Cambridge Bay is located on Victoria Island, Nunavut, and is the administrative hub for the Kitikmeot region (Figure 3-1). With a population of 1,760 in 2021, predominantly Inuit residents (1,400 individuals), Cambridge Bay is the largest community in the Kitikmeot region (Statistics Canada, Accessed February 4, 2026). Cambridge Bay was recommended as a promising study site by several individuals within the Government of Nunavut's Department of Community and Government Services (now the Department of Community Services and GN-TIN) because of its capacity to participate in the study, the availability of the Polar Knowledge Canada facility and the Canadian High Arctic Research Station (CHARS), and the uniqueness of its dual drinking water distribution system. The research project took place in the community in 2024.

Figure 3-1: Map of Nunavut. (Geology.com accessed 13 April, 2026)

During the study period (2025), CBC reported that the community had a population of approximately 2,000 (CBC, 2025) and during the initial site visit the lead author determined that the community owned four water trucks. However, during the study period, only three water trucks were in operation. Most of the buildings in Cambridge Bay are owned by the Nunavut Housing Corporation and are managed by Nunavut Housing Association. There were approximately 570 residential buildings with an average household size of 3.1 people (Statistics Canada, 2021). However, there were 120 buildings with 5 or more people residing (Statistics Canada, 2021). The lead author determined that during the study period there was approximately 25 institutional buildings, only six of which are connected to the utilidor line.

The community's water system was initially built in 1980 as an intake pumphouse and has since been upgraded several times, with the latest upgrade occurring in 2017. The water treatment plant was designed with a coagulation system (ferric chloride), pressure media filters, UV, chlorine injection and a treated water storage tank to provide contact time. Pressure media filters are not an approved filtration method by the GCDWQ. The coagulation system was taken offline shortly after commissioning due to severe corrosion and has not been used since. Although considered one of the more sophisticated treatment plants in the territory (prior to current upgrades in other communities, such as Whale Cove), the facility does not meet GCDWQ's basic requirements for surface water treatment. Drinking water is distributed via truck or utilidor to the community. There are several institutional buildings that receive water through the utilidor, such as CHARS and the schools. The remaining buildings receive water via trucked distribution. This is not a typical distribution system in Nunavut. There are three municipalities (Iqaluit, Resolute Bay and Rankin Inlet) that have extensive utilidor networks that deliver to the majority of the communities, with only new buildings receiving water via truck (Government of Nunavut, 2023) due to the high capital expenditure required to extend the existing utilidor network.

3.3 Recruitment

A public consultation was held in December 2023 at the community hall in Cambridge Bay to discuss research objectives and receive feedback and guidance on the proposed research (See Appendix C for poster). Additional meetings were held with Municipality of Cambridge Bay employees, the Kitikmeot Heritage Society, Polar Knowledge Canada (at the Canadian High Arctic Research Station [CHARS]), and Kiliinik High School during this visit. Additional recruitment activities undertaken for specific parts of the research are described in the subsections below.

Water Sampling Recruitment

Facebook is widely used in Cambridge Bay and is considered the best option for reaching most community members. Recruitment posts were shared on the local Facebook page "*Cambridge Bay News - Ikaluktutiak*". Posts would indicate which parameters we were sampling for, the types of sampling available to residents, and a request for individuals to direct message us stating their interest, the time they would be available, and their address. In addition, recruitment was conducted informally through my conversations with residents during daily activities. Participants were informed about the different sampling methods and advised that sampling would be conducted twice on separate days. Participants selected the sampling method that best fit their availability (water and time). Data collected from the participants supported the results found in Chapter 5.

Workshop Recruitment

Stakeholders identified in the organizational chart (Figure 2-1) were approached at their workplaces to introduce the research and explain the activities that they were being asked to participate in. At this time they were also provided with the anticipated time commitment. If the stakeholder group expressed interest, a date and time were arranged for the first workshop session. Participants were asked to review and sign an informed consent form ahead of the workshops. Results from the workshops are presented in Chapter 6.

Interview Recruitment

I approached local residents for one-on-one interviews at community events. Similarly with workshop recruitment details regarding research activities were explained to residents. If there was interest, meetings were arranged via Facebook. Participants were asked to review and sign an informed consent form ahead of the interview. Results from interviews are presented in Chapter 6.

3.4 Nunavut Youth Water Operator Program

Funding was provided by the Nunavut Association of Municipalities (NAM) to develop and deliver a youth water operator training program in Cambridge Bay. This led to the recruitment of three grade 11 students from Kiliinik High School. The principal of Kiliinik High School identified and recommended the students who participated in the program based on their strong academic ability and interest in environmental science. Further details on the youth program can be found in Appendix D. These students assisted with the collection of water samples during spring and summer 2024 and are named as co-authors in the peer reviewed paper featured in Chapter 5.

3.5 Data Collection

Water Quality Sampling

Water samples were taken from multiple locations, including: the water source, multiple points within the water treatment plant (before and after filtration; after UV disinfection; after initial chlorination; within the storage tank; and during water truck filling); during trucked distribution, and from the cisterns (9 buildings) and taps in 50 buildings in the community. Water samples were collected in accordance to instructions provided by the laboratory and analyzed for standard water chemistry parameters, metals, organics, and microbiological content. Samples were analyzed for free and total chlorine, turbidity, adenosine triphosphate (ATP) and pH in-house at CHARS. Samples collected for lead, copper, manganese, iron, magnesium, aluminium, zinc, nickel, silver, sodium, fluoride, chloride, nitrate, nitrite, sulphate, total and dissolved carbon and trihalomethanes (THMs) were sent to an accredited lab in Ottawa, Caduceon Laboratories, for analysis.

Health Canada recommends various sampling techniques for monitoring lead and copper corrosion (Figure 3-2). For example, sequential sampling after 6 hours of stagnation can help identify where lead and copper nodes may be present in a distribution system (Health Canada, 2025) or internal plumbing systems. Water is flushed through the system for 5 minutes and then left to sit for 6 hours before taking 4 1L samples. The tap is then flushed for a further 5 minutes and a fifth 1L sample is taken (Krkošek, et al, 2022). Random daytime sampling can be done to determine if there is a community wide problem or a specific building issue. These recommendations have been developed for centralized systems which can have multiple residents connected to a main distribution line that may have lead components. For decentralized truck-to-cistern systems, the only way to determine if it is a community wide issue is through sampling all residences.

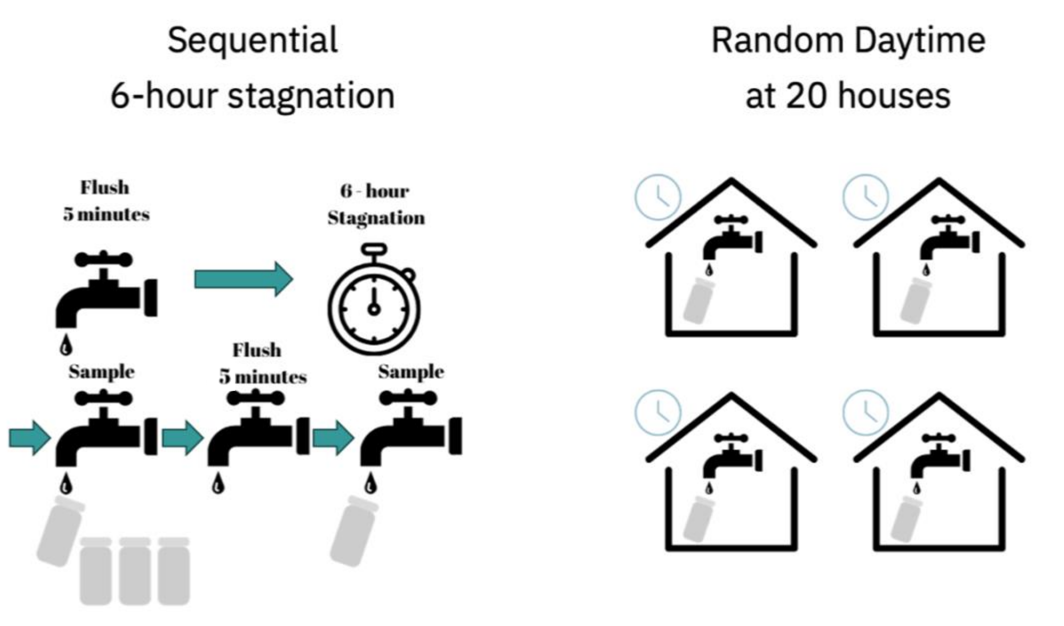

Figure 3-2: Sampling methods recommended by Health Canada for corrosion monitoring

Statistical Analysis of Water Quality Data

Data provided by the GN for Chapter 4 were reviewed and cleaned for statistical analysis. The dataset spanned 2017 to 2023; however, it did not have consistent quarterly sampling throughout the years, nor was sampling taken in the same month each year. After review, it was determined that there was sufficient annual data for the months during the spring freshet from 2017 to 2023. This was used to identify any annual trends. Data from other months were not used in this analysis. A second data subset covered 2022 to 2023 and included all quarterly sampling events, enabling examination of potential seasonal variations.

In Chapter 5, Water quality data was reviewed for any anomalies using the z-score method. One sample in the TOC data was more than three standard deviations from the mean and was therefore removed from the statistical analysis. A Shapiro-Wilks test was performed on all water quality data to assess normality, and the parameters showed varying degrees of normality. ANOVA, Kruskal-Wallis, and Mann-Whitney tests were performed to assess statistical significance ($p < 0.05$) for parameters between sample locations and between samples. R Studio was used for statistical and visual data analysis.

Workshops

Semi-structured interviews and focus group discussions with a total of 27 participants were conducted and qualitative documentation and quantitative datasets spanning over 2024 were collected. Workshop group sizes ranged from two to ten people. The first series of workshops was in spring between April and June 2024. The second series of workshops was held in the fall between September and November 2024, depending on stakeholder availability. Interviews and focus groups were conducted in English, a language in which all participants were fluent. Informed consent was obtained from all participants before the workshops.

The first workshop was to identify hazards, hazardous events and risk drivers associated with Cambridge Bay's water system. These were then collated and rephrased and distributed back to the stakeholders. In workshop two, stakeholders chose their top 10 risk drivers in each location of the water system and performed a polarity matrix to determine interconnection between risk drivers.

3.6 Model Building

Hazard Lists

The list of risk drivers developed during workshop one, prior to workshop two, was divided into six categories: Environment, Infrastructure, People, Social/Cultural, Policy, and Economic. Since many of the identified risk drivers did not fit within the traditional WSP framework, this categorization offered an alternative perspective for assessing which category had the greatest influence on water safety, rather than grouping them together as external factors, as is common in small-system WSPs (WHO, 2012).

The risk driver list was used in Workshop Two to help stakeholders identify their priority hazards related to different locations of the water system. These hazards were collected and evaluated to determine where consensus existed on which hazards or risk drivers were most important to the stakeholders.

Polarity Matrices

A polarity matrix is a tool used to define the direction of influence (positive or negative) between variables in a model (Schoenenberger et al., 2021). With the priority risk drivers identified, stakeholders were tasked with conducting a polarity matrix to assess the interconnectedness among the risk drivers. Polarity matrices are commonly used to assist in constructing causal loop diagrams and to understand how variables relate to one another (Forrester, 1971; Forrester, 1994). Stakeholders were asked to determine whether the risk drivers had a positive, negative, or no relationship with each other.

Causal Loop Diagram

All risk drivers were renumbered to H1-H204. The numbering continued from the start of the water system (source water) to the end (buildings) to reduce potential confusion on numbering.

The polarity matrices created by the stakeholders were digitized in Excel to evaluate the polarity of causal links between the risk drivers. This is a core building block for causal loop diagrams (Pruyt, 2013). In long form on excel, links between risk drivers were evaluated to see if there was any consensus. An example of input is shown in Table 3-1. All risk drivers are listed in Appendix H.

Table 3-1: Snapshot of Excel input of workshop data to identify links between risk drivers

Group	Matrix	From	To	Polarity
G1	Source Water	H20	H40	+
G1	Source Water	H20	H28	0

There were various risk drivers that could fall under the same umbrella term. For example microbial contamination could occur from various avenues such as wild life, unhygienic practices from water truck operators, low chlorine residual etc. This is common to keep models simple and readable as was seen in Chapter 2 with an example from Daniel et al (2021) Figure 2-4.

Causal links and loops identified were used to create a baseline causal loop diagram with further inspiration from other studies (Daniel et al, 2021; Cannon et al, 2022; Loo et al, 2023).

Stock and Flow Model

Variables were created from the priority risk driver lists and the CLD by translating the risk drivers into measurable factors that could influence system behavior. For example, microbial contamination and lead in plumbing (risk drivers) would be represented by a flow variable “contamination”. The constructure of the model drew upon multiple sources (Figure 3-3), including the drinking water strategic framework (Government of Nunavut, 2023), grey literature (Stantec, 2018; Nunavut Water Board, 2020; Associated Engineering, 2025), water quality data (Duncan, Chalmers & Gora, 2025; Duncan et al, 2026) and hazard and risk identification data (De Coste et al, 2024; Duncan, Slowey & Gora, 2025), and SD literature (Forrester 1994; Meadows, 1999; Sterman, 2000; Phan et al, 2021; Cannon et al, 2022; Daniel et al, 2021; Loo et al, 2023; Loo et al, 2025).

Other studies using system dynamics have relied on database data (Cannon et al., 2022; Loo et al., 2023; Loo et al., 2025) and have a baseline for verifying the SD structure. Information from Duncan, Chalmers & Gora (2025) and Duncan et al. (2026) was used to verify aspects of contamination impacts on water safety, turbidity, and THM data, as data was available over multiple years (Appendix I).

Data harmonization was undertaken to integrate quantitative and qualitative datasets into the SD model. Temporally, data was aligned to a common time step to support a 10-year time-series simulation. For example, water quality measurements and water usage data were aggregated to a monthly time step. Spatially, both empirical data and workshop-derived insights were categorized into four overarching system components, namely source, treatment, distribution, and buildings. This spatial structuring defined the model boundary. Conceptually, qualitative data from stakeholder workshops were used to inform the model structure, including the identification of key variables and causal relationships. Quantitative water quality data were used to validate the model, ensuring that simulated outputs reflected observed system dynamics.

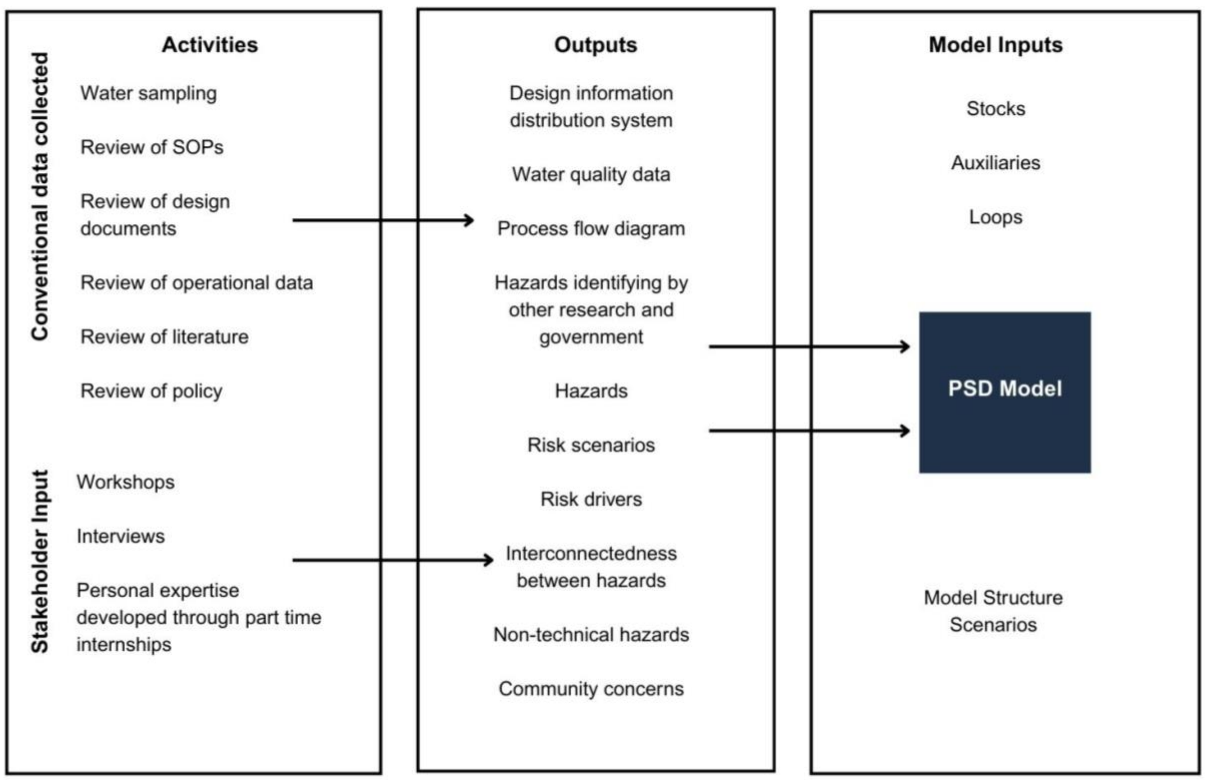

Figure 3-3: Activities performed that led to the outputs used to develop the participatory system dynamics model to determine areas of improvement for drinking water safety in Cambridge Bay, NU.

Identifying Risk Drivers for Simulation

The risk drivers identified by stakeholders in the workshops were assessed against criteria to determine their suitability for simulation. These risk drivers were already included in an initial conceptual model provided to the community. Five risk drivers met the criteria and could be developed into practical policy recommendations.

The primary stock in the model is the Water Safety Level. Water Safety Level serves as the key performance indicator (KPI) and is measured using a water safety index scale from 0 to 100 (Table 3-2). The index functions as a stock variable that reflects improvements and degradations resulting from treatment effectiveness, infrastructure condition, environmental stressors, operational performance, and human behaviour. A baseline safety index of 50 is used in the model.

Table 3-2: Descriptions of water safety index

Water Safety Index	Description
0-20	Unacceptable risk, immediate action required
21-40	High risk, controls failing
41-60	Marginal safety, elevated risk
61-80	Generally safe, monitoring required
81-100	Controls effective, low residual risk

Scenario Analysis

Simulations were carried out on six variables within the model that related to the risk drivers identified as potential leverage points. Variables were manually changed one at a time for simulation (Table 3-3).

Table 3-3: Variables used for manual changes for scenario analysis and their relation to the key stocks, flows or auxiliary variables.

Variable for manual changes	Stock (S), Flow (F) or Auxiliary (A) variable
Base Knowledge	Watershed Knowledge (S)
Base Unknown Contaminant Risk	Unknown Contaminant Risk (A)
Base Capacity	Regulatory Capacity (S)
Funding Level	-
Base Service Disruption	Service Disruption (F)
Regulatory Framework Strength	-

**If there is a (-) present, it is because it has been made a constant in the model that links and influences various variables.*

3.8 Research Dissemination

Throughout the research project, the Cambridge Bay Council, the Mayor and the Senior Administrative Officer (SAO) were kept informed through multiple informal in-person meetings and several formal meetings conducted in person or in hybrid format. Presentations and informal meetings were given to share emerging findings and confirm approval to disseminate the community's information to broader audiences. This further dissemination was achieved through conferences, academic publications, and interviews with news broadcasters. Chapters 4-6 were presented to Council, and permission was granted before publishing all results.

Participants in the water sampling campaigns received their water test results individually, either via Facebook Messenger or email. If their samples were elevated in one or more parameters, suggestions were made to reduce risk exposure (e.g. flushing taps to reduce exposure to lead and copper) and to reach out to the Government of Nunavut - Department of Health for further assistance and recommendations.

In June 2025 a series of public events and meetings were held in Cambridge Bay. This included a public lecture and water testing demonstration at CHARS, a drop-in information and water testing event at the Municipal Office in Cambridge Bay, an in-person meeting with the Cambridge Bay Council, and informal meetings with representatives from territorial government departments, local organizations (e.g. housing), and other stakeholders who had participated in water sampling, focus group workshops, and interviews. These events and meetings showcased the information presented in Chapters 5 and 6, and provided a preview of a baseline stock and flow model that would form the final model in Chapter 7. Attendees were invited to provide feedback on what they would like to see modelled. The presentation held at CHARS was provided to Polar Knowledge Canada for its dissemination, and Chapter 5 was posted on the local Facebook page to celebrate the students' becoming authors. Chapters 4 and 6 are published as open-access articles. The research has been featured in two media outlets: a French newspaper, Le Nunaviox, and CBC. For both interviews, consent to share project information was provided by the Cambridge Bay Council.

3.9 References

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4. Application of Water Safety Planning to Improve Drinking Water Safety in an Arctic Community – a Case Study in Cambridge Bay, Nunavut

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Contributions: Caroline Duncan: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Elan Chalmers:** Writing - review & editing. **Stephanie Gora:** Writing – Review & Editing, Supervision.

4.1 Abstract

Water safety planning is an established risk management approach that accounts for both quantitative and qualitative drinking water hazards and explicitly includes ongoing input from both community and regulatory stakeholders. This approach has been applied in jurisdictions across the world including in Canada. Rural and remote communities in Canada, which are often disproportionately impacted by water safety hazards while having less capacity to respond, stand to benefit most from holistic approaches to water safety risk management such as water safety planning. Unfortunately, these communities typically have limited resources to engage in water safety planning. Additionally, most remote communities rely on truck and cistern water systems, which have different and less understood water safety hazards and hazardous events than less remote communities in Canada with piped service. In this study we report the results of an initial water safety planning case study in Cambridge Bay, Nunavut. The case study relied on

existing design information, operational records, and historical water quality data. We identified numerous site specific water safety quality hazards including disinfection byproducts in trucks, manganese in the source water, and copper in tap water samples at levels above aesthetic-based guidelines as well as operational and design challenges that increase the risk of water quantity and water safety emergencies in the community. We conclude that water safety planning has the potential to substantially improve water safety in Nunavut and other Arctic jurisdictions but that current information gaps in design, operational, and water quality records as well as complex stakeholder interactions are likely to hinder top-down attempts to accurately characterize water safety risks in these communities. A dynamic and inclusive approach to water safety planning is recommended that incorporates a wider variety of stakeholders and targeted exploration of key water safety hazards.

Imanik aniktailigiyiit paknaiyautikhait hanahimaliktut ayokhaktitailigiyiinik munagitjutikhait piflutik ilauyut tamamik amigaitjutainik ovalo nakuutjutainik imilaaktainik imat ilauplutik ikayugutainik tamamik nunalaani ovalo maligaliligiyiinit ilauyunit. Hamna piliktait atulaaliktut munagitjutainit tamaat nunakyuami, ilauplutik Kanatami. Mikiyut ovalo avaliitut nunalaat Kanatami, pikaktut ikpinagutainik imanut aniktitailigiyiinik nakuuyumik pikaktitlugit mikiyumik kiulaagutainik, ikayugutigilaaktait tamaat pilutik imanik aniaktitailigiyukaktumik munagitjutainit paknaiyautiinit. Mamiana kihimi hapkoa nunalaat keelinigutikaktut pitkutikhainik ilauyaangank imanut paknaiyautikhait. Ovalo, mikiyut nunalaat atukpangmata akhaluutinik imiktagutainik ovalo kuviligutainik atugutainut, aalangayut ovalo kangikhitiaktauhimaitut imanik aniktitailigiyiinut imanik aniktitailikaktunik ovalo aniaktilaaktunik mikiyuni nunalaat Kanatami imanik atukataktut paipakuukhutik. Hamani kimilguugutainituhaktihimaliktuk pitkutait imanik aniktitailigutikaktunik paknaiyautainik pihimaliktuk Ikaluktutiami, Nunavut. Pihimaliktait kimilguugutait atuktut hanauyakhimalikhimayumi tuhagutikhainit, havaagutainik naunaiyaktaakhimayunik ovalo kingulimi imanik kanugitjutait katitihimayunik. Naunaiyakhimaliktugut amigaitunik nunami imat aniktitailigiyiit ilauyunik halumaktigutait pifaktunik akhaluutikuukhimayunit, halumaktigutait imat ovalo paipait imainut ilaani angitkiyauyut maligutikhaini nanihimaliktut ovalo havaagutainit ovalo hanauyautainit ayokhagutigilikpaktait ilanganut imat naamagutaini ovalo aniktitailigutaini paknaiyautainut pilaaktunik nunalaani ayokhaktilaaktait. Inikhugit imat aniktitailigutait paknaiyautait nakuuhiliktuugaluit imanik Nunavumi ovalo aalani Ukiuktaktumi munagiyiit kihimi ublumi tuhagutikhait ilaani pikangitut hanauyautainik, havaagutikhainik ovalo naunaiyautainik ovalo angiyuni ilauyunut havakatigiiktut kayumiiktivaktait angikataktunit atuktunut aalangukpaktut imanut aniktitailigiyiit tahapkononga nunalaani. Angiyut ovalo ilaukatauyut pivaktait imanik paknaiyautainut ilaani ilauyukhat amigaitunut ilauyunut ovalo tugaakhimayunut kinikhiakataktut kitkaniitainik imat naamaktigutikhait aniaktilaigaaganik atuktunut.

4.2 Introduction

The Territory of Nunavut is part of the Canadian Arctic and makes up one of the four regions of Inuit Nunangat (Inuit Tapiriit Kanatami, n.d.). All communities in Nunavut rely partially or entirely on decentralized truck and cistern drinking water distribution systems because of the cost and complexity of building and operating water piped networks in communities underlain by permafrost and that are subject to extreme cold temperatures (Chalmers, Duncan, & Gora, 2024). Only limited drinking water quality data exists for most Nunavut communities (Elliott, et al., 2022), much of which has been collected by the territorial governments and some academic studies over the last ten years. Past peer-reviewed studies have primarily examined microbiological water quality parameters in the Qikiqtaaluk and Kivalliq Regions (Gora, et al., 2020; Daley, et al., 2018; Masina, et al., 2019) of Nunavut, as well as neighbouring Inuit-majority jurisdictions in Nunavik (Northern Québec) (Martin, et al., 2007) and Nunatsaivut (Northern Labrador) (Wright, et al., 2018) (Wright, et al., 2018). In Nunavut, total coliforms have been found in both taps and cisterns in four of the communities, and *E.coli* in two communities (Gora, et al., 2020; Daley, et al., 2018). In Nunavik, Martin et al (2007) analysed household water cisterns in 4 communities, detecting total coliforms in 21 of 64 cisterns, but no *E.coli* (Martin, et al., 2007). Masina et al (2019) found that untreated culturally significant surface water sources in Iqaluit contained *Giardia* (20.0%) and *Cryptosporidium (*1.8%) (Masina, et al., 2019). The authors determined that the public health risk to residents that consume these alternative sources was low but may increase over time due to climate change (Masina, et al., 2019). The exact percentage of Nunavut Inuit residents who consume untreated drinking water is unknown, however, Cassivi et al (2024) found that 60% of Inuit residents surveyed in Kangiqsualujjuaq, Nunavik relied on untreated water sources instead of tap water (Cassivi, Carabin, Dorea, Rodriguez, & Guilherme, 2024).

In contrast to the emphasis on microbiological parameters in previous studies and government policies, studies examining chemical water characteristics of treated drinking water in Nunavut have only been conducted in four communities (Daley, et al., 2018; Gora, et al., 2020). However, a recent hydrocarbon contamination events in 2021 in Iqaluit have underscored the importance of monitoring chemical water safety hazards

(Nunatsiaq News, 2021). Chlorination, the only treatment applied in 10 of the 25 communities, targets microbial contamination but does not remove metals, particulate matter, or most dissolved organic compounds (Health Canada, 2022). For raw water, Elliot et al (2022) provided an overview of the source water quality for all communities in Nunavut, with a case study on Sanikiluaq which experienced high salinity in the source water. It was hypothesized that the permafrost thaw allows for the defrosting of historic marine sediment salts that had frozen historically in the fresh water source (Elliott, et al., 2022).

Health Canada is the federal body that establishes the *Guidelines for Canadian Drinking Water Quality (GCDWQ)* that the provinces and territories in Canada can choose to adopt into regulation. In Iqaluit, Coral Harbour and Pond Inlet, Daley et al (2018) found that the concentration of iron in samples taken from building taps was above the aesthetic objective (AO) set in the GCDWQ, and the AO for manganese was also exceeded in Pond Inlet (Daley, et al., 2018). In 2018 the AO for manganese was 0.05 mg/L, the new AO is 0.02 mg/L. Health Canada publishes revisions to the GCDWQ as new information becomes available and the AO's for iron and manganese have since been reduced (Health Canada, 2024) (Health Canada, 2019). As only percentages were provided in the Daley et al (2018), it cannot be determined how many more buildings would now above the revised AO's or MAC in the communities. Similar AO exceedances for iron and manganese were found in Pond Inlet by Gora et al (2020) throughout the water system in the months spanning from February to June, 2018 (Gora, et al., 2020). The authors also reported a manganese concentration increase that exceeded the MAC (0.12 mg/L) during the winter months (Gora, et al., 2020). It was noted that this may attributed to oxygen depletion caused by the decomposition of organic matter in the lake during ice cover, which would affect the speciation of these metals. The high iron and manganese levels in the lake were then carried through the distribution system to consumers due to a lack of treatment barriers (Gora, et al., 2020; Davison, Woof, & Rigg, 1982; Munger , et al., 2019).

Water storage and exposure to plumbing materials can also impact on the biological and chemical aspects of drinking water safety. The control of bacterial growth in distribution infrastructure and domestic plumbing, is improved by maintaining disinfectant residual throughout the system, reducing the natural organic matter (NOM) that enters the distribution system, and implementing corrosion control measures (Health Canada, 2019a) (Health Canada, 2009). Multiple studies have reported incidences where chlorine residual levels were below the regulated concentration in the distribution system and/or below detection in domestic water storage cisterns, increasing the risk of recontamination (O'Keeffe, 2024) in Nunavut (Gora, et al., 2020), Nunavik (Martin, et al., 2007), and Nunatsiavut (Wright, et al., 2018; Harper, et al, 2011). Besides serving as a food source for microorganisms, NOM can combined with free chlorine can yield to disinfection byproducts (DBPs) (Beauchamp, Bouchard, Dorea, & Rodriguez, 2020) (Beauchamp, Dorea, Bouchard, & Rodriguez, 2018), including species that are regulated in most jurisdictions in Canada such as trihalomethanes (THMs) (Health Canada, 2006) and haloacetic acids (HAAs) (Guilherme & Rodriguez, 2014). There is no MAC nor AO for NOM set in the Canadian guidelines (Health Canada, 2020), however, in the US, the US EPA recommends an upper limit for total organic carbon (TOC), a measure of NOM, to be 2 mg/L for the prevention of THM formation (U.S EPA, 1998).

Corrosion of domestic plumbing system components, which can lead to the release of metals like lead and copper, is a well-documented concern in non-Arctic municipalities (Health Canada, 2009; Chowdhury, Mazumder, Al-Attas, & Husain, 2016; Schwartz, et al., 2021). In 2006, in Alaska, Hart and White (2006) undertook a study to examine metal corrosion in rainwater cisterns and found a correlation between collection material utilized and metal exceedances, however, there were no investigations focused on domestic cisterns in remote Arctic communities served by trucked distribution systems until 2017 (Daley, et al., 2018; Hart & White, 2006). Daley et al. (2018) found lead levels in random daytime grab samples that exceeded Health Canada's MAC (5 ug/L) and copper above the AOs in three communities. Gora et al. (2020) conducted a targeted follow-up study in Pond Inlet, using random daytime and sequential stagnation water sampling to test for heavy metals in plumbing and determine their sources buildings. Factors such as raw water quality, stagnation times, temperature, and disinfectant residuals (Wang, Devine, Zhang, & Waldroup, 2014) influence heavy metal release and biofilm formation, compromising treated water quality and facilitating pathogen proliferation (Liu, Verbeek, & Van Dijk, 2013; Cullom, et al., 2020; Pinto, Xi, & Raskin, 2012). Corrosion of iron-based distribution and storage components can also encourage the proliferation of microorganisms (Li, et al., 2022), however, there is no evidence these components have been used in Nunavut.

Water Safety Planning and Water Safety Risk Assessment

Water safety plans (WSP) use a holistic approach to managing drinking water systems that was originally developed by the World Health Organization for use in low resource communities in the Global South (Figure 4-1). A WSP is often used as a prevention tool which incorporates both qualitative infrastructure information and quantitative water quality and operational data to support hazard identification and risk assessment. A risk score is calculated for each water safety hazard by multiplying a likelihood score by a consequence or score (Bartram, et al., 2009; WHO, 2012; WHO, 2016). This score is then used to categorize the hazard as low, medium, or high risk using a predefined risk matrix. Water safety matrices have performed well in situations with scarce or unavailable data; however, there are limitations related to the precision of probability and impact estimations (Lane & Gagnon, 2022).

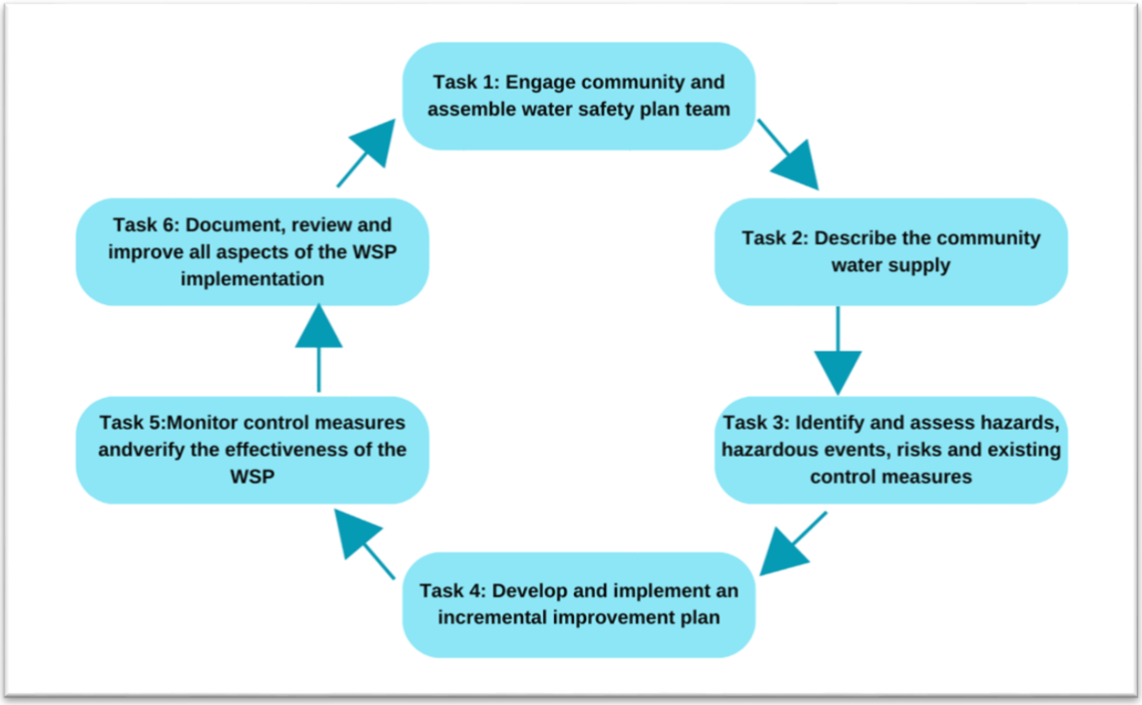

Figure 4-1: The water safety planning process as presented in WSP for small communities (adapted from WHO, 2012)

WSPs have been applied in Canada to improve water safety management, including a government led initiative in Alberta and a pilot project in Atlantic Canada First Nations. In the latter case, Lane et al. (2022) co-developed a risk assessment web application with First Nation stakeholders from six communities to build capacity for water safety management (Lane, Fuller, Dyment, & Gagnon, 2022). The study scope was limited to treatment and distribution hazards for individual systems and those common across the participating communities. Although increased communication and data ownership offered considerable benefits, Lane et al. (2022) found that operators viewed risk assessments as 'strictly diagnostic' and were unlikely to include it in operational practice if it was 'considered to not be required' (Lane, Fuller, & Gagnon, 2022). The fragmented governance within First Nations means that adopting these proactive risk reduction strategies into regulation will require acceptance by multiple levels of government and a shift from focusing only on water quality monitoring (Lane, Fuller, Dyment, & Gagnon, 2022).

Historically, only one study had reviewed the suitability and potential application of WSP in an Arctic context (Lane, Stoddart, & Gagnon, 2018). Recently, Chalmers et al. (2024) developed a WSP framework for Nunavut and proposed a new risk matrix constructed using the Cox Criteria (Cox, 2008), after determining that risk matrices criteria from other jurisdictions could not be directly applied to the unique factors found in Nunavut (Chalmers, Duncan, & Gora, 2024).

Cambridge Bay, NU

Cambridge Bay is located on the southern point of Victoria Island (Figure 4-2) and serves as the government, administrative, and transportation hub for Nunavut's Kitikmeot Region. It sustains a population of nearly 2,000 individuals, not including visiting researchers to the Canadian High Arctic Research Station (CHARS). In 2017, CHARS was constructed by the federal government to encourage and facilitate northern research endeavours. This prompted upgrades to the water treatment plant and piped water distribution system in Cambridge Bay to accommodate the influx of people at the station and to comply with fire safety regulations. The community now has some of the most comprehensive water treatment infrastructure in the territory.

Figure 4-2: Map of the Municipality of Cambridge Bay on Victoria Island (Inuit Tapiriit Kanatami)

Objectives

The objective of this study was to conduct a case study WSP for the community of Cambridge Bay, NU using the proposed water safety framework and risk matrix developed by Chalmers et al (2025). This study relied on findings from literature, the professional experience of the authors, and data provided by the Government of Nunavut (Dillon Consulting & Outcome Consultants, 2021). The community's existing water quality data, design documents, and operational records (Chalmers, Duncan, & Gora, 2024) were analyzed to find any temporal and location-based trends to establish gaps and to conduct a preliminary water safety risk assessments for Cambridge Bay.

The secondary nature of the data used in this study may have introduced human input errors, and inconsistent data collection in earlier years necessitated the removal of some data for meaningful statistical analysis.

Positionality Statement

The individual researchers whom have authored this paper identify as settlers performing research at York University, Lassonde School of Engineering. Caroline and Elan have both worked/are currently working at Government of Nuanvut, Department of Community and Government Services (GN-CGS) in the roles of municipal support and senior municipal planning officer, respectively. Various written support has been provided to Caroline from from GN-CGS, the Municipality of Cambridge Bay and the Kitikmeot Heritage Society to undertake this research. This paper highlights hazards from the personal experiences of the authors and a review of literature.

4.2 Materials and Methods

Description of Cambridge Bay Drinking Water System.

Cambridge Bay's water system was initially constructed in 1970 as an intake pumphouse adjacent to the source "Water Lake" and has undergone several upgrades over the years, with the latest in 2017. The water delivery system comprises three 12,500L water trucks, along with a spare, operating seven days a week with a ten-hour work day. Additionally there is piped water delivery that serves a limited number of facilties including CHARS. The current water infrastructure includes a pumphouse at the water source with pre-treatment chlorine injection, a transmission line, and a treatment plant. The treatment plant consists of: filter feed pumps, raw water circulation pump, coagulant dosing (currently inactive), a pressure filtration system with three filters and backwash holding tank, two UV reactors, a chlorine dosing system, treated water storage tank, truck fill pumps and core servicing pumps for the piped delivery (Stantec, 2018) (Figure 4-3).

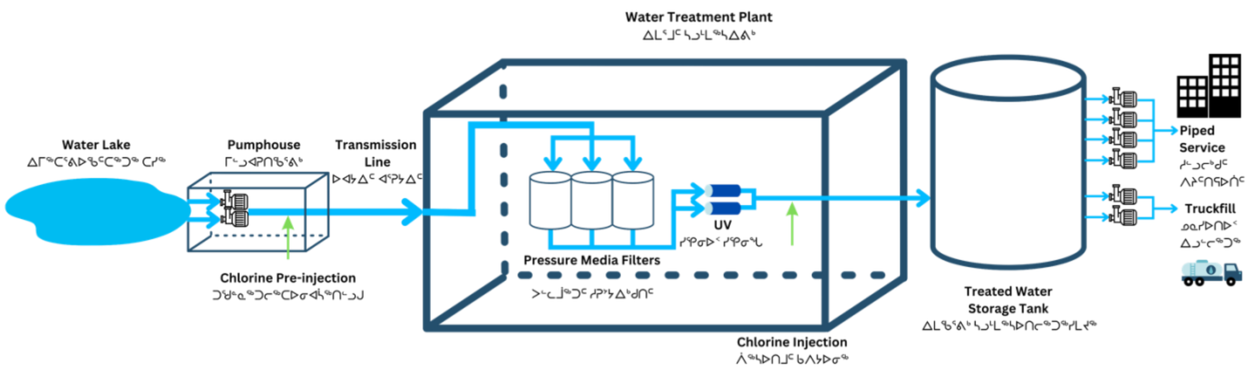

Figure 4-3: Schematic of Cambridge Bay water system

Identification of Water Safety Hazards Present in Cambridge Bay

Cambridge Bay was chosen as a case study because the available historical water quality data is extensive compared to other communities in Nunavut. A list of hazards relevant to Cambridge Bay was developed using the data, the water quality assessment report prepared for the Royal Canadian Mounted Police and the master list of hazards for communities in Nunavut developed by Chalmers et al (2025) (Chalmers, Duncan, & Gora, 2024). The list was refined to include only hazards with documented occurrences (Table 4-1) and excluded subjective opinion. Five hazards were then selected for detailed analysis using the Chalmers et al (2025) WSP framework.

It should be noted that there could be additional information held by GN-CGS that requires Access to Information and Protection of Privacy (ATIPP) access to information. For this paper, we have included this in the table with a “yes – ATIPP required”.

Water Quality Data

The data used in this analysis was provided by GN-CGS via WaterTrax Data Management Platform. The chemical water quality parameters provided by GN-CGS included the general water quality analysis of pH, turbidity, organics, anions, cations, metals, hydrocarbons, as well as THMs and HAAs. No microbiological data has been reviewed as there have been no boil water advisories issued for the detection of E. coli in the water system from 2017 onwards (Government of Nunavut - Department of Health, 2024).

Water Quality Data Analysis

Prior to analysis, the data was reviewed for anomalies and cleaned, which included the grouping of sample location names. For example, 'Lake' originated from different identifiers such as CAM-01, WTP-01 and Water Lake. These disparate names were confirmed by GN-CGS staff to refer to the same location, thereby enabling the grouping of sample locations for statistical analysis and visualization.

The dataset spanned from 2017 to 2023, with varying numbers of sampling events each year. To investigate annual and seasonal trends, the dataset was split into two subsets. The first subset covered the period from 2017 to 2023, focusing solely on spring freshet months (April, May, June) to identify any annual trends. The second subset encompassed the years 2022 to 2023 and included all sampling events, allowing for the examination of potential seasonal variations.

All water quality datasets were tested for normality to determine if the ANOVA or Kruskal-Wallis test should be used to identify any statistical significance for parameters between locations and between years at specific locations. Spearman's Correlation analysis was employed to assess the relationship strength between parameters. Attempts were made to conduct a Mann-Kendall test to detect seasonal water quality trends; however, due to limited data, these tests yielded inconclusive results. All data analysis was conducted in R using the tidyverse, dyplr and ggplot packages

Water Safety Risk

Water safety risk (R) is most commonly calculated as the product of the likelihood of a hazardous event occurring (L) and the resulting consequence (C):

$R = L \times C$ Equation 4

As described in the introduction and Chalmers et al. (2025) includes likelihood and consequence scores are assigned based on jurisdiction specific criteria (Chalmers, Duncan, & Gora, 2024). Likelihood criteria are often based on the past frequency or future probability of hazardous events and consequence scores are generally informed by local water safety regulations and/or the anticipated severity of health impacts (e.g. acute vs. chronic health effects).

Application of Water Safety Planning to Cambridge Bay, NU

The Nunavut risk matrix proposed by Chalmers et al. (2025) includes likelihood and severity scoring criteria specifically tailored for Nunavut, an alternative weighted risk scoring equation, an risk scoring matrix that adheres to the Cox criteria, and a community-by-community approach to hazard identification that incorporates feedback from multiple stakeholders (Chalmers, Duncan, & Gora, 2024). The scoring criteria took into consideration past frequency, existing treatment and operational barriers, existing regulations and practices, planned updates to regulations and practices (Government of Nunavut - Department of Community and Government Service, 2023), and the potential health impacts of different hazardous events.

The Nunavut risk matrix breaks the likelihood score into a system readiness score and an optional past frequency score. This reduces speculation and bias by using records of past events as well as evidence of barriers being in place to address the hazard (Chalmers, Duncan, & Gora, 2024) (Lane & Hrudey, 2023).

$Likelihood = xPF + ySR$ Equation 5

Where PF is past frequency, SR is system readiness, and x and y are weights assigned to each factor, where x and y add to 1. This likelihood score is then multiplied by the consequence score to determine the water safety risk score.

$$Risk\ score = (xPF + ySR) \times C \quad \text{Equation 6}$$

Two of the proposed formulas for calculating the likelihood score were evaluated, one that considered only system readiness (Equation 5, x = 0, y = 1) and one that assigned a weight of 0.25 to past frequency and a weight of 0.75 to system readiness (Equation 6).

Table F4-1 (Appendix F) outlines the scoring criteria definitions along with risk equations that were proposed in Chalmers et al. (2025). These risk equations were recommended as a weighted past frequency and system readiness, allowing the scoring to leverage important past information when available while still keeping risk scores high during catastrophic events (Chalmers et al., 2025). These equations are then applied to five hazards selected based on evidence of having occurred in Cambridge Bay.

4.3 Results and Discussion

Identification of Water Safety Hazards in Cambridge Bay

Past Evidence of Non-compliance with Territorial or Federal Water Treatment and Operational Guidelines in Cambridge Bay

Dillon Consulting conducted a water quality assessment for the Royal Canadian Mounted Police in 2021, and identified that the water supplied did not meet the Canadian Drinking Water Quality Guidelines (Dillon Consulting & Outcome Consultants, 2021; Health Canada, 2022) (Table F4-2). The assessment, based on treated water quality data from 2018-2020, revealed THM and turbidity exceedances above the MAC, and aluminum and manganese concentrations above the AO, along with no detectable free chlorine residual within delivery trucks on 37 counts. The filtration system used in Cambridge Bay is a pressure filter, which is not included in Health Canada's list of recommended pathogen removal technologies (CCME, 2002). Moreover, sampling results indicate that the filtration system is ineffective at removing particles and without a functioning coagulation system there is limited NOM removal, leading to THM exceedances.

Water Safety Hazards in Buildings

Although the territorial and municipal government do not have any formal responsibility to monitor water quality in cisterns and domestic plumbing, the available literature suggests there is evidence that these systems can contribute to hazards (Gora, et al., 2020; O'Keeffe, 2024), including:

- Microbiological contamination in storage cisterns
- Low chlorine residual in storage cisterns
- Continued formation of DBPs during onsite storage
- Lead and copper from premises plumbing in individual buildings

Characterizing these hazards will require the participation of community members and stakeholders during sample collection as well as for validation. This may prove challenging as there are currently no water safety regulations or guidelines related to the design, installation, maintenance, or monitoring of cisterns and domestic plumbing in Nunavut and sampling only occurs on an ad hoc basis.

Other Water Safety Hazards

A fuel spill near the source water intake was identified in Cambridge Bay by Dillon Consulting in 2021 and is further documented in the Northwest Territories Spill Database (Dillon Consulting & Outcome Consultants, 2021; Government of NWT, n.d.). The fuel tank at the pumphouse has now been relocated to a minimum of 60m distance from the source water and has been provided with an additional bunding to reduce the likelihood of spills contaminating the source water.

Water Hazards Observed in Nunavut Communities in Past Academic Studies, Government Reports, and Consulting Projects

Previous work by researchers, government scientists and engineers, and private consulting firms has identified numerous water safety hazards in Nunavut communities. Hazards that are potentially relevant to Cambridge Bay are summarized in Table 4-1 along with their potential causes.

Table 4-1: Identification and characterization of water safety hazards that have been reported in the academic literature, government documents, and consulting reports in Nunavut and that could conceivably impact water safety in Cambridge Bay

Location	Hazard	Potential causes (a.k.a. hazardous events)
Source Water	*E. coli* in source water (Dillon Consulting & Outcome Consultants, 2021)	Faecal contamination from wildlife and dogs in source water
	Cryptosporidium and *Giardia* in source water (Daley, et al., 2018; Masina, et al., 2019)	Faecal contamination from wildlife in source water
	Manganese in source water (Elliott, et al., 2022; Gora, et al., 2020)	Naturally occurring, potential increase with permafrost thaw
	Iron in source water (Gora, et al., 2020)	Naturally occurring, increase with permafrost thaw
	High turbidity (Dillon Consulting & Outcome Consultants, 2021)[1]	Spring freshet, permafrost thaw
	Hydrocarbons in source water (Dillon Consulting & Outcome Consultants, 2021)	Recreational vehicles on or near lake in the winter could spill contaminants to watershed (Dillon Consulting & Outcome Consultants, 2021)
	Insufficient water supply	Increase water usage from population growth
	Access road (Dillon Consulting & Outcome Consultants, 2021)	Road to source, minor fuel leaks
	Fuel spill at intake (Dillon Consulting & Outcome Consultants, 2021)	Emergency generator leak and entering source
Water Treatment Plant (WTP)	*E. coli* in treated water (Gora, et al., 2020; Daley, et al., 2018)	Source water contamination, treatment failure
	THMs above guideline in treated water (Dillon Consulting & Outcome Consultants, 2021)	Excessive chlorine dose, presence of THM precursors

	Manganese in treated water (Gora, et al., 2020)	Inefficient backwashing Use of incorrect media
	Iron in treated water (Gora, et al., 2020)	Treatment failure
	Copper in treated water (Daley, et al., 2018) (Gora, et al., 2020)	Corrosion in treatment plant plumbing
	Low chlorine residual in treated water (Gora, et al., 2020; Daley, et al., 2018)	Treatment failure Increased chlorine demand from source water turbidity (> 1 NTU) Upgrades in pipes and pumps impacting CT
	Turbidity (Dillon Consulting & Outcome Consultants, 2021)	Sediments in treated water storage causing recontamination
	Cryptosporidium and *Giardia* in treated water (Dillion Consulting, 2023)[1]	UV disinfection system not operating properly Not using LT2 1 micron cartridge filters
	Pump failure and repair	Power surge Lack of maintenance and asset management
	Inadequate water supply	Inefficient water pumping/ truck delivery to meet supply and demand (open community Facebook group provides evidence of insufficient water deliveries) (Daley, Castleden, Jamieson, Furgal, & Ell, 2015)
	Inadequate water supply	Pipe failure – heat trace fails, frozen transmission line and utilidor Lack of maintenance and asset management
	Manganese in distributed water (Daley, et al., 2018; Gora, et al., 2020)	Resuspension
	Iron in distributed water (Daley, et al., 2018; Gora, et al., 2020)	Failure or no coagulation
	Lack of water deliveries to community, low water availability	Truck failure and repair
	Aging infrastructure	Deterioration of treatment plant

	THMs above guideline in distributed water (Gora, et al., 2020; Dillon Consulting & Outcome Consultants, 2021[1])	Excessive chlorine dose and presence of THM precursors
Utilidor	Aging infrastructure	Deterioration of distribution infrastructure
Trucks	Aging infrastructure	Lack of operator training
	THMs above guideline in distributed water (Gora, et al., 2020; Dillon Consulting & Outcome Consultants, 2021)	Excessive chlorine dose and presence of THM precursors
	Road access	Blizzard prevents water delivery
	Low chlorine residual in truck (Dillion Consulting, 2023)	Treatment failure Operators not trained Improper disinfection of trucks
	Lack of water deliveries to community, low water availability	Sick truck driver/ on vacation/ no cover
	E. coli in distributed water (Gora, et al., 2020; Daley, et al., 2018)	Treatment failure, improper disinfection of trucks
Water cisterns	*E. coli* in distributed water (Gora, et al., 2020; Daley, et al., 2018)	Inadequately maintained cistern/ stagnation time
	General microbiological contamination	Disinfectant decay due to long stagnation time or cistern hygiene
	Legionella in distributed water (Daley, et al., 2018; WHO, 2011)	Stagnation of water in water cisterns
Taps	Copper in distributed water (Daley, et al., 2018; Gora, et al., 2020)	Corrosion of plumbing components

	E. coli in distributed water (Gora, et al., 2020; Daley, et al., 2018)	Improper cleaning around tap after food prep
	Lead in distributed water (Daley, et al., 2018; Gora, et al., 2020)	Corrosion of plumbing components

[1]*Dillon Consulting and Dillon Consulting & Outcome Consultants reports requires ATIPP.*

4.3.1 Review of Historic Water Quality Data and Identification of Water Quality Safety Hazards

ANOVA and Kruskal-Wallis tests were conducted to two main questions:

1. Is there a variation in water quality across different points in the system (source, WTP, truck, cistern, tap) and does this vary over time, both seasonally and in the long term?
2. Are there correlations between different water quality parameters?

4.3.2 Water Quality from Source to Tap and Over Time

General Water Chemistry

Tables S4-3 & S4-4 in the supplemental file list the averages, minimums and maximums for the general water quality parameters analysed in this study (Appendix F). In the source water, ANOVA analysis showed significant differences in pH and alkalinity (both $p < 0.05$) between different sampling events. Additionally, ANOVA analysis revealed that there were significant differences in alkalinity ($p < 0.05$) in the source water across different years. Within the treatment plant, only turbidity showed a significant difference between the years ($p<0.05$). Turbidity levels varied significantly in the trucks between March 2022 and June 2022 ($p<0.05$) and March 2022 and June 2023 ($p < 0.05$). Parameters analysed in the trucks using ANOVA, showed significant differences in pH and turbidity ($P < 0.05$).

Lead and Copper

Lead and copper release is influenced by the amount of time that the water has spent in contact with plumbing components (stagnation time) (Health Canada, 2019a) (Health Canada, 2009) (Health Canada, 2019b). Lead is rarely detected in surface or groundwater supplies in Canada (Health Canada, 2019b) and lead components are not used in water equipment or delivery trucks, so the presence of lead would likely be attributed to domestic plumbing systems. Only two samples were collected from buildings in Cambridge Bay, and neither of these samples exceeded Health Canada's MAC (5 ug/L). Historically public housing buildings across the territory are commissioned by Nunavut Housing Corporation (Nunavut Housing Corporation, 2015) and were constructed by the same limited pool of contractors. Although there is no information available on building-specific conditions in Cambridge Bay, it can be hypothesized that plumbing systems would be similar to those across the territory if the same contractor was used.

The MAC for copper set by Health Canada (Health Canada, 2019a) is 2,000 ug/ L with an AO of 1,000 ug/ L. In 2017, non-routine regulatory samples were taken twice at the high school in Cambridge Bay, the exact location is unknown, however samples showed significantly higher levels compared to samples from the lake, water treatment plant and trucks (Kruskal-Wallis $p < 0.05$). The elevated copper levels at the school align previously published findings. Daley et al (2018) found that over 15% of their samples exceeded the AO for copper in the four Nunavut communities (Daley, et al., 2018). Gora et al (2022) conducted a more comprehensive study in Pond Inlet identifying copper levels ranging from 51 ug/ L to 3,915 ug/ L in random daytime samples from various buildings (Gora, et al., 2020). While there is not enough data for Cambridge Bay to determine if copper leaching exists in other buildings, the minimal amount of copper found in the source water and water trucks suggest that the high school's copper levels stem from plumbing within the building (Figure 4-4). General water quality impacts and NOM are discussed in more depth below, however, it is apparent that further investigation is required to gain a proper understanding on what is causing the release of copper in the high school and potentially in other buildings as well.

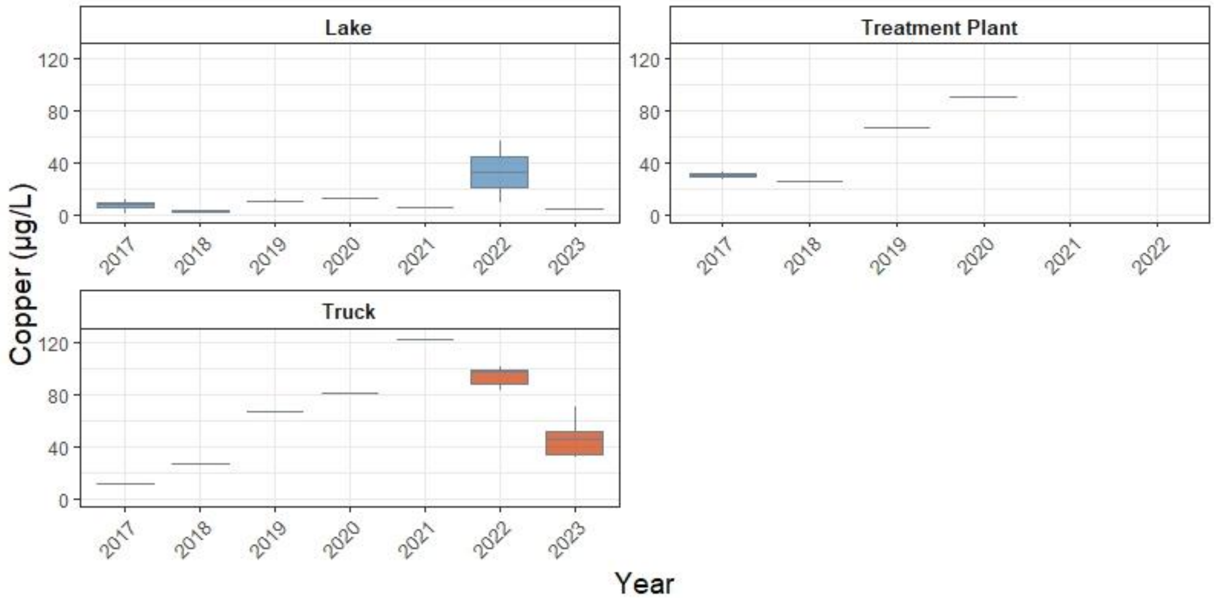

Figure 4-4: Copper levels within the lake, treatment plant, and trucks from sampling events during spring freshet months Sample numbers for each location: lake (#13), treatment plant (#7), trucks (#18)

Other factors that contribute to copper and lead release from building plumbing include: general water quality impacts, natural organic matter, iron and manganese, and building-specific conditions (Gora, et al., 2020). It is known that pH lower than 7 and soft waters can cause corrosion (Health Canada, 2019a). However, pH levels from 2017 to 2023 remained within the range of 7.4 to 7.8, and the water in Cambridge Bay exhibits high alkalinity and hardness (>200 mg L $CaCO_3$) compared with communities in the Kivalliq and Qikiqtaaluk Regions, which all showed relatively low alkalinity (Daley, et al., 2018). This high alkalinity effectively maintains a stable pH throughout the distribution system for corrosion control (Health Canada, 2019a). High alkalinity groundwaters are known to be aggressive towards copper (Health Canada, 1979) (Schock & Lytle, 2011). For instance, tap water samples from relatively new copper plumbing in large buildings yielded copper releases ranging from 1.4 – 2.4 mg/L in water with a pH of 7.4 and alkalinity of 273 $CaCO_3$ mg/L. Similarly, Schock and Fox (2001) reported that in water with a pH of 7.3 and alkalinity of 280 mg $CaCO_3$/L, the 90th percentile copper levels exceeded 1.63 mg/L (Schock & Fox, 2001). However, the data available for Cambridge Bay does not indicate any correlation between hardness, alkalinity or pH with copper release. Further investigation will be conducted in subsequent research within the community to explore this relationship.

Manganese

Health Canada's guidelines set the MAC for manganese at 120 ug/ L with an AO of 20 ug/ L (Health Canada, 2016). Manganese concentrations above 20 ug/L can lead to complaints about discoloured water, staining of plumbing fixtures and laundry, and overall dissatisfaction with drinking water quality (Sommerfield, 1999) (Casale, LeChevallier, & Pontius, 2002) (Kohl & Medlar, 2006) (Tobiason, et al., 2008). Additionally, there are several studies that have linked the consumption of drinking water with elevated levels of manganese to neuropsychological disorders in infants and children (Dobson, Erikson, & Aschner, 2004) (Erikson & Aschner, 2019).

In 2017, manganese levels exceeded the MAC in the source water, treatment plant, and trucks (Figure 4-5 & S4-3). Manganese levels in the water treatment plant and trucks were significantly lower in 2018 than in 2017, coinciding with a major upgrade to the water treatment plant including the installation of three pressure filters. Manganese remained over the AO within the treatment plant and trucks in 2018 but remained below the AO thereafter. Analysis of the 2022-2023 dataset confirmed an ongoing and statistical difference between source water and treated water (Kruskal-Wallis $p < 0.05$). Indicating that the treatment plant upgrades have effectively reduced naturally occurring manganese to levels below the AO.

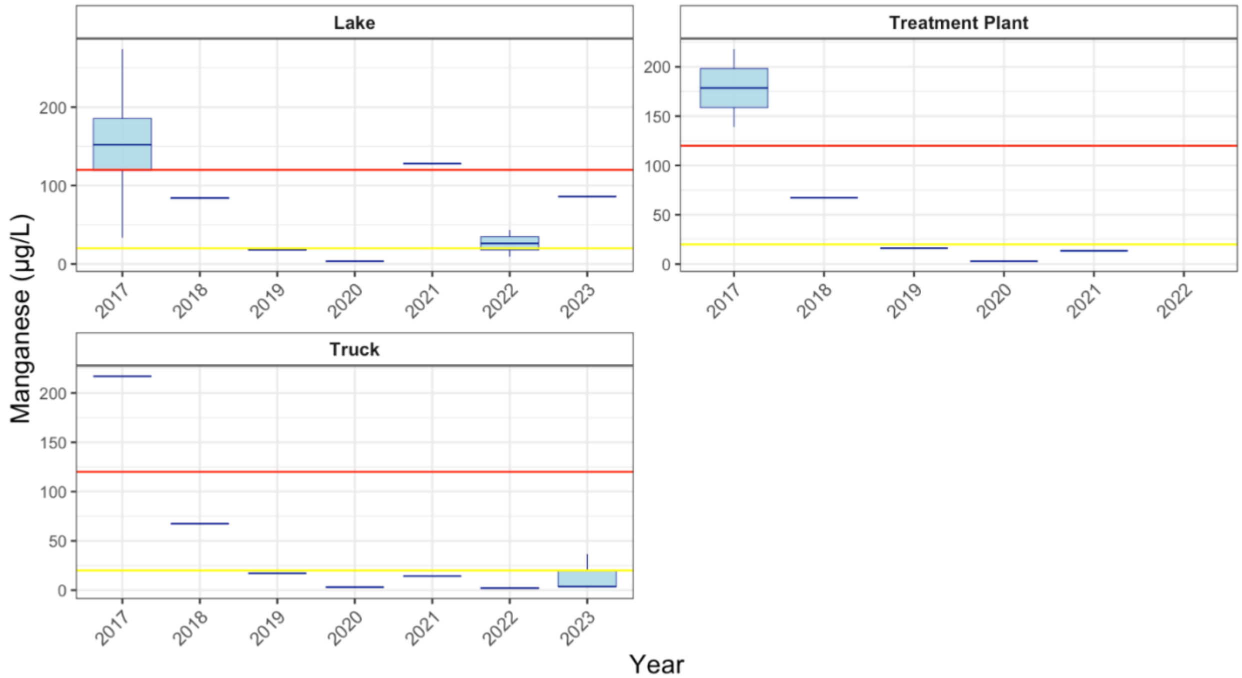

Figure 4-5: Manganese concentrations in the lake, treatment plant and trucks from 2017 to 2023 during spring freshet in Cambridge Bay, NU. Red line represents Health Canada's MAC (0.12 mg/L) and the yellow line represents the AO (0.2 mg/L). Sample numbers for each location: lake (#13), treatment plant (#7), trucks (#18).

Other Metals

Significant variations in aluminium ($p < 0.05$), iron ($p < 0.05$), and zinc ($p < 0.05$) were noted over different years (Kruskal-Wallis), indicating potential variations in general water quality across the system. Water trucks were over the operational guideline for Aluminium (0.1 mg/L) on two counts between 2017-2023, both which were during sampling events taken during spring freshet. There is evidence to suggest seasonal trends of other water quality parameters could influence the levels of aluminium concentrations such as natural organic matter (Health Canada, 2021). Levels of iron did not exceed the AO (100 ug/L) (Health Canada, 2024) after the treatment upgrades, there were significant differences between locations and over the years ($p < 0.05$), suggesting the upgrades was removing natural sources of iron. Similarly, zinc was found to be significantly different between locations ($p < 0.05$) and between the years ($p < 0.05$), but did not exceed the AO (5 mg/L).

Natural Organic Matter (NOM)

NOM was measured as total organic carbon (TOC) and dissolved organic carbon (DOC) during each sampling event from 2017 to 2023 in all locations. Significant differences were observed for TOC ($p < 0.05$), among locations (ANOVA), and DOC ($p < 0.05$) over different years (Kruskal-Wallis). In the source water, ANOVA analysis showed significant differences in DOC and TOC (all $p < 0.05$) over the years.

Cambridge Bay's DOC results during spring freshet ranges from 7.2 to 9.5 mg/l depending on the year (Figure 4-6, Table F4-3). This range of DOC is consistent throughout the system, which is the be expected since the coagulant system is offline and thus there is no treatment for NOM removal. NOM, left in water can lead to THM levels surpassing recommended guideline limits, and will also increase chlorine demand reducing disinfection effectiveness even with dosages aimed at achieving 4-log removal for viruses (Dillion Consulting, 2023).

Beginning in 2022, sampling was carried out on all trucks for physical and chemical water quality parameters. The dataset contains data points from March and June which are the start and end of spring freshet (Figure 4-7). Within the trucks, DOC was significantly different in the sampling events June 22 and September 22 ($p < 0.05$) indicating a seasonal variation in DOC. There is a wide range of DOC values measured during sampling events in the trucks in 2022 (5.60 mg/L in September and 9.20 mg/L in June). This variation can also be seen in the source water, indicating that the treatment processes in the plant are not removing DOC. ANOVA analysis revealed significant differences in DOC ($P < 0.05$) and TOC ($P < 0.05$) in the source water between sampling events. In June 2023 the sampling point was taken from the surface of the lake rather than where the intake draws water from, providing an outlier in the data, this data point was removed.

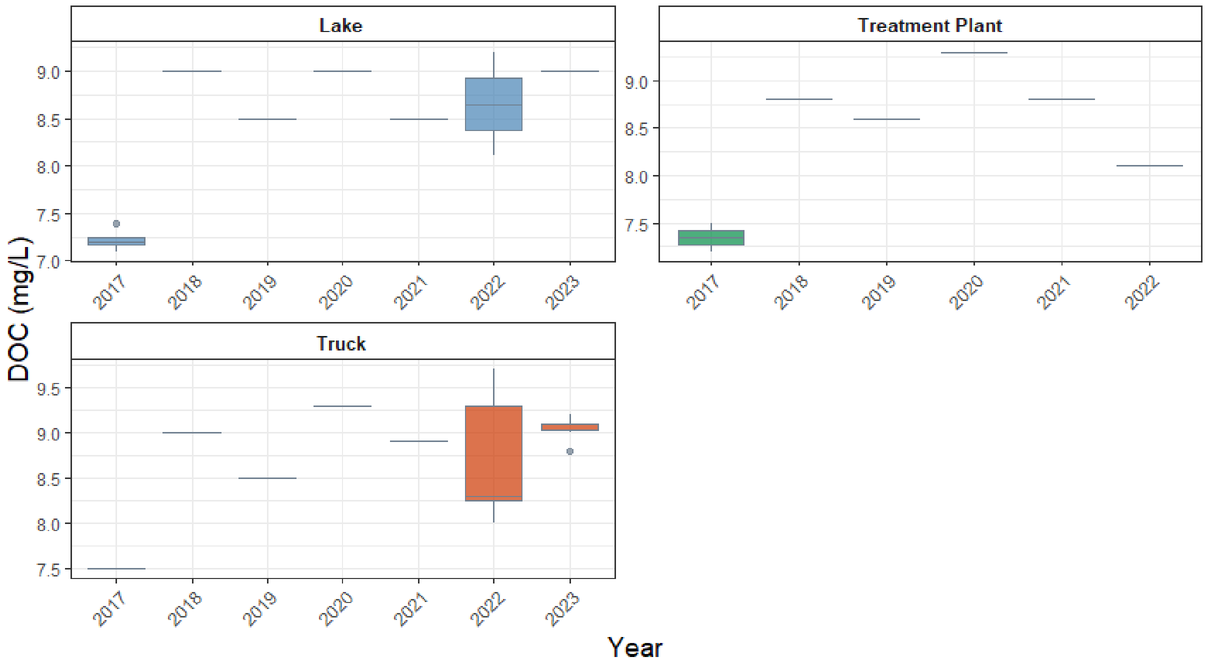

Figure 4-6: Dissolved organic carbon levels in the lake, treatment plant and truck in Cambridge Bay, NU. No removal of NOM from treatment plant.

UV transmittance (UVT) is commonly measured ahead of UV disinfection systems to ensure that an adequate amount of UV light can travel through the water to inactivate the target microorganisms. UVT is usually measured and reported at 254 nm, which is the wavelength emitted by low pressure UV lamps. UVT is also widely used as a measure of NOM in drinking water because aromatic NOM compounds like humic and fulvic acids absorb UV light [68]. UVT measurements only began in September 2022 and measured values ranged between 79% to 91%, with three out of four sampling events not meeting the minimum UVT requirement of the UV disinfection system of 85%. UVT was converted to UV_{254} to determine the specific ultraviolet absorbance. All sampling events were below 2 L mg^{-1} m^{-1}, indicating there may be challenges removing NOM through enhanced coagulation should the system be brought back online (Health Canada, 2020).

Disinfection By-products

DBP formation is a function of three factors: Chlorine dose, holding time, and the characteristics of the organic matter present in the water (Kalita, Kamilaris, Havinga, & Reva, 2024; Hua, Chao, Huang, & Huang, 2020). Cambridge Bay does not record the chlorine dosage. Instead, the chlorine feed rate is changed daily to maintain a free residual of roughly 1 mg/L in the treated water tank prior to entering the truck fill. The free chlorine residual is monitored in the trucks after they are filled (Figure F4-3) and historical data indicates that at this stage free chlorine ranges from below detection (0.02 mg/ L) to 2.1 mg/L and an average of 0.48 mg/L from 2017 to 2023, with many measurements below the limit of detection of the instrument used for analysis.

Figure 4-7 shows the concentrations of DOC and THMs recorded within the water trucks from 2022 to 2023. The concentration of THMs was also normalized by DOC (THM/DOC), an approach widely used in applied drinking water treatment studies to provide rough information about the propensity of the organic matter present during a given sampling event to interact with chlorine to form THMs (Golea, et al., 2017). There was a statistically significant difference between sampling events for DOC, THMs, and THM/DOC ($p < 0.05$), which indicates a potential for a seasonal influence on the levels of these parameters (e.g. THMs were 70-80 ug/L in Sept 2022, and 150 ug/L in June 2023).The results suggest that the quantity of DOC appears to have had a stronger influence on THM formation compared to the NOM's reactivity towards chlorine as measured by THM/DOC, i.e. the humic content of the water (Figure 4-7). For example, March 2022 had DOC levels of 8.0 - 8.3 mg/L, but the THM/DOC was lowest of all sampling events (0.0135-0.014 mg/L). This period corresponded with THMs exceeding the MAC. Further investigation is required to comprehend the dynamics of THM formation and DOC in Cambridge Bay, which may influence the treatment of the source water.

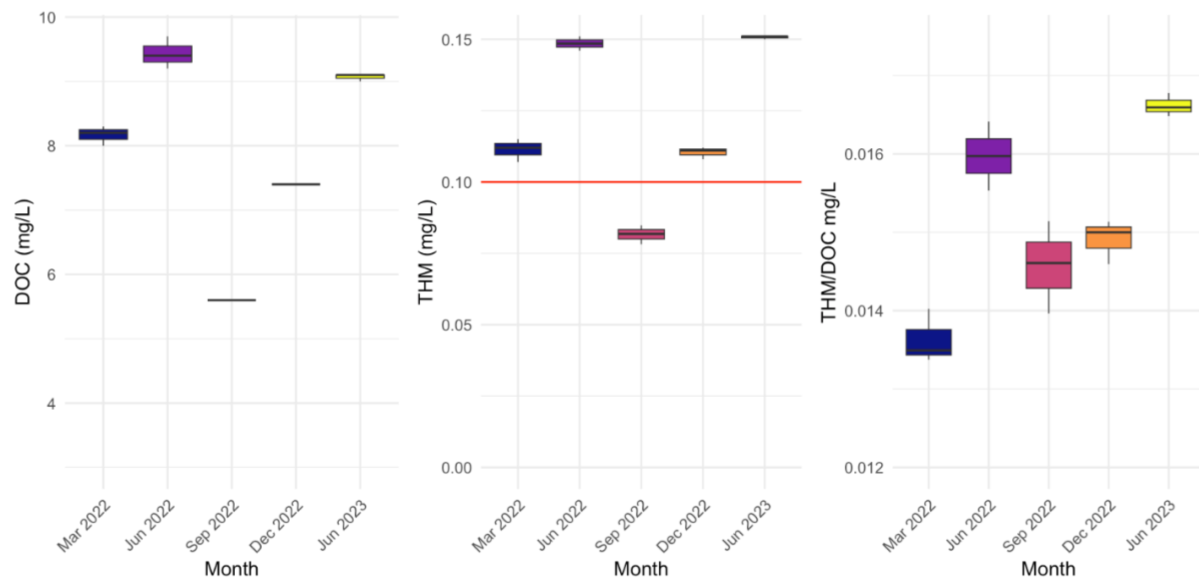

Figure 4-7: Left – DOC within each truck during sampling events in Cambridge Bay, NU. Middle - THMs within each truck during different sampling events red line indicates Health Canada's recommended MAC for THMs in drinking water (0.1 mg/L) [24]. Right – DOC/THM from March 2022 to June 2023 from samples taken from the water trucks.

Correlations Among Different Water Quality Parameters

Spearman's correlation analysis was conducted to examine relationships between water quality parameters. Clear relationships were observed (Table F4-7), particularly between the formation of THMs and DOC levels with a strong correlation ($\rho > 0.90$) in the 2022-2023 dataset.

DOC and THMs

The formation of THMs is a result of chlorine disinfectants reacting with organic matter (Health Canada, 2006)·, Figure 4-8 illustrates a distinct relationship between the formation of THMs and DOC. However, likely due to the inconsistent sampling performed between 2017 and 2023, our analysis of seasonal trends was inconclusive.

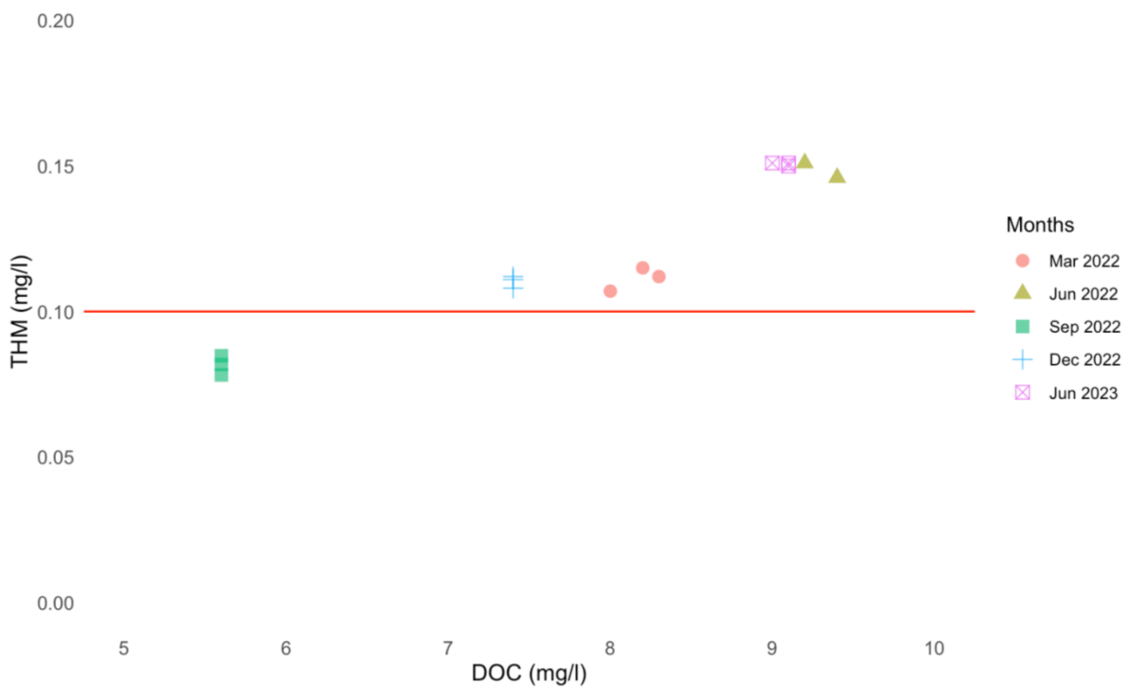

Figure 4-8: Correlation of DOC and THMs in Cambridge Bay, NU. The red line represents the maximum allowable concentration of THMs of 0.1 mg/L [24].

TOC and Copper

There is evidence suggesting that NOM can facilitate copper leaching (Health Canada, 2019a). Arnold et al, (2012) found that a TOC reduction to 0.25 mg/ L was required to sufficiently control copper release which was consistent with other researchers (Arnold, Griffin, & Edwards, 2012; Edwards & Sprague, 2001; Edwards , Schock, & Meyer, 1996; Korshin, Pery, & Ferguson, 1996).

There was no statistical relationship between TOC and copper release within the trucks. Sampling techniques can vary from project to project, depending on the knowledge and training provided to operators. From the authors' experience working with water operators in Nunavut, it is common practice for the operators to take samples directly from the truck hose without flushing. Samples taken can be considered grab samples. Copper, showed an unusual trend within the trucks (Figure 4-4 and F4-1) with a significant difference between March 2022 and September 2022 (ρ <0.05) and June 2022 and September 2022 (ρ <0.05). However, copper release within the trucks decreased over time (Figure F4-1).

Copper and Zinc

There was a strong correlation between copper and zinc within the 2022-2023 truck samples ($\rho > 0.85$) and a moderate correlation between zinc and iron ($\rho > 0.54$) (Table F4-7). It is currently unknown if there are some brass fittings within the water trucks. Although levels found within the trucks are not considered elevated, these strong correlations between copper, iron and zinc suggest that corrosive activity is occurring (McFarland, Provin, & Boellstorff, 2012). Further testing is needed to determine the cause and consequence of the potential corrosion.

Summary of Water Quality Hazards Identified in the Historical Water Quality Data

The analysis of Cambridge Bay's historical water quality data identified four major water quality hazards in the community:

- Seasonal DOC elevation in source water that reaches levels that may decrease the effectiveness of treatment and promote DBP formation (not currently controlled by treatment)
- Seasonal elevation of manganese in source water (currently controlled by treatment)
- THM exceedances in delivery trucks
- The copper-zinc relationship suggests corrosion of metallic components in trucks and in building plumbing systems.

4.3.3 Evaluating Water Safety Risks in Cambridge Bay Using the Proposed Water Safety Framework for Nunavut

This paper follows through on steps 2-4 of the framework proposed in Chalmers et al.(2024). Three of the hazards were selected from the water quality analysis and two hazards that have occurred in Cambridge Bay were selected from Table 4-1.

Hazard 1: THMs in Trucked Water

At present THMs are monitored quarterly in water delivery trucks, giving a past frequency score of 2. The water treatment plant has no barriers to remove THMs, so the hazard receives a system readiness score of 4. Due to the association of THMs with carcinogens, this scenario receives a consequence score of 4 for potential chronic illness from long-term exposure. When first upgraded in 2017, the system in Cambridge Bay included ferric chloride coagulation, however, due to corrosion issues coagulation was stopped to maintain the integrity of the treatment plant. GN-CGS has hired a consultant to plan the reintroduction of coagulation for NOM removal, as reducing chlorine dosing is not a viable strategy for DBP while maintaining chlorine residual levels. Until the proposed recommendation from the consultant is implemented the THMs in trucked water will remain high risk with a score of 16 (Equation 5) or 14 (Equation 6).

Hazard 2: Copper in Tap Water

For hazard 2, a past frequency score of 1 was given because two non-routine samples taken in 2017 at Kiilinik High School had copper levels close to the MAC. Corrosion causing copper to leach into drinking water from pipes is not being monitored in the community and there is little information available because water quality testing in buildings is not a regulatory requirement. The high school has water filtration stations which could be offering a sufficient barrier, however, it is unlikely that the same level of filtration is available in individual dwellings and other community buildings. Therefore, a score of 5 was given for system readiness. As copper levels are only above the AO (1000 ug/L) a consequence score of 2 has been given (Health Canada, 2019a). There is insufficient data to inform risk mitigation within the community. However, a small sampling campaign that took place in 2024 by the first author to identify where the corrosion issues are likely to be occurring, that included sampling in the high school. The results will determine if the consequence can remain at a score of 2 or needs to be increased. As there is no ongoing monitoring nor barriers in place for copper levels exceeding the AO in tap water, this risk will remain moderate with a score of 10 (Equation 5) or 8 (Equation 6).

Hazard 3: Hydrocarbons in Source Water Due to Fuel Spill

The hazard received a score of moderate as once identified that a fuel leak from the generator was occurring, the fuel storage was moved to meet the minimum distance from the water source and placed within a bund wall. The past frequency score for hazard 3 was 1 as it occurred in the last 5 years. As interventions have already occurred, as mentioned above, the system readiness score given was a 2. Additionally, monitoring of hydrocarbon takes place 4 times a year within the source water and there have been no exceedances. If the source water were to become contaminated, the community would require identifying an alternative source for water deliveries to continue, while the source water and treatment plant is cleaned up. The consequence score is therefore a 5. This hazard is considered a moderate risk of 10 (Equation 5) and 8.75 (Equation 6).

Hazard 4: Manganese in Tap Water

Prior to the treatment plant upgrades, manganese levels in the treated water were above the MAC (120 ug/L). In 2018 after the new WTP was commissioned the concentration of manganese in the treated water was brought below the MAC and then further reduced to levels below the AO (20 μg/L). A past frequency score of 1 has been assigned as an exceedance has occurred at least once in the last 5 years. Current treatment includes pre-chlorination which oxidizes manganese before water enters the pressure filters, acting as a barrier resulting in a system readiness score of 2. If the barriers were to fail, depending on the season, the highest consequence level would be a 4, as it is possible that manganese levels would be over the MAC. This hazard is of moderate risk of 8 (Equation 5) and 7 (Equation 6).

Hazard 5: Inadequate Water Delivered to Cisterns Due to Breakdown of Truck

Water trucks in Nunavut undergo stress from unfavourable road conditions and extreme temperatures. Water trucks are often run until they fail which time they are placed into the municipal garage to await repairs for weeks or months, interrupting delivery. This has occurred on numerous occasions in Cambridge Bay in the last 5 years. This hazard received a past frequency score of 2. There is no preventative maintenance, only storage in a garage to reduce the impacts from weathering and vandalism. As no parts are readily available for repairs, should there be one or more trucks out of commission for extensive periods of time this would significantly reduce water delivery. Therefore, a system readiness score of 4 was assigned. A consequence score of 3 was assigned, as a reduction in consumption and hygiene is anticipated based on a previous study in Coral Harbour, Nunavut (Daley, et al, 2015). This hazard is considered high risk with a 12 (Equation 5) and moderate in Equation 6 (10.5).

Table 4-2: Use of proposed approach to hazards that have evidence of being present in Cambridge Bay, Nunavut.

Hazard	Hazardous event	Past frequency	System readiness	Consequence	Risk score (E5 & E6)	Risk level
THMs in trucked water	Presence of THM precursors	2	4	4	16	High
					14	High
Copper in tap water	Corrosion of copper piping components	1	5	2	10	Moderate
					8	Moderate
Hydrocarbons in source water	Fuel spill	1	2	5	10	Moderate
					8.75	Moderate
Manganese in tap water	Natural manganese not removed via treatment	1	2	4	8	Moderate
					7	Moderate
Inadequate water supply to buildings	Aging infrastructure - breakdown of water truck	2	4	3	12	High
					10.5	Moderate

Table 4-2 presents the risk scores and levels for both equations. The risk score calculated with E5 (no past frequency) is always higher than that predicted with E6 (includes past frequency). Unless past frequency scores are high ($\geq$ 4), the risk level assigned to the hazards decrease, potentially diminishing the true risk level for the hazard. No hazards reviewed in this paper had a high past frequency score. As previously stated, Cambridge Bay has one of the more comprehensive water quality datasets in Nunavut, but important gaps remain, including information about the occurrences of pathogens such as *Cryptosporidium and Giardia* in source water, a hazard previously identified in Iqaluit (Masina, et al., 2019). If risk equations were applied in other Nunavut communities, the past frequency score could hinder the true risk scores and levels. Instead, past evidence that something has occurred in some part of the territory (See master list in Chalmers et al. (Chalmers, Duncan, & Gora, 2024) and Table 4-2) could be used to develop a template of potential hazards that should be assessed in all communities. Each hazard/hazardous event can be evaluated based on whether a barrier exists for it (Walker, 2023).

Ultimately, the WSP water safety risk matrix approach can only realistically be used to assess discrete hazards/hazardous events that have been recorded in the territory and does not meaningfully engage with the complexity of the governance, climate, and logistical context in Nunavut. New approaches that engage with the system on many levels – design, monitoring, operation, and a wide range of stakeholders, are required to understand and improve water safety in the territory. To improve public health through risk management and optimize operations, the facilitation of the WSP approach needs to be community-specific, collaborative, and iterative. Despite the advantages, however, this approach will impose continuing time demands on community members and other participating stakeholders and will be expensive, which could hinder its adoption, especially over the long term. One potential way to increase potential adoption is through the use of participatory system dynamics. Recent policy changes like the Nunavut Drinking Water Strategic Framework (Government of Nunavut - Department of Community and Government Service, 2023) and the Drinking Water Action Plan (C. Duncan, personal communication) will support the development of rigorous and appropriate water safety management approaches in the territory. The Drinking Water Action Plan is a direct outcome from the strategic framework, and will include all the stakeholders that were identified in the framework to create and deliver the action plan.

4.4 Conclusions and Recommendations

The primary objective of this study, to conduct a case study on the application of a Nunavut specific framework for water safety management and water safety risk matrices in Cambridge Bay, NU was achieved. The secondary objective of characterizing temporal and location-based trends was only partially met because of a lack of available water quality data. This work serves as a foundational study for understanding water quality and water safety risk in Cambridge Bay, highlighting areas that need attention and further research. Design and operational records and historical water quality datasets provided by the Government of Nunavut were used to assess a selection of water safety hazards including metals (copper and manganese) and organics (dissolved organic carbon, disinfection byproducts). With minor exceptions, this dataset represents water from the source, the treatment facility, and within the trucked distribution system. This data established the past frequency score for the selected hazard using the Nunavut water safety risk matrix.

Since upgrading the treatment plant the community is now maintaining levels below both the MAC and AO for manganese and the AO for iron. Copper levels were above the AO localized to tap water, indicating potential plumbing corrosion occurring in buildings. The use of copper pipes could also be an indicator for lead. Lead solder historically has been used in buildings in Nunavut identified in previous studies and could be potentially another hazard to consider (Gora, et al., 2020). The quantity of NOM during spring freshet, as opposed to the composition of NOM, appears to be the driving factor for THM formation (Figure 4-7 and 4-8).

This case study is the first to trial the Nunavut-specific WSP framework proposed by Chalmers et al (2025). Although Chalmers et al. (2025) identified that inclusion of past frequency in the risk equation increased the ability to leverage past data, this case study demonstrated that its inclusion reduced the overall risk score even if system readiness score and consequence scores were high. This is because official past records are extremely limited, resulting in most hazards being assigned low scores for past frequency and consequently low overall risk scores. Therefore, Equation 5, which only considers whether effective barriers are present to prevent the risk of a hazard impacting the community, is preferred for use in the territory.

Suggestions for future research in Cambridge Bay, NU and other Arctic communities include:

- Conduct comprehensive metals testing in various community buildings, including municipal and residential buildings, using different sampling techniques to provide more accurate information on distribution/plumbing water quality,
- Assess and explore potential solutions to improve the water quality in cisterns and explore potential solutions to improve water quality in cisterns,
- Collaboratively assess culturally significant alternative water sources and storage methods outside the municipal system to support community awareness of water quality,
- Collaborate with communities to develop WSPs, thus enhancing community understanding of the watershed, water systems, and home-based strategies to

reduce contamination risk. This will require buy-in from operational staff, community members and local organizations and regulators to support a WSP approach.

Finally, there remains a pressing need to better grasp and incorporate the social, cultural, and economic factors influencing drinking water safety conditions in remote communities, especially those serving vulnerable populations (Daley, et al, 2015; Basedo & Bharadway, 2013; Waltner-Toews, Kay, Neudoerffer, & Gitau, 2003; Black & McBean, 2017). Future research by the first author intends to tackle this through participatory research using system dynamics with community members and drinking water stakeholders in the Territory.

4.5 References

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5. Identifying Drinking Water Safety Hazards Throughout an Arctic Community's Water Supply System

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5.1 Abstract

Arctic communities, ecosystems, and infrastructure are increasingly coming under scrutiny due to ongoing attempts at decolonization and reconciliation with Indigenous groups and the potential for geopolitical conflict in the region. There is also increased attention to the region from various industries because of its economic potential, especially as climate change allows for increased access for development. This increase in attention has highlighted the lack of understanding about drinking water sources and infrastructure in the Arctic. In this study we conducted extensive water quality monitoring in Cambridge Bay, an Arctic community in the territory of Nunavut in Canada, that uses a mixed utilidor and truck-to-cistern water system and has a history of water safety challenges. Three water sampling campaigns conducted in the spring, summer, and fall of 2024, targeted water safety hazards from source to tap that were identified by local stakeholders as well as water safety challenges described by researchers and engineering professionals in previous studies. These included microbial activity in

cisterns, the formation of trihalomethanes (THMs) from natural organic matter (NOM), metal corrosion in buildings, as well as the impact of the spring freshet on turbidity and microbiological activity in the water supply and the treated water. The treated water from the trucks was found to have acceptable levels of free chlorine and low levels of microbial activity, measured as adenosine triphosphate (ATP), however, free chlorine residuals were low, and microbial activity were elevated in many cisterns. The concentration and composition of NOM in the source water varied from one sampling campaign to the next and both were found to have an influence on THM formation. Microbial activity increased in the source water and the treated water over the course of the spring freshet. Lead exceeded Canadian federal health-based recommendations (>5 µg/L) in tap water in 6/50 buildings based on random daytime sampling. Copper exceeded 2 mg/L in 9/50 buildings and 14/50 buildings had >1 mg/L. A water safety hazard risk analysis methodology specific to truck-to-cistern water systems in Arctic communities was used to score each hazard from low to very high risk. Of the eight hazards identified in this study, four were scored high or very high risk. Further investigation into seasonal impacts on source water quality and water treatment processes as well as corrosion in domestic plumbing systems in older buildings across the territory of Nunavut and in other Arctic jurisdictions is recommended to improve understanding of these water safety hazards and to identify appropriate interventions to address them.

5.2 Introduction

Delivering safe drinking water to rural and remote communities in the Arctic comes with unique challenges. Drinking water sources vary across the Arctic and include surface water, groundwater, and even seawater (Chalmers, Duncan, & Gora, 2025; Maréchal, Truelstrup Hansen, & Jensen, 2023), however all Nunavut communities rely only on surface water sources (Chalmers, Duncan, & Gora, 2025). Treatment infrastructure in Arctic communities ranges from simple pumphouses with chlorination to full conventional treatment facilities. Various methods are employed for water delivery across the circumpolar North. In Canada and Alaska, truck-to-cistern systems are common, while in Greenland, overground utilidors are often used. However, many Arctic and sub-Arctic communities still lack access in-home water and sanitation services (Eichelberger, 2010; Eichelberger, 2016; Eichelberger, 2018; Daley, et al, 2015; Berner, et al., 2016; Thomas, et al., 2016; Wilson, 2019).

Previous studies have identified onsite water quality as a major concern in Arctic communities including low free chlorine residuals, especially in cisterns and at the tap (Daley, et al., 2018; Gora, et al., 2020; Duncan, Chalmers, & Gora, 2025; Mahgoub, et al., 2025), elevated microbiological activity at various locations from source to tap (Daley, et al., 2018; Gora, et al., 2020; Mahgoub, et al., 2025), disinfection byproducts (DBPs) (Duncan, Chalmers, & Gora, 2025) (Associated Engineering, 2025), lead corrosion (Daley, et al., 2018; Gora, et al., 2020; Stalwick, et al., 2023), and iron and manganese (Daley, et al., 2018; Gora, et al., 2020; Duncan, Chalmers, & Gora, 2025; Associated Engineering, 2025).

The treatment, distribution and monitoring of potable water in Nunavut are regulated under the Public Health Act, *Public Water Supply Regulations* (1990) (Government of Nunavut, 1990). Routine regulatory water sampling is conducted at the source, within the treatment facility and the municipal water distribution system and do not directly address onsite water quality in homes and other buildings. Monitoring efforts primarily focus on verifying the absence of microbiological hazards and the maintenance of free chlorine residuals in treated water. In contrast, chemical parameters such as natural organic matter (NOM) and metals have been monitored much less frequently. Recent amendments by the GN Department of Health have increased the frequency of sampling and expanded the list of monitored parameters (Government of Nunavut, Department of Health, 2021; Chalmers, Duncan, & Gora, 2025). The Government of Nunavut (GN), which administers the Canadian Arctic territory of Nunavut, is currently prioritizing upgrades to drinking water infrastructure as part of the Nunavut Drinking Water Strategy (Government of Nunavut , 2023). Jurisdiction over onsite water quality is complex in Nunavut, and there is no consistent territorially mandated monitoring of domestic water cisterns or internal plumbing.

Water safety planning is a proactive framework developed by the World Health Organization to assist with improving cooperation and engagement with drinking water stakeholders, technical experts and community members (World Health Organization, 2012). Its applicability in Nunavut has been under evaluation since 2017 (Lane, Stoddart, & Gagnon, 2018). In previous work, we proposed a Nunavut-specific water safety plan (NU-WSP) with a scoring system dividing the likelihood score into two components: a system readiness score and past frequency score. This framework was used to assess hypothetical hazard scenarios based on a Nunavut specific hazard list (Chalmers, Duncan, & Gora, 2025). In subsequent research, the NU-WSP was applied to historical water quality data from Cambridge Bay (Duncan, Chalmers, & Gora, 2025), demonstrating the proposed scoring system reduced the overall hazard risk score, primarily due to limited data on past frequency.

The central goal of the current study was to identify and comprehensively evaluate important drinking water safety hazards in an Arctic community served by a hybrid utilidor and truck-to-cistern water distribution system. The focus was predominately on microbial water safety, the formation of disinfection byproducts, and the presence of metal contaminants like lead, copper, iron, and manganese. Additionally, this is the first study to explore how spring freshet can impact treated water quality in Nunavut. The study will serve as a template for exploring water safety hazards in other Arctic communities and provides baseline data that will enable researchers and territorial stakeholders to apply a water safety planning framework to the management of water infrastructure in Cambridge Bay.

5.3 Methods

5.3.1 Study Site

Cambridge Bay is located on Victoria Island in the Kitikmeot Region of Nunavut. Drinking water is obtained from Water Lake (Figure 5-1). The water is pre-chlorinated at the pumphouse to oxidize naturally occurring manganese in the raw water prior to going through pressure filters UV treatment. The treated water is chlorinated again before entering the municipal water storage tank located next to the water treatment plant (WTP). Water is then distributed either via trucked delivery or the water main (utilidor) (Duncan, Chalmers, & Gora, 2025; Associated Engineering, 2025).

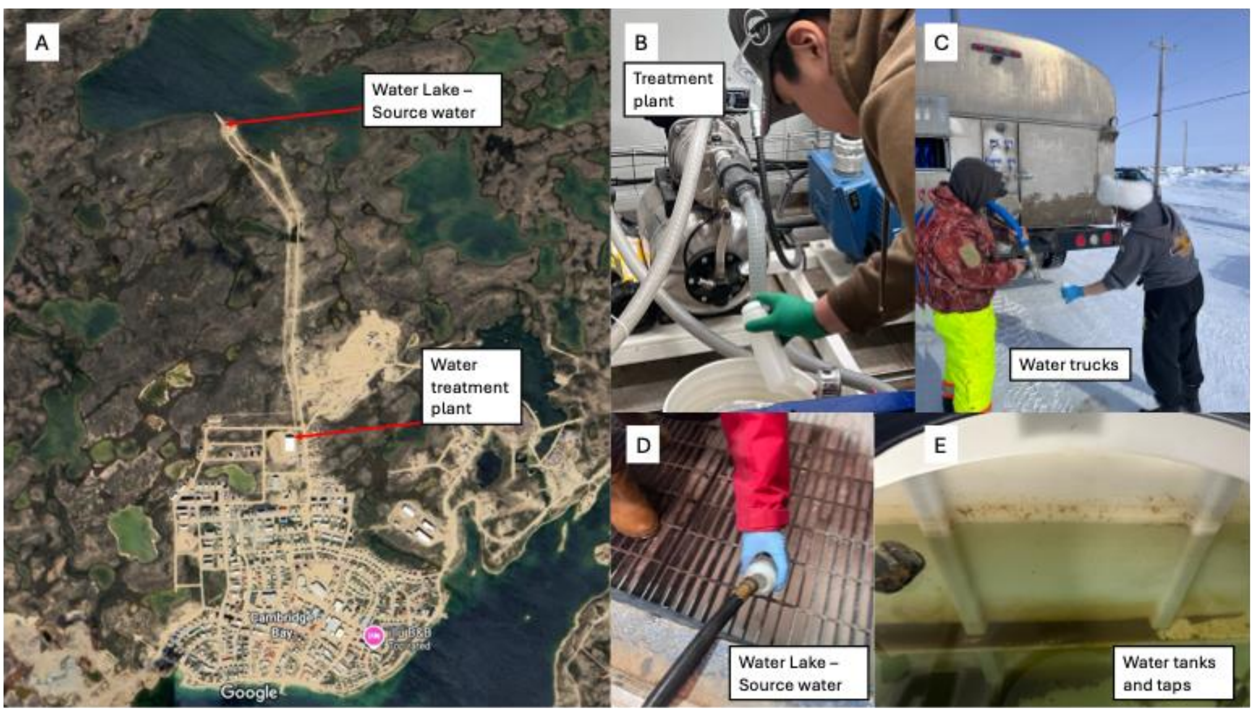

Figure 5-1: (A) Photo of Cambridge Bay, NU taken from Google Maps, indicating the source water and the WTP within the community boundaries. (B to E) Sampling locations, including within the WTP, the water trucks, at the source water and within one of the building cisterns. Taps were also sampled (not shown).

5.3.2 Research Ethics and Recruitment

Prior to research activities, approval was obtained from the York University Ethics Board and the Nunavut Research Institute. Community members and government and technical stakeholders were deeply involved in this research. Volunteer requests were made via the community Facebook page and in person, for researchers to conduct water sampling in homes. Informed consent was obtained from volunteers to allow access to their cisterns (if cisterns were easily accessible) and taps for a short period of time that was convenient on two separate occasions. To maintain the privacy of participants, exact sampling locations are not identified in this paper. All adverse water quality results were reported to building users, local water system staff, and government regulators.

5.3.3 General Water Chemistry and Microbial Activity from Source to Tap

A total of 199 water samples were collected from source to tap over three sampling campaigns conducted between April 2024 and October 2024 and analyzed for general water quality. Sample locations included source water, WTP (before the truck fill and at the core service line), trucks, building cisterns and the first flush at the kitchen sink taps (Table G5-1, Appendix G). Campaign 1 samples were taken over eight weeks spanning April to early June. Campaign 2 was from late June to August and Campaign 3 encompassed a two-week period in late September and early October (Figure G5-5, Appendix G). All samples were collected in duplicate for quality assurance and control purposes.

Sterile wide-mouth HDPE bottles were used to collect water for onsite general chemistry analysis. Standard water quality parameters were analyzed onsite, including pH and TDS (HACH HQ2200 Portable pH/EC/TDS/DO Meter); turbidity (HACH 2100Q Portable turbidimeter); and free and total chlorine (HACH DR300 Pocket colorimeter and DPD reagent). All onsite sample analysis was conducted at the Canadian High Arctic Research Station or the Cambridge Bay Municipal Office.

Caduceon Laboratories, an accredited private laboratory in Ottawa, ON, supplied sampling bottles for the collection of water samples for fluoride, chloride, nitrate, nitrite, and sulphate analysis. These were collected in accordance with their instructions and shipped to their laboratory for analysis using ion chromatography.

Out of these 199 samples, 127 were also analyzed for adenosine triphosphate (ATP), an indicator of microbial activity. ATP was analyzed according to the manufacturer's instructions (LuminUltra PhotonMaster Luminometer and 2nd Generation ATP Quench-Gone Aqueous (QGA) Test Kit. Some sample locations were not analyzed due to shipping delays of materials. Due to the delay for sterilized bottles, we took two 50 mL ATP syringe samples directly from the sample location in the sterile syringe instead of collecting the sample in a sterile sample bottle and dispensing the sample into the sterilized syringe. A t-test confirmed that there was no statistically significant difference between sampling methods.

An additional 100 water samples were collected from the source and the truck fill sample locations from May to June 2024 to evaluate the influence of the spring freshet on source water and treated water from the WTP. Duplicate measurements of free chlorine, total chlorine, turbidity, and ATP were taken from these samples.

5.3.4 Organics and THMs

Samples were collected from the source water, treated water, trucked water, and various buildings in the community and analyzed for dissolved organic carbon (DOC), total organic carbon (TOC), and THMs. Samples were collected in bottles provided by Caduceon Labs, according to sampling instructions provided by the laboratory and analyzed at their central laboratory in Ottawa, Ontario using gas chromatography with mass spectrometry (GCMS) according to EPA Method 8260 for THMs and UV persulfate oxidation with non-dispersive infrared spectroscopy for DOC and TOC according to EPA Method 415.2. Some sample bottles from the source water and water treatment plant were lost in transit by the shipping company during Campaign 2 and Campaign 3.

5.3.5 Lead and Copper

Metals sampling occurred during Campaign 1 and Campaign 3. Samples were collected in 1 L acid washed bottles (2% nitric acid) provided by Caduceon Laboratories, according to their instructions and shipped to their laboratory for lead, copper, aluminum, zinc, manganese, magnesium, iron, and sodium analysis using inductively coupled plasma with mass spectrometry (ICP-MS) or inductively coupled plasma with optical emission spectroscopy (ICP-OES).

Samples were taken from source to tap. Duplicate grab samples were taken from the source water, outlet of the WTP, and trucks during Campaign 1 and Campaign 3. Health Canada recommends three methods for lead and copper analysis in buildings: Random daytime grab sampling (RDT), 30 minutes of stagnation followed by two sequential samples (30MS) and 6 hours of stagnation followed by sequential sampling (6HRS). Samples were collected from the taps in 50 buildings according to the RDT procedure described by Health Canada (Health Canada, 2019b). Two public buildings had two sample taps as requested by community members. These samples were taken as a 'first draw' at random times of the day. However, most participants were available during lunch or directly after work, so samples were usually drawn near these times. Due to resource limitations, only five buildings were analyzed using the 6HRS method (Table G5-1). Through discussion with local council, buildings sampled were either public buildings of interest or participants who were in a position to accommodate the six hour stagnation period. Taps were flushed for 5 minutes prior to the initial six hour stagnation. After six hours, the tap was opened, and four 1 L sequential samples were collected. The tap was then flushed for five minutes and a fully flushed sample was taken.

5.3.6 Data Analysis

Data was reviewed for any anomalies using the z score method. One sample in the TOC data was more than three standard deviations from the mean and thus was removed for statistical analysis. A Shapiro-Wilks test was performed on all the data to test for normality, and there were variations in normality for the parameters. ANOVA, Kruskal-Wallis and Mann-Whitney tests were performed to test for statistical significance ($p < 0.05$) for parameters between samples locations and between samples. R Studio was used for statistical and visual data analysis.

5.3.7 Hazard Identification and Evaluation

Hazards were identified based on documented water safety challenges in the community and/or in other communities in Nunavut (Duncan, Chalmers, & Gora, 2025) and input from community leadership, onsite technical staff, and community members (Duncan, Slowey, & Gora, 2025). The hazards were evaluated and validated based on our water quality results and the NU-WSP proposed in our previous work (Chalmers, Duncan, & Gora, 2025) (Duncan, Chalmers, & Gora, 2025). From the analysis of each hazard, the system readiness and consequence score is provided. See (Chalmers, Duncan, & Gora, 2025) for descriptions. The risk scores were then calculated using the equation from (Duncan, Chalmers, & Gora, 2025):

$$Risk\ score = SR\ x\ C \qquad \text{Equation 5}$$

Where SR is system readiness based on the presence or absence of interventions designed to manage the hazard (e.g. chlorination for pathogen control), C is the potential human health consequence, and risk score is a value between 0 and 25 that describes the water safety risk associated with a given water safety hazard.

5.4 Results and Discussion

5.4.1 Identification of Water Safety Hazards

Water safety hazards were identified based on past academic literature, water quality and operational challenges previously identified in Cambridge Bay and similar communities in the Canadian Arctic, and concerns reported by community leaders, technical staff, and community members in Cambridge Bay.

Hazard 1: Low Free Chlorine Residual in Cisterns

Chlorination is a globally recognized and widely used method for preventing waterborne diseases, and its application is a regulatory requirement in Nunavut. Several studies have found that free chlorine residual often fall below effective disinfection thresholds by the time water reaches the point of use in Indigenous and Arctic communities (Bradford, et al, 2018; Farenhorst, et al., 2017; Martin, et al., 2007; Harper et al, 2011). Low chlorine in cisterns was identified based on previous studies conducted in Nunavut (Gora, et al., 2020; Daley, et al., 2018) and past water quality results in Cambridge Bay (Duncan, Chalmers, & Gora, 2025).

Hazard 2: Microbial Activity in Cisterns

The inactivation or destruction of microbial pathogens is the central goal of drinking water treatment. Microbial activity in cisterns was identified as a potential hazard based on previous studies in Nunavut and Nunavik (Gora, et al., 2020; Mahgoub, et al., 2025) and concerns about microbial water safety expressed by stakeholders in Cambridge Bay (Duncan, Slowey, & Gora, 2025).

Hazard 3: Microbial Activity and Turbidity in Source and Treated Water During Spring Freshet

This hazard was identified by technical staff in Cambridge Bay based on their past experiences managing the drinking water system. This hazard has not been characterized in past studies conducted in Nunavut, though it is well established that water from melting snow and ice can entrain solids as it travels over the land and into surface water bodies, increasing the turbidity of the receiving water.

Hazard 4: THMs in Distributed Drinking Water

Disinfection byproducts, specifically trihalomethanes (THMs), were previously detected at levels above recommended values during regulatory sampling in Cambridge Bay (Duncan, Chalmers, & Gora, 2025) and were identified as contaminants of concern during community engagement sessions led by the lead author (Duncan, Slowey, & Gora, 2025). Elevated levels of NOM have been reported in the raw and treated water in Cambridge Bay (Associated Engineering, 2025; Dillon Consulting & Outcome Consultants, 2021; Stantec, 2018). There is no direct impact on health from consuming NOM, but its presence can interfere with treatment and disinfection processes. NOM interacts with disinfectants, such as chlorine, to form disinfection by-products (DBPs). The formation of DBPs depends on the amount, chemical character and reactivity of NOM in the water. Trihalomethanes (THMs), are associated with adverse health outcomes at levels above 100 µg/L, including increased risks of multiple cancers (Mian, et al, 2018; Diana, Felipe-Sotelo, & Bond, 2019). A previous analysis of water truck samples from Cambridge Bay suggested that NOM quantity had a greater influence on THM formation than NOM composition (Duncan, Chalmers, & Gora, 2025); however, this finding was based on limited data provided to the authors by the Government of Nunavut.

Hazard 5: Lead in Tap Water

Exceedances in lead levels have been identified in several communities in Nunavut. Lead exposure is associated with irreversible neurodevelopmental effects and impaired cognitive function in children and can lead to numerous disorders in adults (Health Canada, 2019b). Until 1986, lead was commonly used in drinking water infrastructure across North America, with lead solder being prohibited in 1990 in Canada. (Health Canada, 2019b). Leaching is more likely to occur in older buildings with pre-1990 plumbing systems, although lead has also been used as a stabilizer in PVC piping and may leach under certain conditions (Zhang & Lin, 2015; Mehdar, 2025). Even 'lead-free' fixtures may contribute to contamination, especially when newly installed (Greiner, Foster , Batog, & Bills, 2018). Lead in tap water has been documented in previous studies in communities in Nunavut (Gora, et al., 2020; Daley, et al., 2018) and was brought up as a concern during initial community engagement activities.

Hazard 6: Copper in Tap Water

Copper often enters drinking water from copper pipes used in domestic plumbing systems. Acute exposure to elevated copper may cause gastrointestinal symptoms, while chronic exposure has been linked liver and kidney failure (Health Canada, 2019). Elevated copper levels, often co-occurring with lead, have been reported in several Nunavut communities. Copper in tap water was identified as a hazard in our past study in Cambridge Bay based on a tap water sample collected by the Government of Nunavut during regulatory sampling (Duncan, Chalmers, & Gora, 2025) as well as in multiple past studies conducted in other communities in the territory (Gora, et al., 2020; Daley, et al., 2018)

Hazard 7: Iron in Tap Water

Concerns around iron have been raised in multiple drinking water studies conducted in Nunavut (Daley, et al., 2018; Gora, et al., 2020; Duncan, Chalmers, & Gora, 2025). Iron is not associated with adverse health effects, however, it can negatively impact the aesthetic quality of the water at levels above 0.1 mg/L (Health Canada, 2024).

Hazard 8: Manganese in Tap Water

Manganese has been linked to neurotoxicity (Dobson, Erikson, & Aschner, 2004; Erikson & Aschner, 2019) and Health Canada has recently lowered the MAC to 0.12 mg/L and the AO to 0.02 mg/L (Health Canada, 2019). Manganese was previously identified as an aesthetic and health concern in Cambridge Bay based on past regulatory sampling (Duncan, Chalmers, & Gora, 2025) and has also been detected in tap water in past studies conducted in other communities in Nunavut (Gora, et al., 2020; Daley, et al., 2018).

5.4.2 Water Quality Results

Hazard 1 and Hazard 2: Low Chlorine Residual in Cisterns and Microbial Activity in Cisterns

A total of 199 measurements were taken for free chlorine and 127 measurements for ATP in the source, WTP, trucks, cisterns and at the taps (Table G5-1). Free chlorine residual levels varied by location, particularly between the WTP and trucks compared to buildings ($p < 0.05$) (max = 1.29 mg/L, min = <0.02 mg/L, median = 0.05 mg/L) (Figure 5-2). Regulations in Nunavut require a minimum of 0.2 mg/L free chlorine residual in trucks prior to delivery. Only once did one of the trucks not meet compliance during our sampling campaigns. In 2023, a private engineering consulting firm determined that a minimum of 0.7 mg/L was required in Cambridge Bay to achieve 4-log removal credits for viruses (Dillon Consulting, 2023). The recommended free chlorine residual was at or above this value in the water at the outlet of the WTP in all three sampling campaigns except for one occasion.

We analysed taps in buildings served by the truck-to-cistern distribution system and taps that were on the core service utilidor line (B1, B6, and B29). We hypothesized that water from buildings connected to the utilidor would maintain a free chlorine residual above 0.2 mg/L, however, we found no statistically significant difference in free chlorine residuals between the two distribution systems. Figure 5-2 shows that some buildings had free chlorine readings above 0.2 mg/L. These residences often were sampled directly after the water truck visited due to time restrictions (confirmed by co-authors with local operations staff and residents).

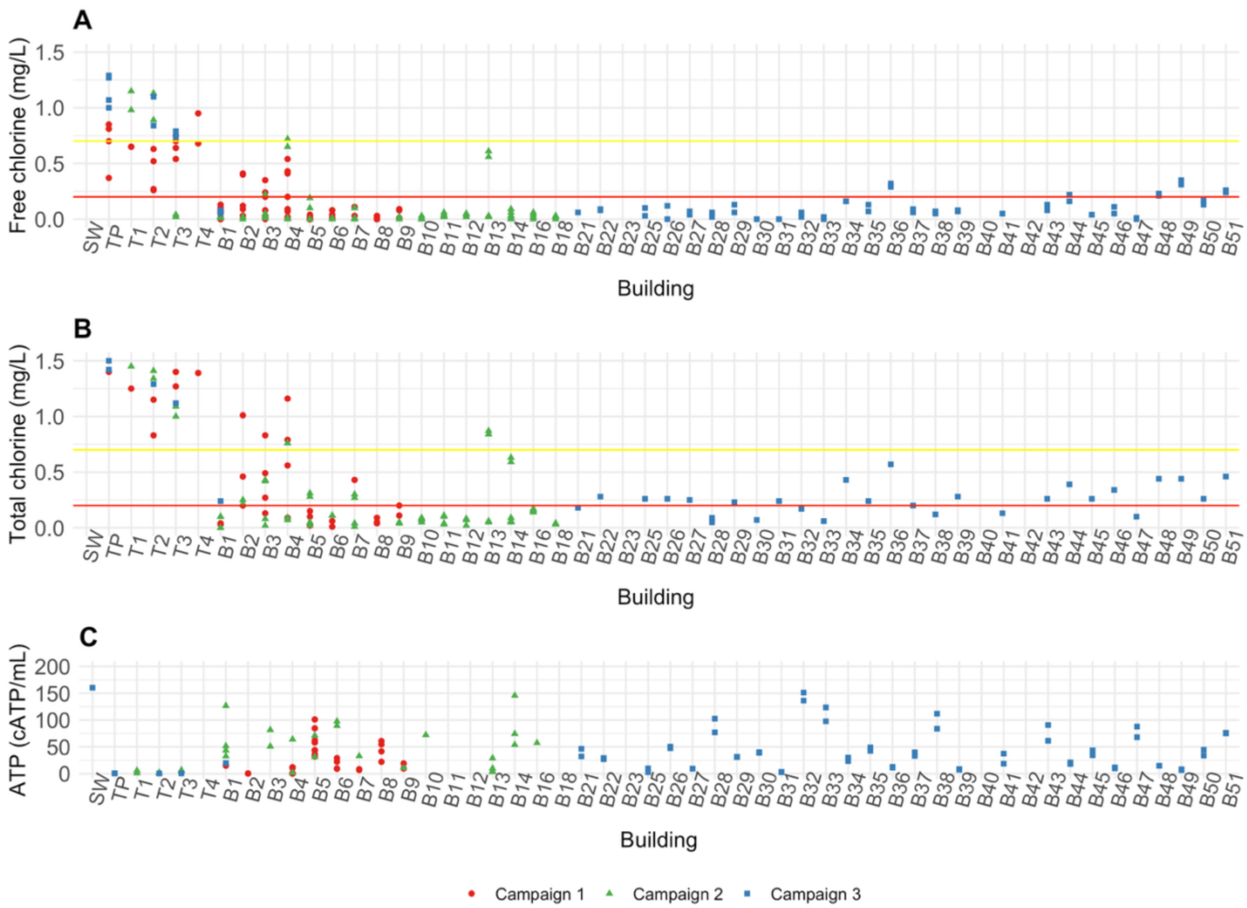

Figure 5-2: (A) Free chlorine, (B) total chlorine, and (C) ATP measured in water samples collected from various locations in the water system in Cambridge Bay, NU during different seasons. The red line shows the current Government of Nunavut regulatory requirement of 0.2 mg/L of free chlorine and the yellow line is the recommended free chlorine residual at 0.7 mg/L leaving the WTP to achieve log-4 removal of viruses through disinfection. Acronyms: SW- Source Water, TP – Treatment Plant, T1-4 – Trucks, B – Building.

ATP results indicated that high levels of microbiological activity were occurring in the water cisterns during the sample period (Figure 5-2). ATP does not provide information about the types of microorganisms present in a sample and we did not test for total coliforms and *E.coli* in this study due to logistical and resource restrictions, so it is unknown pathogens were present in the cisterns. Nonetheless, the elevated ATP results suggest that many of the sampled cisterns provided an environment conducive to the growth of microorganisms. In Figure 5-2, it is clearly shown that levels of ATP in water samples taken from the WTP and trucks had very low microbial activity, so the microbial activity in the cisterns is likely to be related to microbial regrowth and/or recontamination within the cisterns.

The goal of secondary disinfection (i.e. maintaining a free chlorine residual throughout the distribution system) is to prevent microbial regrowth. There was a strong correlation between free chlorine residual and ATP in the cisterns ($\rho = -0.8$, $p < 0.05$) in this study, however only a weak correlation existed in the taps ($\rho = 0.24$, $p = >0.05$). This incongruous result may be related to the locations of the inlet (top) and outlet (bottom) of the cistern, poor mixing within cisterns influencing water age, biofilm formation within cisterns, or interactions between the water and the onsite plumbing system. Plumbing material can vary depending on the age or renovations (Rogers, et al, 1994) and can influence the free chlorine residual and biofilm formation within the pipes from building to building, complicating the expected correlation between free chlorine and ATP at the tap.

Hazard 3: Microbial Activity and Turbidity During Spring Freshet

During initial visits to Cambridge Bay by the researchers, water operators and other technical staff expressed concerns about increases in turbidity and potentially microbial activity during the spring freshet, a time when snow and ice that have accumulated over the winter and early spring melt quickly, replenishing water bodies surrounding the community and potentially entraining solids and other contaminants into surface water (Favaro & Lamoureux, 2015; McDonald & Lamoureux, 2009).

In this study, duplicate water samples were collected from the pumphouse source water hose and the WTP sample tap and analysed every two to three days between April and July 2024. The samples were analyzed for turbidity and ATP as described previously. Turbidity ranged from 0.72 to 2.11 NTU in the source water and from 0.41 to 1.09 NTU in the WTP. There was a significant difference between the source and WTP for all parameters analyzed ($p < 0.05$). There were increases in turbidity and ATP in the source water and ATP for treatment (Figure 5-3) over time with all showing statistically significant differences ($p < 0.05$). In Figure 5-3, an increase in ATP in the treated water can be observed in late June. This suggests that microbiological growth was increasing as the temperature rose, an expected trend that may point towards a need to increase the chlorine dose to deal with the demand. There was no information on daily chlorine dosage available during this time.

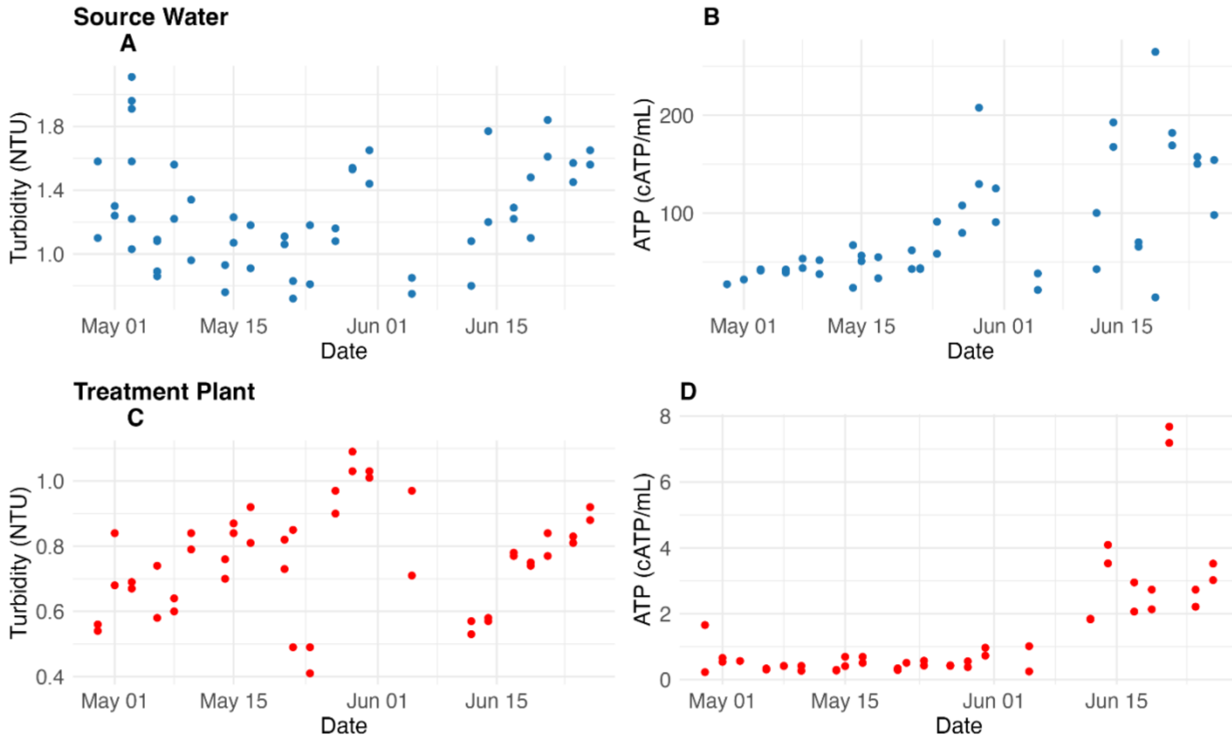

Figure 5-3: (A) Turbidity (NTU) over time in Water Lake, (B) ATP (cATP/mL) over time in Water Lake, (C) turbidity (NTU) over time in the WTP, and (D) ATP (cATP/mL) over time in the WTP.

There was a moderate correlation ($\rho = 0.4$, $p < 0.05$) between turbidity and ATP in the source water (Figure G5-1). Although ATP and turbidity measure different phenomena (microbial contamination and particulate matter), we expected to see higher ATP with increased turbidity; however, the turbidity never exceeded 2 NTU, while microbial activity increased over the course of the freshet period (Figure 5-3). The weather station in Cambridge Bay recorded the monthly average of daily median temperatures as -4.4°C in May and 3.9°C in June 2024 (Government of Canada, 2025). The rise in lake temperature could potentially have impacted ATP levels by increasing ice melting rates and allowing for dissolved oxygen to enter the lake, and consequently increasing the microbial activity (Somers, Strock & Saros, 2020).

Hazard 4: THMs in Tap Water

THMs are formed when NOM interacts with chlorine added for disinfection. Chlorine is added at multiple points in the Cambridge Bay water system, including at the pumphouse where it is applied to the water to oxidize naturally occurring iron and manganese. In Campaign 3 of the current study we identified that THMs were being formed after the initial dose of sodium hypochlorite at the pump station (identified as "before filter"), albeit at levels < 100 µg/L (Figure 5-4). A water quality study conducted by a private firm on behalf of the Government of Nunavut in June 2024 reported similar results (Associated Engineering, 2025). The source and WTP were not initially included during Campaign 1 because the focus was on water quality in buildings. The THM samples collected from the source and WTP in Campaign 2 were lost in transit by the shipping company, so the formation of THMs within the WTP could not be confirmed during these sampling campaigns.

THMs can also form during water distribution and storage when chlorine added for primary and secondary disinfection interacts with NOM that remains in the water after treatment. In this study, 70% of kitchen tap results in homes with water cisterns had THM results above 100 µg/L. However, one location (B5) had much lower THM levels that other buildings sampled in Campaign 1. This location received water deliveries less regularly than other buildings, which may have influenced THM levels, but defining the relationship between water quality and water age in specific cisterns was beyond the scope of this study and the specific frequency of water deliveries to this building was not confirmed. THM levels at the taps were lower during Campaign 3 (fall 2024) than during the two earlier campaigns, potentially indicating that one or more of the elements influencing THM formation (mass and character of NOM, free chlorine dose, water age, etc.) were different during different campaigns.

TOC, which is a bulk measurement of the mass of NOM in a sample, was higher during the first campaign (spring 2024) than in subsequent campaigns. TOC ranged from 5.5 to 10.2 mg/L (median = 6.25 mg/L) in Campaign 1, from 3.1 to 4.4 mg/L (median = 4.05 mg/L) in Campaign 2, and from 4.1 to 4.9 mg/L (median = 4.55 mg/L) in Campaign 3.

THMs ranged from 38 to 169 mg/L (median = 130 mg/L) in Campaign 1, from 111 to 153 mg/L (median = 138 mg/L) in Campaign 2, and from 63 to 88 mg/L (median = 75 mg/L) in Campaign 3. The Mann-Whitney test indicated that there was a statistical difference ($p < 0.05$) between Campaign 1 and Campaign 3 and between Campaign 2 and Campaign 3 for both TOC and THMs (Figure 5-4).

TOC levels were similar during campaigns 2 and 3 but THMs were higher during Campaign 2 than Campaign 3. TOC and THMs were not significantly correlated during Campaign 1 and Campaign 2 but were strongly and significantly correlated in Campaign 3 ($\rho = -0.89$, $p < 0.05$). The mismatch between TOC levels and THM levels during some sampling campaigns suggests that other factors besides NOM quantity are contributing to DBP formation. The ratio of THMs normalized by TOC (THM/TOC) provides information about the reactivity of the NOM towards chlorine. In Figure 5-4, a higher value for THM/TOC in Campaign 2 suggests that the organics in the water in the campaign had a higher reactivity towards chlorine than in Campaign 1 and Campaign 3. Other factors, including free chlorine dose, water age, and other water quality parameters may also have influenced DBP formation.

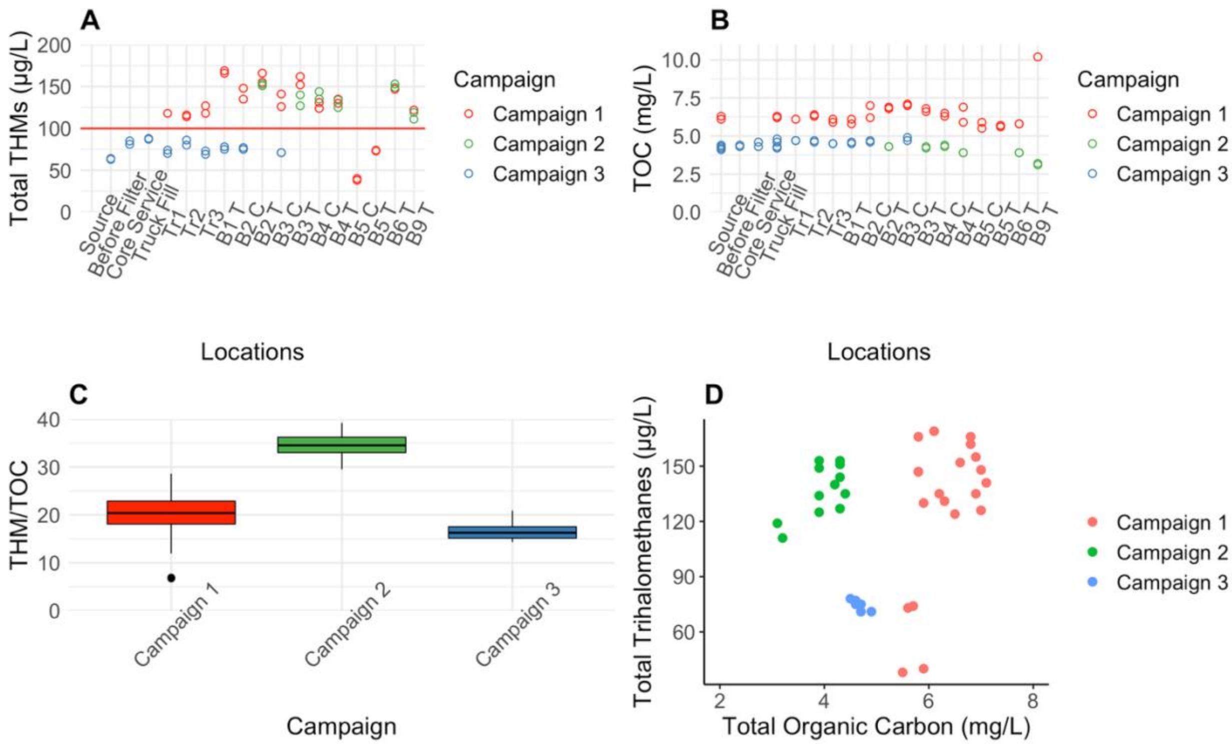

Figure 5-4: (A) Total THMs from source to tap in the three campaigns. The red line represents the maximum allowable concentration (100 µg/L) (B) TOC from source to tap in the three campaigns. (C) THM over TOC in the three campaigns. (D) Correlation of THMs and TOC in the different sampling campaigns.

There are multiple remaining unknowns that require future investigation to determine how chlorine dosage at the WTP can influence the formation of THMs at different times of the year. Further sampling and collaboration with operators are necessary to determine if there are seasonal and/or operational factors influencing DBP formation. High levels of NOM in the water are also known to interfere with treatment processes (Goss & Gorczyca, 2013) but this was not explored in this study.

Hazard 5 and Hazard 6: Lead and Copper in Tap Water

Information collected for hazards 5 and 6 is described in two separate sections below based on the methodology used: Random daytime sampling (RDT) or six hours of stagnation followed by sequential sampling (6HRS). Sample locations were chosen opportunistically based on concerns expressed by technical and government stakeholders and community members who volunteered to be part of the study (Campaign 1) and/or building age (Campaign 3). Although this approach did not result in a perfectly random sample, a sufficient number of buildings (51) was sampled using the RDT method to meet federal guideline recommendations for identifying whether widespread lead and copper corrosion is occurring in a community (Health Canada, 2025).

Random Daytime Sampling

Metals sampling occurred in two of the three sampling campaigns: Campaign 1 between April 2024 and June 2024 and Campaign 3 in late September and early October 2024. Based on RDT sampling, Campaign 1 identified 4/20 buildings (Figure 5-5) and Campaign 3 identified 2/31 buildings (Figure 5-6) with lead levels in the tap water above 5 μg/L.

Campaign 1 was a scoping exercise to gain a better understanding of the potential hazards related to metals in tap water after concerns were raised by community members and technical staff about copper and lead at the tap (Duncan, Chalmers & Gora, 2025). Through this campaign we found that elevated lead readings were mostly associated with buildings built in the 1970 and 1980s while elevated copper levels were more prevalent in buildings built in the 1980s and 1990s (Figure 5-6). The results from Campaign 1 suggested a moderate correlation between lead and copper ($\rho = 0.624$, $p < 0.05$) and lead and zinc ($\rho = 0.534$, $p < 0.05$) and a weak correlation between lead and manganese ($\rho = 0.26$, $p > 0.05$). This information helped inform a targeted approach to sample buildings that were built before the 2000s for Campaign 2.

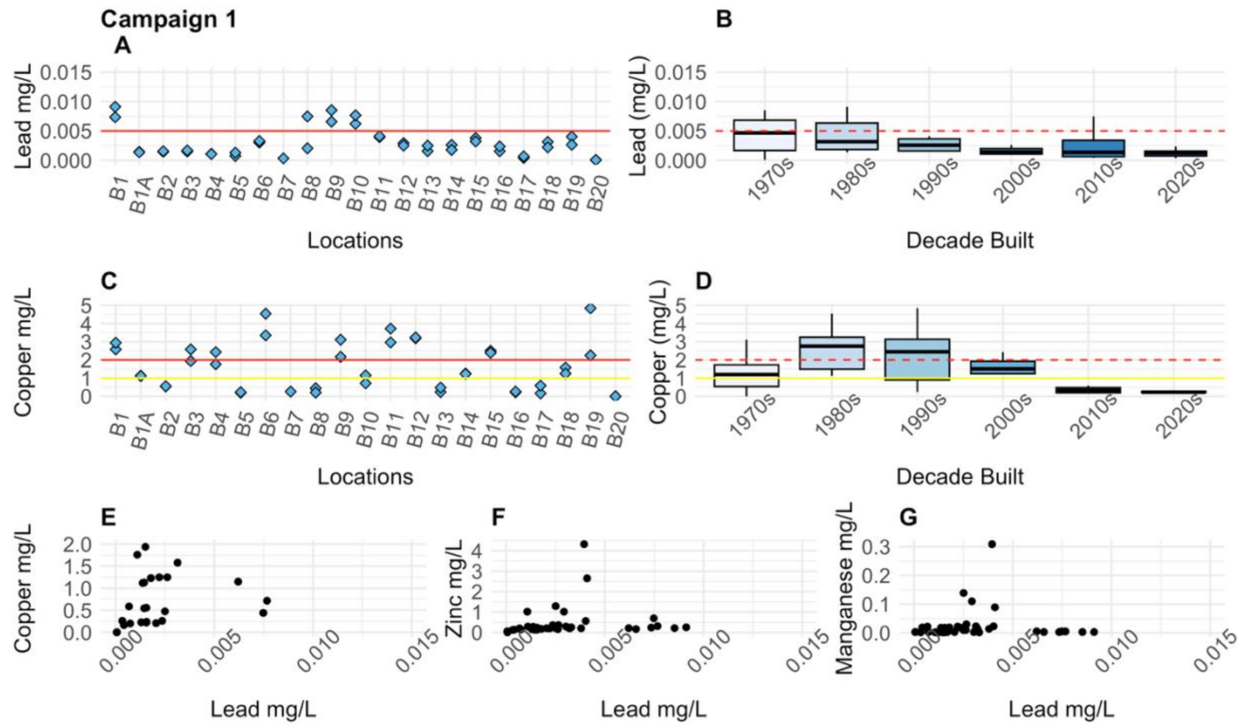

Figure 5-5: (A and C) Random daytime samples taken at various locations during Campaign 1 (spring 2024) for lead and copper. (B and D), lead and copper found in tap water in buildings built in different decades, and (E, F, and G) correlations between lead and different metals in tap water. The red line represents the maximum allowable concentration for lead (5 µg/L) or copper (2 mg/L), the yellow line represents the aesthetic objective for copper (1 mg/L).

Campaign 3 focused on older buildings in the community. We assumed that the updated plumbing code would not have been implemented in Nunavut right away and included a 7-year buffer to take this into consideration. This gave an upper limit of 1997 for building age. The Nunavut Housing Corporation provided an inventory list for all public housing and the owners of private residences who had volunteered to be part of the study were asked to provide the year the building was built. A total of 31 buildings that were built between 1970 and 1997 were sampled using the RDT method in Campaign 3. Overall, there were lower levels of lead and copper in the buildings sampled in Campaign 3 apart from single elevated hits in B24 (9 µg/L) and B37 (12 µg/L). Copper was >1 mg/L in B1 and B41. Weak correlations were found between lead and iron ($\rho = 0.05$, $p > 0.05$) and lead and manganese ($\rho = 0.03$, $p > 0.05$), moderate correlation were found between lead and copper ($\rho = 0.46$, $p < 0,05$) (Figure 5-6).

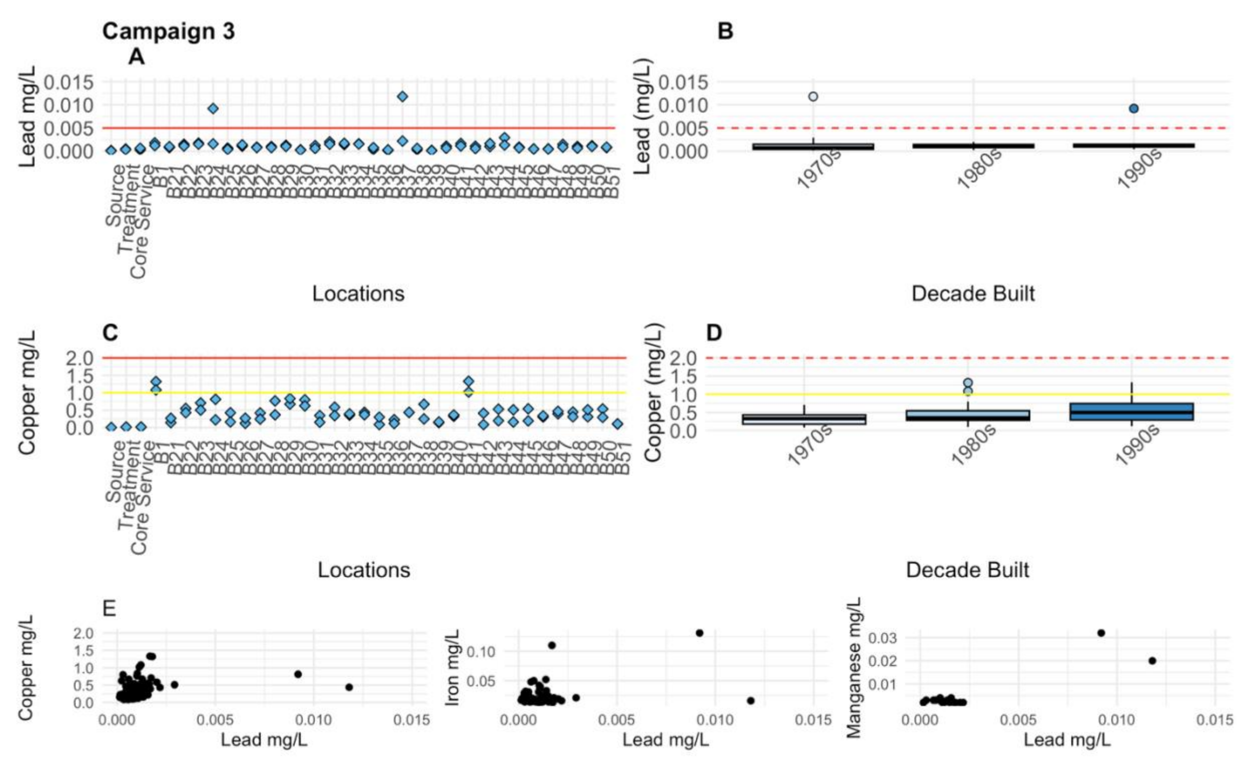

Figure 5-6: (A and C) Random daytime samples taken at various locations in Campaign 3 (fall 2024) for lead and copper, (B and D) lead and copper levels in tap water from buildings built in different decades, and (E, F, and G) correlations between lead and different metals. The red line represents the maximum allowable concentration for lead (5 µg/L) and copper (2 mg/L), the yellow line represents the aesthetic objective for copper (1 mg/L).

The 90th percentile values from Campaign 1 RDT samples for lead (7.35 µg/L) and copper (3230 µg/L) and Campaign 3 for lead (1.7 µg/L) and copper (765 µg/L) suggest that corrosion of plumbing components is occurring within multiple buildings in the community and merits further investigation and corrective action.

Lead and Copper: Stagnation Followed by Sequential Sampling

Sequential sampling after six hours of stagnation (6HRS) was used to identify potential nodes of lead corrosion in the plumbing of five buildings. In many cases, samples taken after six hours of stagnation had at least one sequential sample with lead or copper levels above federal recommendations. Figure 5-7 provides an example of the sequential sampling results for lead based on the results from B24.

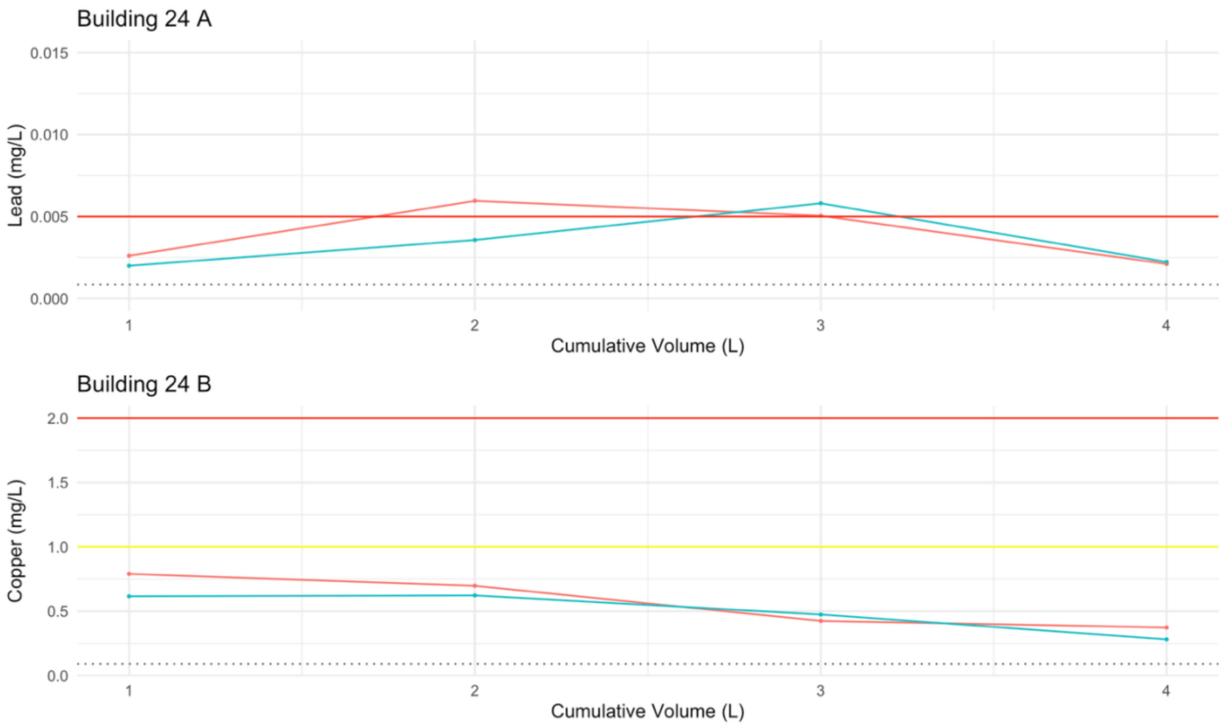

Figure 5-7: Lead (A) and copper (B) results in Building 24 in Cambridge Bay. The red and green line represent separate sampling events. The straight red line represents the maximum allowable concentration for lead (5 µg/L) and cooper (2mg/L) and the yellow represents the aesthetic objective for copper (1 mg/L) recommended by Health Canada. The dotted line represents the concentration of lead (A) and copper (B) in the flushed sample, which is assumed to be representative of the water in the cistern prior to exposure to the internal plumbing.

The results of the sequential sampling were not always consistent with the RDT sampling. For example, B24 had low levels of lead and copper in the RDT samples (Figure 5-6). However, the 6HRS sampling indicated that corrosion was occurring at some point in the system (Figure 5-7). Six-hour stagnation provides an indication of exposure after overnight stagnation but has the potential to overestimate the average lead levels that users are exposed to over the course of the day. Consistent with other research from truck-to-cistern and decentralized systems (Gora, et al., 2020; Schwartz, et al., 2021) our results showed that a five minute flush reduced lead and copper to acceptable levels for drinking (Figure 5-7). Five minutes of flushing may not be feasible for households relying on a cistern with a limited water storage capacity.

Many factors can influence the release of lead and copper from domestic plumbing, including the presence of iron and manganese (Health Canada, 2019b). Iron and manganese in distributed water can co-transport lead released from pipes (Trueman &

Gagnon, 2016; Trueman, et al., 2019). Significant weak correlations were found in 6HRS samples between lead and manganese ($\rho = 0.324$, $p < 0.05$) and lead and copper ($\rho = 0.332$, $p < 0.05$).

The specific source(s) of lead in each building cannot be confirmed without conducting a comprehensive autopsy of each plumbing system. The research team was able to visually confirm that there was copper piping in most of the sampled buildings, however, without access to the full plumbing systems, it was not possible to confirm the total length, age, or condition of the copper piping, nor was it possible to confirm the specific source(s) of lead in the systems with elevated lead levels. Recent studies undertaken by the NSF on lead-free faucets found that these fixtures were still able to release high levels of lead (Greiner, Foster , Batog, & Bills, 2018), particularly after recent installations. Other plumbing components that can release high levels of lead include brass elbows and ferrules and plastic lined connectors (Boyd, et al, 2008). It is unknown if these fittings are used in Nunavut.

Hazard 7 and Hazard 8: Iron and Manganese in Tap Water

Iron levels in Campaign 1 ranged from 0.01 to 0.191 mg/L and 0.015 to 0.131 mg/L in campaign 3 from RDT at the taps. Exceedances of the AO were observed during both sampling campaigns that included metals analysis. All but two samples taken from the building taps in Campaign 1 (spring 2024) were above the AO, and only two samples in Campaign 3 (fall 2024) exceeded the AO. There were no significant differences between buildings in Campaign 1 ($p > 0.05$), however there was in Campaign 3 ($p < 0.05$).

Unfortunately, metals sampling did not occur at the WTP in the first campaign and the sample bottles from the source water and the WTP were lost by the shipping company during Campaign 2, however, the results in Campaign 3 indicate that naturally occurring iron in the source water was not removed by the WTP (source water average = 0.0215 mg/L , WTP average = 0.019 mg/L). Additionally, sampling from the GN took place late June 2024 corroborates this (source water = 0.115 mg/L, WTP = 0.097 mg/L). Taken together, these results suggest, but do not confirm, that there are seasonal effects on iron in the source water and that the existing water treatment system is not optimized for iron removal. Alternatively or additionally, buildings that had iron exceedances may have iron-based plumbing components, however, there is no evidence of these fixtures being used in Nunavut (Duncan et al, 2025) to date. We recommend further investigation over multiple years to evaluate potential seasonal patterns in iron occurrence in the source water and their impacts on treated and distributed water in the community.

Our previous study of historical data provided by the Government of Nunavut determined that manganese levels in the source water varied seasonally and were occasionally above recommended values and also that manganese removal by the WTP had been effective after the installation of pre-oxidation and pressure filtration (Duncan, Chalmers, & Gora, 2025). In the present study, manganese levels in nearly all of the collected samples, including those taken from the source water and the outlet of the WTP, were below the limit of detection provided by the private laboratory that analyzed the samples (0.01 mg/L) with a couple of notable exceptions. Manganese levels at the tap exceeded the AO in Campaign 2 in B24 (0.034 mg/L) and in B17 (0.022 mg/L) and B18 (0.023 mg/L) in Campaign 1. Manganese levels surpassed the MAC in Campaign 1 in B11 (0.309 mg/L) and B12 (0.139 mg/L). B11, and B12 were unoccupied units in multiplexes. It is unknown how long they have been unoccupied for or whether they share cisterns with other units in the multiplex. The lack of use may have contributed to manganese build-up in the cisterns or the premise plumbing.

5.4.3 Evaluation of Water Safety Hazards Using Nunavut WSP Framework

A water safety risk score was calculated for each of the eight water safety hazards described above using the NU-WSP framework originally described by (Chalmers, Duncan, & Gora, 2025). Briefly, the water safety risk score incorporates information about the current water system’s ability to prevent hazardous events (system readiness, G5-2) and the severity of the potential human health impacts of the hazard (consequence, Table G5-3). These are multiplied to yield a water safety risk score and a water safety risk level (Table G5-4). The scoring process for each hazard is described in the subsections below and the final scores and water safety risk levels are summarized in Table 5-1. Hazards have been evaluated as stand alone, and do not take into account the complexity and dynamic nature of each hazard and how they could influence one another.

Hazard 1: Low Free Chlorine Residual in Cisterns

The cisterns and taps sampled during this study contained very low levels of free chlorine (Figure 5-2). Free chlorine is monitored in the WTP and trucks daily based on regulatory requirements but is not measured in cisterns or at taps. A previous study indicated that four log removal of viruses, in line with current territorial requirements, can be achieved if a free chlorine residual of 0.7 mg/L is maintained at the outlet of the storage tank. This is being achieved daily, providing a baseline barrier to low chlorine residuals in the cisterns, however, it is not monitored at the cisterns or taps, resulting in a score of 3 for system readiness. Low free chlorine residual is an indicator of conditions that can promote microbial growth, but is not directly linked to adverse health effects so a score of 3 was assigned for consequence. The water safety risk for this hazard was determined to be 9, or moderate according to the NU-WSP.

Hazard 2: Elevated Microbial Activity in Cisterns

This study demonstrated that many of the water cisterns in Cambridge Bay had elevated microbial activity (Figure 5-2). Although we relied on ATP as an indicator of microbial activity rather than testing directly for indicator organisms (e.g. *E.coli*) or pathogens, the likelihood of gastrointestinal illness inducing microbes being present is greater when overall microbial activity is elevated. The potential consequence of elevated microbial activity on human health did not map directly to the NU-WSP consequence scores, falling between 3 for preventative indicators of health risk and 5 for actual acute health risks but without a direct link to the chronic health risks that would be required for a score of 4 (Chalmers et al., 2025). We nonetheless opted for a consequence score of 4 to communicate the serious nature of this hazard. System readiness was assigned a score of 3 because although microbial water quality is not measured in the cisterns, they are cleaned once every two years by the Nunavut Housing Association, which represents a potential barrier to microbial growth. The water safety risk level for this hazard is considered high with a score of 12.

Hazard 3: Increased Turbidity and Microbiological Activity in Source and Treated Water During Spring Freshet

This is the first time analysis has occurred for this hazard and the water quality data collected in this study confirmed an increase in turbidity and microbial activity in the source water over the course of the spring freshet (Figure 5-3). Turbidity and microbiological activity are indicators of potential pathogen presence, so this hazard was assigned a consequence score of 3. The increase in turbidity and microbial activity in the source water was mostly addressed by the water treatment processes in the plant, indicating that existing barriers are able to remove these contaminants. Although turbidity and microbial activity are not regularly monitored at the water WTP, there are barriers in place within the WTP to remove microbial contaminants (e.g. chlorination) and these are monitored regularly. This hazard does not map clearly onto the NU-WSP criteria for system readiness, so we assigned a system readiness score of 3 to balance the effectiveness of the existing barriers with the lack of direct regular monitoring. The total water safety risk score was determined to be 9 (moderate risk).

Hazard 4: THMs in Distributed Drinking Water

THMs were detected at levels above 100 μg/L in the cisterns and at the taps in multiple buildings during multiple sampling campaigns (Figure 5-4). Currently there are no barriers to prevent the formation of THMs (e.g. NOM removal), but they are monitored quarterly, so a system readiness score of 4 was assigned for this hazard. THMs are regulated as potential carcinogens with chronic human health impacts and as such were assigned a consequence score of 4. The total water safety risk score for THMs in distributed drinking water was 16 (high risk).

Hazard 5: Lead in tap water Lead was detected in the taps at multiple buildings in the community at levels above federal health-based recommendations (Figures 5-5 to 5-7). Lead is not monitored in individual buildings and there are no barriers to lead corrosion in the overall system (e.g. corrosion inhibitor chemicals) or in individual buildings. This resulted in a system readiness score of 5. Lead is a known neurotoxin with well established chronic health effects and was therefore assigned a consequence score of 4, resulting in an overall water safety risk score of 20 (very high).

Hazard 6: Copper in Tap Water

Copper was detected at levels above federal health based water quality recommendations in multiple buildings in Cambridge Bay (Figures 5-5 to 5-7). As with lead, copper enters the water from premises plumbing and there are no barriers within buildings, leading to a system readiness score of 5. Long term exposure to high levels of copper can have negative human health impacts and so this hazard was assigned a consequence score of 4. The hazard is also of very high risk with a score of 20.

Hazard 7: Iron in Tap Water

Iron levels are regularly monitored as part of regulatory sampling in Cambridge Bay. There are barriers to remove naturally occurring iron within the WTP but the water quality data collected in this study and in studies by others suggests that the barriers are not adequate. As a result, this hazard was given a system readiness score of 4. The system readiness score is based on a very small number of data points from the source water and the WTP and should be revisited once additional sampling has been conducted to determine whether the WTP is removing iron at different times of the year. Iron is an aesthetic water safety hazard and was assigned a consequence score of 2, resulting in a water safety risk score of 8 (moderate risk).

Hazard 8: Manganese in Tap Water

Manganese levels above the federal health based recommendation of 0.12 mg/L were measured at some of the taps sampled in this study despite the presence of treatment barriers at the WTP. Our previous study (Duncan et al., 2025) suggested that the manganese treatment process at the WTP was capable of removing manganese from the source water in 2023, but the data collected in the current study was insufficient to determine whether or not the WTP was removing manganese during the sampling campaigns in 2024. In light of this, we assigned a system readiness score of 2 based on the presence of barriers, along with regular monitoring. Manganese is a potential neurotoxin with chronic human health effects and therefore this hazard was assigned a consequence score of 4. This hazard was determined to pose a moderate water safety risk with a score of 8.

Table 5-1: Summary of water safety risk scores calculated for each water safety hazard based on the NU-WSP framework

Hazard	Hazardous Event	System Readiness	Consequence	Risk Score
Low chlorine residual in cisterns	High chlorine demand from organics	3	3	9
Microbial activity in cisterns	No disinfectant to prevent microbial growth	3	4	12
Microbial activity and turbidity in source water and treated water	Increase in activity during spring freshet	3	3	9
THMs in tap water	Presence of THMs precursors	4	4	16
Lead in tap water	Corrosion of lead plumbing components	5	4	20
Copper in tap water	Corrosion of copper plumbing components	5	4	20
Iron in tap water	Natural iron not removed via treatment	4	2	8
Manganese in tap water	Natural manganese not removed via treatment	2	4	8

5.5 Limitations

There were several limitations to this research, many of which are common in studies conducted in remote areas. First, sampling only occurred in one community in Nunavut over the course of one year. Additional sampling in this community over multiple years and an expanded sampling program in other communities in Northern Canada and other Arctic jurisdictions will provide a better picture of the water quality hazards that are associated with communities that rely on decentralized (e.g. truck-to-cistern) or hybrid piped and trucked water systems. Due to the remoteness of the study location, logistics and shipping were occasionally problematic. For example, sample bottle delivery from equipment suppliers to Cambridge Bay was often delayed by weeks or months and filled sample containers sometimes did not arrive at the accredited laboratory because of loss or poor handling by shipping companies and had to be retaken. Additionally, although water quality data is useful, it does not provide the wider context required to fully characterize a hazard or a path forward to addressing it. Influence mapping, causal loop analysis, and participatory system dynamics modelling have been applied in low-income countries to better understand functionality (Walters & Javernick-Will, 2015) and improve sustainability of rural water supply (Valcourt, et al, 2020). These approaches may also be beneficial to Nunavut as the territory works towards standardizing the provision of safe drinking water for all Nunavummiut (residents of Nunavut).

5.6 Recommendations for Future Research

Suggestions for future research activities include:

- Performing further lead and copper sampling campaigns in Nunavut and other Arctic jurisdictions that employ truck-to-cistern water distribution to characterize lead and copper corrosion in buildings, particularly residential buildings older than 1995.
- Further assessing the composition of NOM in water supplies used in Cambridge Bay and other Arctic communities to ensure that new WTPs are equipped with technologies that can reliably prevent the formation of disinfection byproducts.
- Exploring how water safety interventions at the WTP, in the trucks, and within onsite plumbing systems can reduce water safety risks associated with low free chlorine residuals and microbial activity in cisterns and at the tap.
- Investigating legacy and emerging water safety hazards in the Arctic such as hydrocarbons, microplastics, and cyanobacteria and their influence on water treatment and water safety in cold climates.

- Employing research methods like participatory system dynamics to collaborate effectively with stakeholders in Arctic jurisdictions to identify and characterize community-specific and region-wide water safety hazards and hazardous events.
- Investigating the influence that individual hazards have on each other and better understand the complexities of drinking water systems in Arctic jurisdictions.

5.7 Conclusion

The goal of this study was to examine water quality-related water safety hazards in an Arctic community served by a hybrid truck-to-cistern and utilidor water system. Secondary objectives included providing baseline data for future research and government studies, and answering research questions related to seasonal water quality changes that were co-developed with system operators, government engineers, and other stakeholders. Water safety hazards such as THM formation in distributed water, elevated manganese levels in source water, low chlorine residuals, and copper in tap water were carefully characterized to provide actionable information to local water operators, engineers and government regulators. This study also investigated hazards such as lead in tap water, microbial activity in cisterns, and increased microbial activity in the source water and treated water during the spring freshet, that were of concern to community members and other stakeholders that require further research.

Ethics and Funding

This research was conducted under Ethics Certificate: 2024–004 from the York University Ethics Review Board and Nunavut Research License: 04 001 24N-A.

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6. Assessing Water Infrastructure, Operations, and Water Safety in Cambridge Bay, NU Using Water Safety Planning and Participatory System Dynamics.

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6.1 Abstract

Water safety planning, a grassroots collaborative approach to infrastructure management and drinking water safety, has been applied in various jurisdictions across the world. Previous research has explored the potential of water safety planning in Nunavut at a high level, but to date it has not been applied in the territory. System dynamics is a way to address complex health problems and has been proposed as a good fit with Indigenous knowledge because both view the natural and built environments (i.e. infrastructure) as interconnected. Like other infrastructure assessment tools (e.g. PIEVC), water safety planning and system dynamics have mostly limited stakeholder consultation to 'experts' in the field and have rarely engaged community members in the conversation. In this case study we explored the use of water safety planning and participatory system dynamics in a format that facilitated engagement by local residents and other community stakeholders, to understand water safety hazards in Cambridge Bay, Nunavut. Based on water system mapping, hazard identification was spilt into four locations (source, treatment, distribution and buildings). Influence mapping was used to assess feedback

loops and hazard interactions. In this presentation we will present preliminary results of these research activities and describe our own experience of using these tools with local residents and stakeholders. This study represents the first time participatory system dynamics have been applied to characterize infrastructure, operations, and drinking water safety in an Arctic community. The results and the lessons learned during the implementation of research activities have highlighted unique infrastructure, governance, and socially mediated hazards that impact water safety in Cambridge Bay and that may also be present in other Arctic communities in Canada and around the circumpolar Arctic.

6.2 Introduction

The delivery of safe drinking water is a complex undertaking in any community, with many stakeholders involved and the ongoing potential for water safety hazards within the water system. Drinking water safety issues can have disproportionate impact on small and remote communities that have little to no support to put in place safety measures to protect their drinking water from contamination. Unsafe drinking water can in turn impact the social welfare of individuals living in the community (World Health Organzation, 2023). Traditional regulatory monitoring of drinking water, particularly in small remote communities, is not always adequate to ensure its safety.

In Nunavut, where most communities are partially or fully served by truck and cistern water systems, regulatory monitoring for microbial, physical and chemical parameters is at the source water and the point of delivery (Government of Nunavut, 1990). The point of delivery is often defined as inlet of the hose that connects the water truck to the water treatment plant. This results in a knowledge gap about potential risks to drinking water safety during trucked distribution and within building infrastructure such as water cisterns and plumbing systems. Water quality testing at both the source and the point of delivery is infrequent compared to other Canadian jurisdictions, mostly due to the logistical challenges of water sampling and shipping in remote communities with extreme climates. The low frequency of microbiological indicator testing, in particular, does not always allow for timely control measures such as boil water advisories to be issued to avoid hazardous events before water consumption (Bartrum, et al., 2009; Godfrey & Howard, 2005).

There are various tools and frameworks such as water safety planning, PIEVC and systems dynamics that can be used to alleviate these knowledge gaps and that include engagement with a multitude of stakeholders.

Water safety planning is a framework developed by the World Health Organization to promote a more holistic approach to keeping drinking water contaminant free. There are 6 stages as identified in Figure 6-1. The risk assessment step of the WSP process (Task 3) allows us to look at risks individually using tools like risk matrices, but when there is little data or evidence, most hazards are speculative and require significant input from various stakeholders to attempt reaching consensus on the assessment of hazards. Hazards under the WSP framework are considered agents that make drinking water unsafe. Hazards can enter the water system via a hazardous event. Evaluating hazards individually can increase decision bias and end up by-passing hazards that require foresight. Additionally, to date risk matrices haven't incorporated the evaluation of social hazards, e.g., insufficient staffing and its implications. Although not initially considered high risk like lead in taps; without a consistent workforce, a community can be subject to water insecurity, particularly in homes that rely on trucked water deliveries. Furthermore, there are various risk drivers that contribute to the safety of drinking water, some of which are not classified as hazards under the traditional WSP risk assessment because they are not agents or exposure events. Governance related risk are an example of risk drivers that can increase the likelihood of a hazard entering the water system. Although WSP is useful, this approach is limited as it only provides a snapshot in time of vulnerabilities to the water system and requires extensive review to update and keep information pertinent.

Figure 6-1: The water safety planning process as presented in WSP for small communities, adapted from (Bartrum, et al., 2009).

System dynamics (SD) builds conceptual models to dynamically simulate complex interactions and feedback loops within systems (Mashaly & Fernald, 2020). "*The systems approach is a discipline for seeing wholes, a discipline for seeing the structures that underlie complex domains. It is a framework for seeing interrelationships rather than things, for seeing patterns of change rather than static snapshots, and for seeing processes rather than objects*" (Simonovic & Fahmy, 1999). SD integrates many variables and parameters into models, such as hydrological, ecological, economic, political, and social aspects of water management policies, to find suitable and effective solutions to complex and challenging water resources and management issues. (Mashaly & Fernald, 2020). One way to build an SD model is through participatory and shared vision modelling. This approach brings together stakeholders, community members and decision makers to assist with the critical decisions related to the water sector (Creighton & Langsdale, 2009; Videira, Antunes, & Santos, 2009; Beall, Fiedler, Boll, & Cosens, 2011).

In this study, we combined WSP hazard analysis with participatory model building methods to identify priority hazards, hazardous events and risk drivers (Collectively referred to as risk drivers) to build a system structure and perform simulations to test key risk drivers as leverage points to improve water safety in Cambridge Bay. Building on participatory system dynamics methods (Valcourt et al, 2020; Walters & Javernick-Will, 2015; Neely & Walters, 2016; Stave, 2010; Luna-Reyes et al, 2006), this work used a polarity matrix to identify the relationship between risk drivers. A polarity matrix is a tool used in participatory system dynamics to determine if the relationship between variables (in this case risk drivers). In a table format, variables are arranged in rows and columns and stakeholders identify how the variables influence one another (Forrester, 1984).

To make this approach accessible to everyone, the water system was divided into four main locations (source, treatment, distribution, and buildings). Each location presents its own safety and risk issues, requiring appropriate barriers and quality assurance to ensure the delivery of safe drinking water. This paper aims to determine the consensus among stakeholders on risk drivers and to develop a causal loop structure from participatory activities. Finally, this paper will evaluate the participatory methods employed to address the following research question with three primary objectives:

What factors account for the challenges in drinking water safety in Cambridge Bay, Nunavut?

Objective 1. To identify direct and indirect hazards associated with drinking water system in Cambridge Bay.

Objective 2. To determine the interconnectivity of factors influencing drinking water safety hazards in Cambridge Bay.

Objective 3. To assess the effectiveness and appropriateness of the data collection methodology employed in this study.

6.3 Methods

6.3.1 Stages of Research

Research activities were split into four sections (Table 6-1). The details of the methods used in each section are laid out below. There were two workshops held with seven stakeholder groups in Cambridge Bay and with government departments (Stages 1 and 2). Stage 3 included the category analysis of the risk drivers and the development of the initial causal loop diagram from workshop inputs. Stage 4 included developing the stock and flow model, using the risk drivers as variables to build the system structure.

After the group sessions were completed, the lead author conducted the three activities under Stage 3 to review risk drivers:
1. Categorization to assess the importance of non-technical hazards
2. Polarity analysis to determine interconnectivity of risk drivers.
3. Develop causal loop diagram.

Stage 4 is beyond the scope of this paper and is described in Duncan and Gora (not published).

Table 6-1: Outline of activities spilt into four stages of works

Stage 1	**Stage 2**	**Stage 3**	**Stage 4**
First round of workshops and interviews conducted - written word only	Second round of workshops to identify top 10 risk drivers	Categorization of risk drivers and analysis	Development of system dynamics stock and flow simulation model from CLD and integrate water quality data
Information digitalized in Excel	Polarity matrix of top 10	Risk driver polarity analysis	
Risk drivers rephrased for anonymization and sent for approval		Development of initial causal loops on Vensim	

Stage 1

Our previous work presented an initial list of water safety hazards that have been documented in communities in Nunavut in the past (Chalmers, Duncan, & Gora, 2025) and specifically in Cambridge Bay (Duncan, Chalmers & Gora, 2025). The first workshop focused on gaining a wider perspective of the water safety hazards and risk drivers that the community faces.

Workshops lasted one hour and groups had a minimum of 2 participants. A total of 7 stakeholder groups and 27 individuals participated in the research. Stakeholder groups were identified from the stakeholder map in the Nunavut Drinking Water Framework document (Government of Nunavut , 2023).

In Workshop 1, participants were provided with Post-it notes, pens, sharpie pens and four laminated A3 sheets of paper, each of which had a different location pictured on it (Figure 6-2). There were several leading questions which the lead author asked participants to help consider different hazards. Hazards identified in the workshops were the digitalized into Excel with a unique identifier for each group (G1-G7). The hazards were reviewed, rephrased and sent back to each group for verification and acceptance. The rephrased hazards were then consolidated and handed back to all participants.

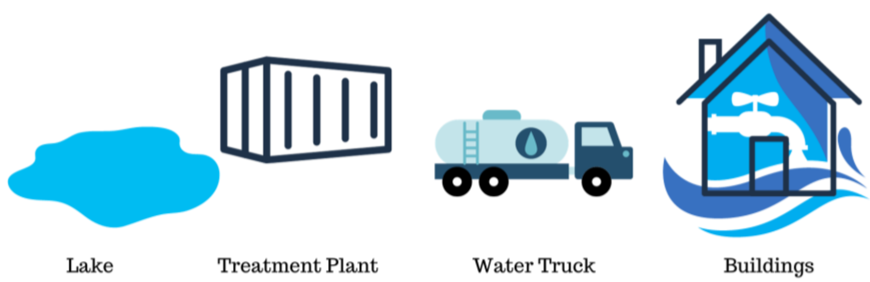

Figure 6-2: Example of location icons used for individual A3 laminated sheets for hazard identification.

Stage 2

Workshop 2 was assigned 1.5 hours; however, the time ranged between an hour and a half and three hours, depending on the stakeholder group. Participants were assigned two tasks to complete within the workshop: 1. To pick their top 10 risk drivers and then 2. perform a polarity matrix on these risk drivers to gather knowledge about the influence the risk drivers had on one another. The risk driver list from workshop 1 was provided to the participants prior to organizing workshops in addition to instructions for the workshop activity.

Task 1*: Review list and identify the top 10 hazards for each location*. This could be done individually, in small groups or as one large group. For workshops that had several groups, they were identified as follows: G3-2.

Task 2**:** *Identify the influence of each hazard on other priority hazards.* A scoring system was provided (Table 6-2) to assess the polarity of influence between the hazards chosen in Task 1. For example, using symbols from the table below options were selected for how Hazard 1 would influence Hazard 2, either: (+) and an increase in Hazard 1 will cause an increase in Hazard 2; (0) there is little or no influence between Hazard 1 and Hazard 2 or; (−) an increase in Hazard 1 will cause a decrease in Hazard 2. For example G7 participants noted that in distribution an "increase" or continuum of inadequate reporting standards for truck could cause an "increase" or continuum in no sterilization procedure for water trucks (Table 6-6). If participants were unsure about the impacts of the hazards on one another then they could use DK for "Do not know".

Table 6-2: Scoring system for Task 2

Impact of hazard		**Source vs Source**			
(-) Negative		Example	1	2	3
(0) Neutral		1		0	+
(+) Positive		2	+		+
Do not know		3	-	+	

Stage 3

Risk Driver Categorization

In Stage 3 the hazards identified by the participants in Stage 1 were categorized by the lead researcher (Duncan) and reviewed by the principal investigator (Gora) to get a better understanding of direct and indirect influences on water safety in the community. Categories consisted of People, Social/Cultural, Environment, Infrastructure, Economic and Policy/Governance. The questions used to identify which risk driver belonged to what category are shown in Table 6-3. The risk drivers identified in Task 1 were analyzed by the researchers to assess which category contained the most risk drivers identified by stakeholders. This analysis aimed to identify which category has the greatest number of risk drivers that impact on water safety.

Table 6-3: Categorization questions for hazards

Category	**Questions for categorization**
People	• How do people engage with the water system? • What behaviours exist that could be a hazardous event?
Environment	• What factors are related to the environment? • How do people and nature interact? • How does the natural world influences community water safety?
Social/Cultural	• What societal programs are in place to reduce hazards? • How are communities contributing to drinking water safety?
Infrastructure	• How does the built environment contribute to hazards? i.e. treatment plants, at home infrastructure for water storage and distribution, use of chemicals for disinfection. • What additional barriers are in place that are not associated with the natural environment?
Economic	• What economic factors are at play and could influence water safety? • What economic challenges contribute?
Policy/Governance	• How do current policies interact with drinking water management? • Are there gaps?

Feedback Loop

To evaluate risk driver interaction, the pairwise polarity matrix was used to identify feedback loops. This is consistent with participatory system dynamics methods used in other studies (Vennis, 1996; Sterman, 2000). Using the polarities identified by participants, feedback loops can be classified as reinforcing or balancing loops. The nature of the loops is determined by the balance of positive and negative relationships within each loop. The matrix outputs were digitized in Excel as a long-form dataset, and links were counted to determine how many stakeholder groups identified similar links. Because hazard sets differed across groups and lacked consensus, we focused on collecting frequency and directional dominance from the data to build the model structure.

The top 10 risk drivers identified by each stakeholder group were reviewed. Several risk drivers could be grouped under a single umbrella term. For example, *equipment failure* might include pump failure, truck failure, water inlet pipe issues at the building, and so on. When assessing the priority hazards and risk drivers, any that could be categorized under an umbrella term were included. This approach was intended to facilitate model building and align with model simplification principles (Forrester, 1971; Sterman, 2000). By collating hazards under umbrella terms such as equipment failure, microbial contamination, or inadequate water supply, it reduced the complexity of feedback loops and made it easier to translate them into a causal loop diagram and stock and flow model (Duncan & Gora, unpublished).

6.3.2 Anonymity

Drinking water can be a cause of tension, and thus all workshops were kept confidential within each group and any information that was redistributed from one group to another was rephrased and anonymized. This was to ensure that all participants were able to share freely without concern of perceived or unperceived repercussions.

6.4 Results and Discussion

6.4.1 Phase 1 & 2: Hazard Identification

Initial Community Engagement and Relationship Building

Before the workshop activities, weeks of in-person engagement with the community had already taken place. This included conducting a Nunavut youth water operator program developed by the Safe and Sustainable Water Research Group at York University. The lead author had also previously visited the community through her employment through the Government of Nunavut. These initial relationship-building activities were key to building rapport and identifying individuals in the community who were part of the different stakeholder groups (Step 1 of WSP) and describing the water system (Step 2).

Step 3 (hazard identification) was carried out in the following workshops, using participatory system dynamics methods. No additional steps under the WSP framework were undertaken as part of this research.

A significant amount of time was required to build rapport with community members prior to workshops commencing. The lead author spent two months in Cambridge Bay attending and volunteering at community events as well as holding the water program in the lead up to holding workshops. The extended trip and multiple engagement activities were influenced by *The Sikumiut Model* (Wilson, et al., 2020) to increase Indigenous participation and knowledge and capacity building in Arctic drinking water research. These engagement activities garnered support by not only the required Council, but also the Kitikmeot Heritage Society – an Inuit led research space. This support confirmed that this research topic was of interest and seen as a priority to Inuit in Cambridge Bay.

Workshop 1

A total of 204 risk drivers were identified by stakeholders during the workshops. There were some risk drivers identified by multiple stakeholder groups; these included *microbial contamination from swimming in the lake* and from *animals defecating*. Some risk drivers were brought up as the community was experiencing a specific problem. For example, a leak in the water main. Additionally, there were "other" hazards that could not be assigned to a single location.

Stakeholders had varying levels of knowledge about water safety hazards at each location. When a stakeholder group worked at a specific site, they were more likely to identify hazards related to that location. However, due to limited knowledge of other areas, they felt less comfortable raising hazards elsewhere. Instead, they shared stories and speculations about incidents that had occurred.

Many of the identified hazards are not classified as hazards under the traditional WSP risk assessment. Traditional WSP risk assessments tend to focus heavily on microbial and chemical contaminants; however, in small system WSPs, these can be regarded as 'external hazards' (WHO, 2012). These "hazards' are more accurately considered governance-related risk drivers, as they are not agents or exposure events. Many of these risk drivers are seen as factors that create conditions for hazards and hazardous events. Nonetheless, for model development, these risk drivers are crucial in understanding the causal pathway. For example, *A lack of regulation of water tanks* leads to insufficient water quality monitoring, increasing the risk of undetected microbial contamination.

Additionally, overarching political risks can significantly impact and should be considered fundamental risks to drinking water safety. While policy and regulation alone do not ensure safe drinking water (Hrudey and Hrudey, 2004; Hrudey and Hrudey, 2019), political commitment is recognised as a vital component alongside technical expertise, good governance, and stakeholder engagement (Roeger and Tavares, 2018). Although not technically hazards, these external drivers identified by stakeholders have the potential to influence the likelihood of hazardous events occurring in drinking water systems in Nunavut.

Risk drivers identified during workshops were often presented as hazardous events, risk drivers, or as something the participant had personally observed or experienced. These risk drivers were revised into a similar format used by WSP risk assessment: risk driver and risk driver event. E.g., "animal faeces" became -

Risk Driver: *Microbial contamination*
Risk Driver Event*:* *Local and migratory animals defecating in the lake*

Workshop 2

Workshop 2 provided insights into what the stakeholder groups identified as priorities. The top 10 risk drivers identified for each stakeholder group were assessed to see where there was agreement on priority hazards. Below, Table 6-4 displays the top 5 hazards identified in each location. These hazards were raised more than four times within the different groups. Umbrella terms, such as equipment failure and microbial contamination, encompassed multiple hazardous events. For example, microbial contamination under distribution was mentioned 19 times. This hazard arises from several risk events related to the distribution system, such as cross-contamination from workers using the same gloves for both water and wastewater trucks, and from unclean trucks.

Table 6-4: Top 5 hazards, hazardous events or risk drivers in each location of the water system in Cambridge Bay, NU, identified by stakeholder groups

Source Water	Treatment Plant	Distribution	Buildings
Inadequate water supply	Low regulatory capacity	Inadequate regulatory reporting	Microbial contamination
Microbial contamination	Equipment failure	Microbial contamination	Inadequate regulations
Lack of watershed knowledge	Extreme weather	Equipment failure	Equipment failure
Global warming, altered aquatic environment	Insufficient water quality testing	Lack of redundant parts	Copper in plumbing system
No water safety plan	Insufficient trained staff	Lack of trained staff	Insufficient personnel

6.4.2 Phase 3: Hazard Categorization Analysis

As part of this study we categorized the hazards from the different locations into six different categories to incorporate other important factors that could influence drinking water safety indirectly. Under the WHO water safety planning a ‘hazard’ is considered to be a biological, physical, radiological or chemical hazard. These all can fall under two larger categories – infrastructure and environment. The approach taken in this research add other categories that have an overarching influence on the delivery of safe drinking water and incorporate IQ. These include: people, social/cultural, economic and policy.

After hazards were reclassified, they were grouped into different factors (Table 6-5). Apart from at the source, where environmental hazards were most common (43%), infrastructure made up 30-40% of all risk drivers identified, with people-related risk drivers being a close second (23-28%). The risk drivers listed in Table 6-4 showed a different pattern. At the treatment plant site, the only category not included was social/cultural. Meanwhile, in the distribution, policy and infrastructure were the dominant factors, and within the building location, infrastructure, and economics were the main risk drivers. Although there were fewer policy and economic risk drivers overall, the same risk drivers were identified repeatedly by different groups.

Table 6-5: Total number of risk drivers identified at each location under the different categories.

Categories	**No. of risk drivers**			
	Source	Treatment	Distribution	Buildings
People	5	8	16	15
Environment	18	3	7	3
Social/Cultural	4	1	6	8
Infrastructure	10	14	19	21
Economic	2	4	4	2
Policy	3	5	9	5

Causal Loops

Feedback Loops and Causal Chains

From the polarity matrix exercise, a total of five feedback loops—including two main reinforcing loops and one causal chain—received consensus among three of the ten groups (Figure 6-3). These were identified at the source water and treatment plant locations, with four out of five loops situated within the treatment plant. Additionally, five feedback loops were identified by two of the ten groups (Figure 6-4), alongside a causal chain. All other causal chains and loops lacked agreement among stakeholder groups. Although there was limited consensus on these causal chains, similarities exist between the identified chains and the top five risk drivers, which had consensus across all stakeholder groups (Table 6-4). Further analysis involved examining the individual polarity matrices, such as Table 6-6, which developed causal chains leading to the water safety level for Cambridge Bay.

Table 6-6: Example of polarity matrix for distribution from G7 workshop 2, representing the interaction of risk drivers

	Inadequate reporting standard of water truck sanitation practices	No sterilization procedure for water trucks	Inadequate disinfection at point of delivery, lack of monitoring	No monitoring of turbidity in trucks	No training in confined spaces leading to physical harm
Inadequate reporting standard of water truck sanitation practices		**+**	**+**	**+**	**0**
No sterilization procedure for water trucks	**+**		**+**	**+**	**0**
Inadequate disinfection at point of delivery, lack of monitoring	**+**	**+**		**+**	**0**
No monitoring of turbidity in trucks	**+**	**+**	**+**		**0**
No training in confined spaces leading to physical harm	**0**	**0**	**0**	**0**	

Note: Many of the risk drivers identified are related to the hazard: microbial contamination.

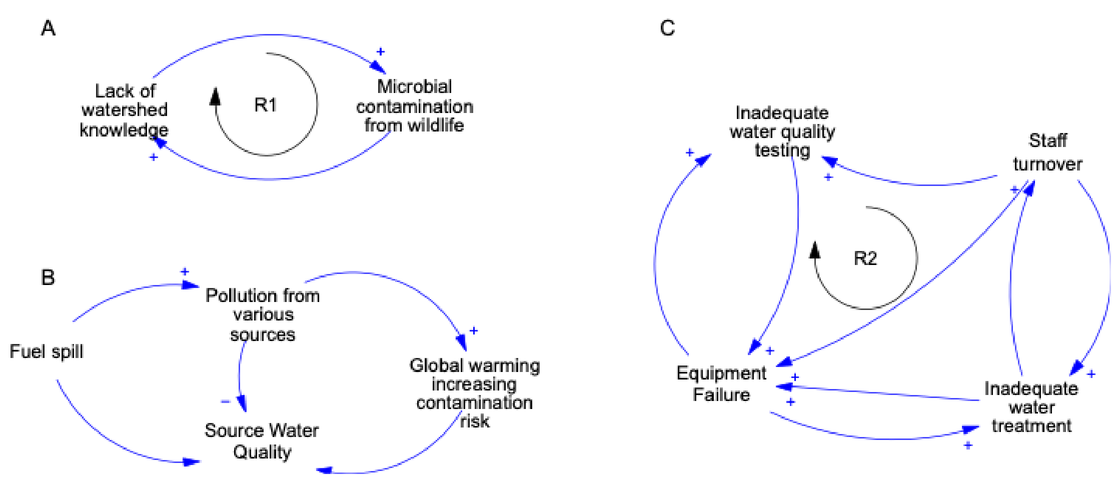

Figure 6-3: A illustrates a closed reinforcing loop involving limited watershed knowledge and microbial contamination from wildlife. B shows a causal chain that all affect source water; however, no loop is formed. C depicts how various hazards can lead to equipment failure in the treatment plant, with a reinforcing loop between hazards.

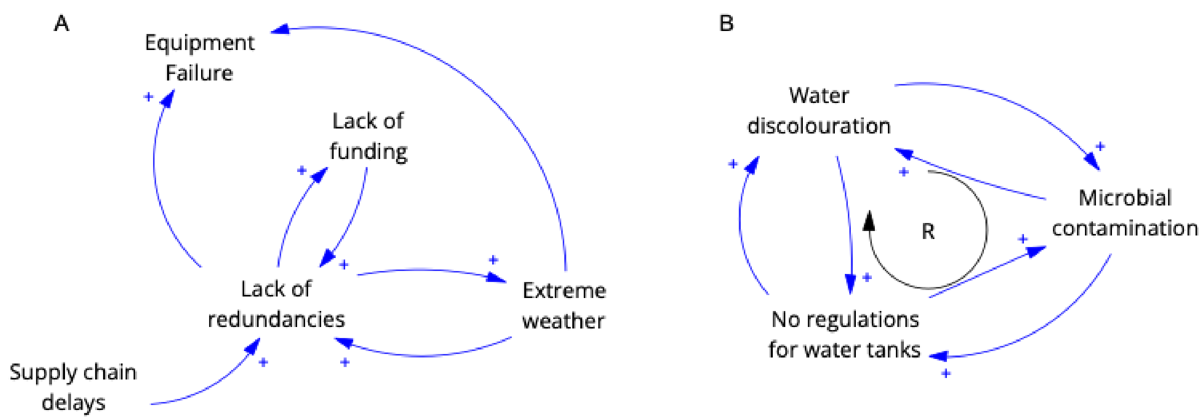

Figure 6-4: A illustrates a causal chain with two closed reinforcing feedback loops within the distribution location. B shows a reinforcing loop of 3 hazards identified in buildings.

The primary feedback loops and causal chains of risk drivers developed from the workshops provided a foundation for constructing a more complex causal loop diagram. Risk drivers could then be transformed into stock, flow and auxiliary variables to develop a stock and flow model. Studies in the Global South that used monitoring programme data (Daniel et al, 2021; Cannon et al, 2021) and participatory system dynamics methods (Walters & Javernick-Will, 2015; Valcourt et al, 2020) to develop causal loop diagrams inspired the creation of this diagram, with variables identified by stakeholders and relevant to Nunavut (Figure 6-5). The system is overall reinforcing, with three reinforcing loops involving technical, environmental, social, and institutional variables.

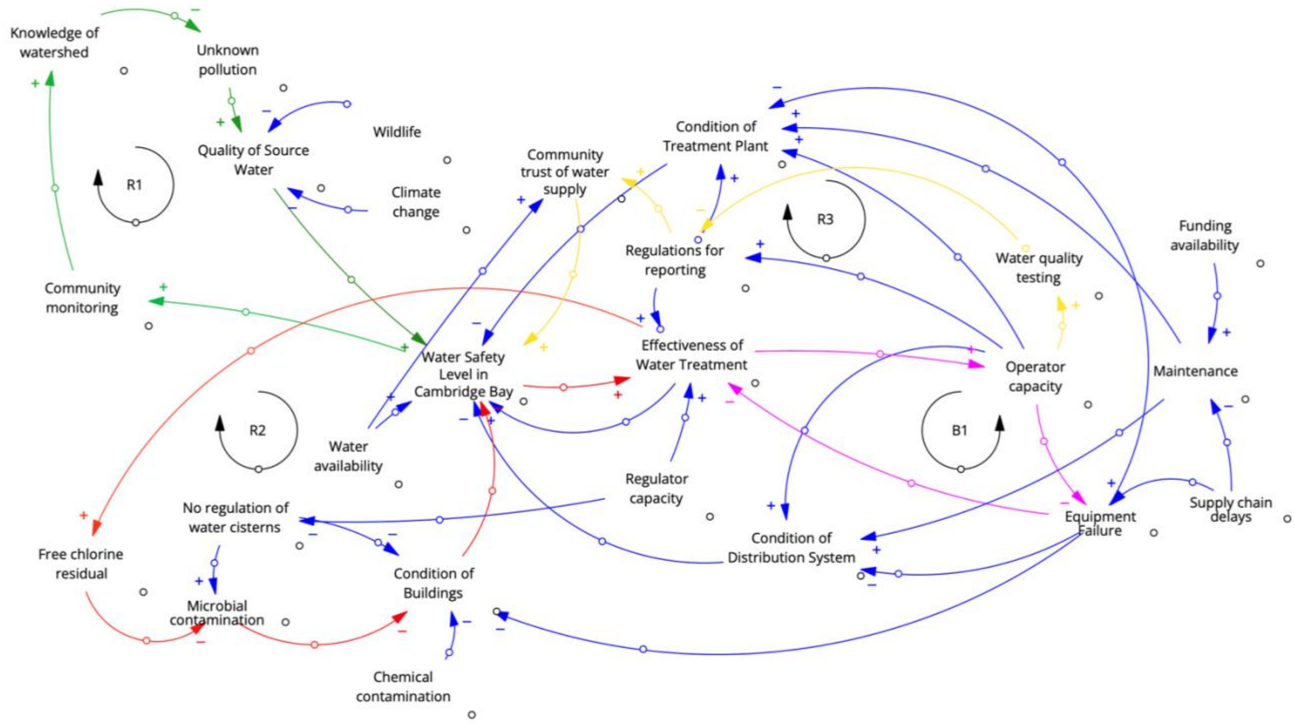

Figure 6-5:Causal loop diagram developed from stakeholder workshops. Green links are related to reinforcing loop 1 (R1), Red links are associated with Reinforcing loop 2 (R2), Yellow links are associated with reinforcing loop 3 (R3), and the pink links are associated with balancing loop 1 (B1)

6.4.4 Limitations

The time and resource constraints for the workshops prevented the development of a cross impact matrix similar to other studies (Walter & Javernick-Will, 2015; Valcourt et al 2020). Reducing the number of priority risk drivers for stakeholders to identify from 10 to 5, may have allowed more time to complete all tasks.

6.5 Conclusions

This study aimed to identify both direct and indirect hazards related to the drinking water system. Since many “hazards” identified were indirect, these were considered risk drivers rather than the traditional hazards as defined by the WSP risk assessment. Some interconnectivity among risk drivers was recognized by the stakeholders, but there was little consensus due to the large number of risk drivers at each water system location. Data collection faced significant challenges from time and resource constraints; however, participants demonstrated a willingness to participate in workshop activities, indicating that this methodology is suitable for engaging Northern communities.

Participatory research demands considerable time, money, and effort to keep it relevant among local residents. Building rapport within the community greatly enhances the development of suitable engineering solutions for Northern communities and allows engineers to incorporate local insights that are often overlooked.

Feedback from Stakeholders

At the end of each workshop, the participants were asked to reflect on their experience participating in the workshop. The participants' feedback was positive. There was curiosity and enjoyment during workshops in addition to a sense of purpose. Some risk drivers identified by participants were seen as tasks that could be rectified immediately within the boundaries of their job responsibilities. There was general satisfaction from participants gathering and interacting to think through the hazards of the water system as a group.

"*This was good, it gave us the opportunity to come together as a team as we're often separated in daily tasks*. *We should do more of this*". (Participant from Group 1).

Reflection on Workshop Structure and Implementation

Workshops varied in their set-up and the researchers were careful to remain attuned to the participants and to provide extra time, information, and high level context as required. The flexibility and fluidity of how the workshops were run was an attempt to encompass Inuit Qaujimajatugangit (IQ). Although materials were provided for participants to write down their thoughts, some groups requested that the lead author scribe while they verbalized hazards in the different locations. Some groups wrote directly onto the laminated sheets while others filled Post-its and stuck them on. Additionally, within groups there were occasionally individuals wanting to participate alone, some forming small groups within the workshop and others participating as one large group. Additionally, one workshop with Department of Environment was held over Zoom, while all others were in-person. Accommodating these different modes of participation was challenging, and the assistance of additional researchers during the workshops would have benefited groups that chose individual and small group work.

Recommendations

The following recommendations were developed based on the researchers' and participant's experiences during the workshops and data analysis phases:

1. Hazards and risk drivers identified in Stage 1 should be categorized into three levels with stakeholder groups to better distinguish between hazards, hazardous events, and risk drivers that could affect the likelihood of hazards occurring in the community.

2. To reach a consensus of over 50%, an extra workshop should be held to review all hazards and further narrow down the risk drivers before the cross impact matrix workshop. This would help to gain a deeper understanding of the key risk drivers for model development.

3. Use refined information from additional workshops, review the causal loop diagram and upgrade the structures with stakeholder feedback.

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7 Integrating Drinking Water Safety Planning with System Dynamics through Participatory Approaches in an Arctic Community

Caroline Duncan[1*] and Stephanie Gora[1]

[1] Department of Civil Engineering, Lassonde School of Engineering, York University

*Corresponding Author

Contributions: Caroline Duncan: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stephanie Gora:** Writing – review & editing, Supervision.

Key Words

Water safety planning, system dynamics, drinking water, Arctic water systems

7.1 Abstract:

The Arctic region can be a challenging environment to supply continuous, clean, safe drinking water. In Nunavut, this is especially difficult due to low capacity, limited training opportunities, extreme weather conditions, and outdated policies. Water safety planning is a framework developed by the World Health Organization that has recently been studied as a tool to identify hazards and risks to communities in Nunavut, with a case study on one community, Cambridge Bay, NU. Participatory system dynamics is another tool, originally designed for industrial systems, where models offer insight into potential strategies for better decisions and effective change. This study aims to integrate the two tools by using hazard information collected in workshops to build a model and simulate high-level mitigation for key hazards that cannot be properly scored under the WSP risk assessment. The study examines six variables that meet the set criteria as potential policy levers. The model explores implementing interventions for these hazards to improve overall water safety in Cambridge Bay. Four of the six modelled interventions predicted increases in water safety to an acceptable level over a 10-year period. Further research is needed for a more detailed analysis of interventions to improve future simulations.

7.2 Introduction

Access to safe drinking water remains a global issue, especially in rural and remote areas where the complexity of delivering safe water is heightened by a lack of capacity in areas such as staffing and funding. Limited capacity often results in little communication among the various stakeholder groups involved in delivering drinking water, leading to silos. Additionally, support for water treatment operators is scarce, resulting in safety measures to prevent contamination not always being followed. Furthermore, traditional regulatory monitoring is not consistently sufficient to guarantee drinking water safety (Charles, Nowicki & Bartram, 2020).

Since 2004, the World Health Organization (WHO) and the Bonn Charter have recommended proactive risk management for drinking water supplies (IWA 2004; WHO, 2004). There are various tools that can be used to support the implementation of the strategic framework and ensure the achievement of objectives for providing safe, clean drinking water. One of these is Water Safety Planning (WSP), which has been used in Arctic water systems by multiple researchers (Lane, Stoddart & Gagnon, 2018; Chalmers, Duncan & Gora, 2025; Duncan, Chalmers & Gora, 2025; Duncan et al, 2026) and has been adopted as a practical policy tool by governments in Canada and 40 other countries worldwide, such as Iceland, Australia, and the UK (Who, 2017).

WSP is an approach for reducing public health risks (Bartrum et al., 2009). A WSP can support the mitigation of potential health threats, as regulations and guidelines specify maximum concentrations for various water quality parameters that affect human health. The updated WSP guidance manual released in 2023 now includes ten modules, organized under the headings: WSP Development, WSP Operation, WSP Verification, and WSP Review and Update (World Health Organization, 2023). The WSP Development phase, after describing the system (Module 2), focuses on identifying potential failures, namely, hazards and hazardous events (Module 3). A common limitation of WSPs is that they often focus solely on the technical and environmental aspects of drinking water delivery, neglecting other hazards related to access to safe, clean drinking water. For instance, the framework document recommends describing hazards using MCRAQ (microbiological, chemical, radiological, accessibility, and quantity) (World Health Organization, 2023). Accessibility hazards can include human and socio-economic factors; there are no guidelines for quantifying these hazards, which can indirectly influence the system. As a result, behaviour and socio-economic risks may be underrepresented. Traditional WSPs tend to be linear and do not account for how behaviour adapts over time. Additionally, conventional WSPs are mainly suitable for standard water systems, with limited guidance available for trucked water systems (Chalmers, Duncan & Gora, 2025). Finally, political considerations often lead to trade-offs among competing hazards (Charles, Nowicki, & Bartram, 2020).

In Canada, water quality guidelines are issued by Health Canada through the Guidelines for Canadian Drinking Water Quality (GCDWQ), which set maximum allowable concentration (MAC) limits for provinces and territories to enforce (Health Canada, 2022). In Nunavut, drinking water remains regulated under the *Public Water Supply Regulations* (Government of Nunavut, 1990), and although the parameter list has recently been updated to include the GCDWQ, many potential hazards are still not considered. Monitoring water quality is limited by available detection methods, treatment technologies, and logistical challenges like transporting samples to laboratories in Southern Canada (Chalmers, Duncan & Gora, 2025). Periodic measurement of water quality parameters alone cannot fully characterize water safety. Ensuring safe water also depends heavily on operations and maintenance (Cannon, Mihelcic, Ghebremichael, & Zhang, 2022). Several studies highlight that treatment and distribution performance suffer due to slow or inadequate repairs, lack of preventive maintenance, and shortages of supplies or poor supply chains (Chowns, 2015; Lackwood, 2004; Sara & Katz, 1997). Similar to rural water supplies, remote communities in Nunavut, due to limited capacity, often follow the common practice of 'run the system to failure and do nothing,' (Boulenouar & Schweitzer, 2015) relying on corrective maintenance only when failures occur.

Governance, cultural and social factors, and individual behaviours, beyond water treatment, can significantly influence risks to drinking water (Daniel et al., 2021). To better understand these complexities, tools and approaches that address dynamic complexity and support the social process of understanding and decision-making are necessary to promote sustainable action (Mahajan, et al., 2019). Several studies have been conducted that predominantly use primary data to improve performance. Various statistical tests are employed to identify which factors need prioritized action (Cannon, Mihelcic, Ghebremichael, & Zhang, 2022; Valcourt, Walters, Javernick-Will, Linden, & Hailegiorgis, 2020). However, these methods have limitations in capturing the complex nature of systems, as they do not account for interactions among feedback mechanisms or emergent behaviours over time (Valcourt, Walters, Javernick-Will, Linden, & Hailegiorgis, 2020).

Systems thinking is a way of thinking that recognises inherent complexity and aims to understand the structure of the systems behind problematic behaviour (Meadows, 2008), rather than focusing only on individual parts like water safety planning. A causal loop diagram developed with rural water stakeholders was used to identify key feedback mechanisms in long-term functionality (Walters & Javernick-Will, 2015). However, causal loop diagrams lack the quantitative ability to explore how different strategies influence outcomes. Using a quantitative system dynamics model is one way to capture feedback loops and time delays to evaluate the effects of various strategies. One approach to building such a model for visualizing complex dynamics is participatory system dynamics (PSD) (Rouwette, Vennix & Mullekom, 2002; Scott, Canvana & Cameron, 2016; Stave, 2002; Stave, 2010; Voinov & Bousquet, 2010). It is especially useful in complex social-environmental-political systems, where high levels of uncertainty and conflict are common. PSD involves collaboratively creating conceptual causal loop diagrams and computer simulation models to better understand a problem and potential policy solutions (Stave, 2010; Sterman et al, 2013; Turner, 2020). These diagrams can help translate implicit knowledge into explicit understanding of a system, enabling participants to learn from one another and from the model itself (Kopainsky, Hager, Herrera, & Nyanga, 2017). Drinking water management in Nunavut involves a range of stakeholders with diverse interests and perspectives. A causal loop diagram (CLD) can serve as participatory tool that fosters trust and consensus among the group during its development. At the same time, it encourages a deeper understanding of how key variables are interconnected (Cassidy, et al., 2022).

Integrating Module 3 (risk assessment) of the water safety planning framework with system dynamics modelling allows for important questions to be simulated within a specified timeframe. Questions such as: what happens to overall water safety if we increase our knowledge of the watershed, modernize the regulatory framework, or expand monitoring capacity? By combining the two tools, it provides a risk evaluation of the entire system, unlike traditional WSP risk assessment. However, the WSP toolkit remains essential for detailing specific risks in a water system, as highlighted in Module 4 Risk Assessment (WHO & IWA, 2023), since system dynamics modelling cannot address operational problems or provide precise solutions (Winz et al., 2009). Nonetheless, using hazards identified under WSP as policy levers can help identify where to focus efforts to reduce system-wide risk over the long term for maximum impact. Both tools are considered holistic, bottom-up approaches to water management, and when used together, they offer crucial information for operators, technical experts, and decision-makers on where to direct investments to improve the safety of drinking water system-wide. This study examines hazards identified through methods similar to those used in Module 3 of the WSP framework (Duncan, Slowey & Gora, 2025; Chalmers, Duncan & Gora, 2025) from a dynamic perspective to determine if they are leverage points within the complex water system, i.e., whether small changes in variables can produce significant impacts across the entire system (Meadows, 1999).

Objective

This study aimed to integrate two well-known tools for optimizing drinking water safety in Cambridge Bay: the WSP risk assessment and system dynamics modelling. This was achieved through four objectives:

- Gather technical and non-technical information about water hazards / hazardous events associated with different elements of the Cambridge Bay drinking water system through stakeholder engagement

- Create a participatory causal loop diagram that highlights both direct and indirect connections between hazards and hazardous events identified by stakeholders.
- Incorporate existing water quality data and WSP results (Duncan et al., 2026; Duncan, Chalmers & Gora, 2025) into the PSD model for validation.
- Simulate modifications to selected hazards to assess their overall impact on water safety.

7.3 Methods

7.3.1 Study Context

The Municipality of Cambridge Bay, located along the southern coast of Victoria Island in Nunavut, Canada, functions as the administrative centre for the Kitikmeot Region of Nunavut. Its water system features a unique ownership and operational structure, employing a hybrid distribution model that includes both a utilidor and truck-to-cistern methods. While the Municipality owns the water treatment plant, its operation is managed by the Government of Nunavut's Department of Transport and Infrastructure Nunavut (GN-TIN). Similarly, the water supplied through the water main is overseen by GN-TIN, while the truck-to-cistern delivery is managed by the Municipality. The Municipality actively monitors both source water and treated water, conducting quarterly physical and chemical sampling in collaboration with GN-TIN and monthly bacteriological sampling (Chalmers, Duncan & Gora, 2025). Within the community, building ownership varies, encompassing both private and public properties, with most being publicly owned and primarily managed by the Nunavut Housing Corporation and, at a more local level, the Nunavut Housing Association.

7.3.2 Participatory System Dynamics Modelling

The system dynamics stock and flow model was built using the Vensim software package (Ventana Systems). The stock and flow diagram includes stocks, flows, and auxiliary variables (Sterman, 2000; Forrester, 1994; Forrester, 1971). Stocks are variables that accumulate or deplete over time, while flows indicate the rate of change (Sterman, 2000). Auxiliaries are variables that have independent meaning outside the flows and can accept multiple information lines (parameters and constants). Constants and parameter variables are often numerical values that describe the characteristics of a system (Pruyt, 2013).

The causal loop diagram developed in Duncan, Slowey & Gora (2025) laid the foundation for the stock and flow model. Causal loop diagrams are useful for illustrating the polarity and connections between variables, but they are limited in identifying stocks, flows, and auxiliary variables (Pruyt, 2013). These terms are described in detail in Chapter 2 of this thesis. Variables that might accumulate were considered potential stocks. This is similar to approaches taken in other studies that employed SD to understand water and/or sanitation systems. For example, stocks could include the *condition of water system infrastructure*, with an inflow of improvements and an outflow of degradation (Cannon et al., 2022), or *increased latrine capacity,* with an inflow of latrine construction (Loo et al., 2023).

SD models are often highly nonlinear and therefore require functions to support nonlinear dynamics (Sterman, 2000; Pruyt, 2013). In the current study, a lookup function was used to define the relationship between a variable and its causes. For example, monthly variations were made to the variable Free Chlorine. This is because water quality monitoring conducted in the community in 2024 found that the free chlorine residual in cisterns was at times below 0.2 mg/L Duncan et al., (2026). With limited multi-year data outside the treatment plant and from water trucks, we could not claim that the residual was always below 0.2 mg/L. Additionally, data from Duncan et al. (2026) showed that the free chlorine residual was not always below 0.2 mg/L in tap and cistern samples.

7.3.3 Risk Drivers for Simulation

The priority risk driver list created during the workshops in Duncan, Slowey & Gora (2025) was reviewed against the simulation analysis requirements (see Table 7-1). Table 7-2 highlights five risk drivers that meet the criteria and can be turned into practical policy levers for the community to explore.

Building on feedback loops and the causal loop diagram presented in Duncan, Slowey & Gora (2025), this led to the creation of the main accumulative stock representing the water safety level. Risk drivers in the CLD were reviewed to determine their relevance to the overarching drinking water system. The umbrella term ‘equipment failure’ was modelled as a negative flow variable from the Water Safety Level stock, specifically an outflow called System Failure. Additionally, multiple risk factors were associated with microbial contamination, but chemical contamination also needed to be considered. To simplify, this evolved into a more comprehensive outflow of Contamination from the Water Safety Level stock. This allowed numerous hazard variables to be incorporated into the outflow equation.

Table 7-1: Requirements that risk drivers need to meet to qualify for simulation

Requirements for simulation analysis
1. Risk Drivers can be identified under the GN Drinking Water Strategic Framework
2. Risk Drivers cannot be assessed by the typical WSP risk matrix
3. Risk Drivers have been identified in the top ten hazards from at least three stakeholder groups
4. Can be considered as practical policy drivers in the model

The WSP format of the risk drivers, hazard and hazardous event (referred to risk drivers from here on out) would produce only reinforcing feedback loops related to water safety. The statements were revised to make them neutral, allowing for increases and decreases in stock levels in the model. For example, a lack of watershed knowledge was represented as a stock called “Watershed Knowledge,” with inflows and outflows of Knowledge Gain and Knowledge Loss.

Table 7-2: Risk drivers *chosen for simulation in stock and flow model*

Risk Driver	Risk Driver Event
Lack of knowledge of watershed	Unknown contaminants of lakes feeding into the source water
Inadequate reporting standards	Water truck sanitation practices not standardized or documented, potential risk of supplying contaminated water
Limited capacity of regulatory agencies	Neglect of water safety concerns due to overextended resources
Inadequate water supply	Increased demand of Water Lake
Outdated regulatory framework	Ineffective oversight of water distribution practices due to regulatory gaps

The risk drivers mentioned can be identified within the model as the following stocks (S), flows (F), auxiliary (A) and constant (C) variables:

1. Watershed Knowledge (S)
2. Unknown Contaminant Risk (A)
3. Reporting Standard Strength (A)
4. Truck Hygiene (A)
5. Regulatory Capacity (S)
6. Supply Adequacy (A)
7. Service Disruption (F)
8. Regulatory Framework Strength (C)

7.3.4 Model Formation

The primary focus of the model is the 'state of the system' represented by the Water Safety Level (WSL). This stock has three inflows (Treatment Impact, Infrastructure Upgrade, Community Change) that can increase WSL, and four outflows (Season Degradation, Contamination, System Failure and Service Disruption) that can decrease it. There are several other stocks within the model that feed into WSL through auxiliaries or flows. These stocks are: Source Water Quality (SWQ), Watershed Knowledge (WK), Infrastructure Condition (IC), Building Water Supply (BWS), Operator Capacity (OC), Regulatory Capacity (RC) and Community Trust (CT). The auxiliary variables in the rest of the model simplify communication and improve clarity (Sterman, 2000). The auxiliary variables offer four ways to simplify the model (Daniel et al., 2021):

1. As constants

2. As exogenous inputs for the stock variable(s)
3. As functions
4. As endogenous variables

The model in the present study was developed using multiple sources, including the Nunavut Drinking Water Strategic Framework (Government of Nunavut, 2023), grey literature (Stantec, 2018;Nunavut Water Board, 2020; Associated Engineering, 2025), water quality data collected by the lead researcher and research assistants (Duncan, Chalmers & Gora, 2025; Duncan et al, 2026), and hazard and risk identification data from previous studies and collected by the lead author during workshops and interviews held with stakeholders in Cambridge Bay (De Coste et al, 2024; Duncan, Slowey & Gora, 2025). Past SD literature was also used as a source of inspiration and guidance (Phan et al, 2021; Cannon et al, 2022; Daniel et al, 2021; Loo et al, 2023; Loo et al, 2025).

WSL serves as the key performance indicator (KPI) and is measured using a water safety index scale from 0 to 100 (Table 7-3). The breakdown of the indices can be compared with the overall risk score in risk matrices. However, the index remains broad in its description of each range. The index functions as a stock variable reflecting improvements and degradations resulting from treatment effectiveness, infrastructure condition, environmental stressors, operational performance, and human behaviour. A baseline safety index of 50 is used in the model. In Cannon et al. (2022), data used for Columbia and Bolivia rural water system performance indices provided initial values of 0.4 and 0.7, determined directly by data from the Rural Water and Sanitation Information System. The index ranges from 0 to 1, where 0 equals no service and 1 equals maximum performance (Cannon et al., 2022). Due to limited quantitative data to draw upon, this initial safety index value is based on knowledge collected by stakeholders and the authors experience; such as the municipality's regular monitoring of the source and treatment, though with minimal oversight from regulatory authorities. Regulations on truck and cistern hygiene have gaps; however, cleaning is conducted annually. Monitoring of contaminants at taps in public and private buildings is inconsistent, and most Nunavut communities lack comprehensive, documented information about their watersheds. To prevent confusion with model variable interpretations (Table 7-6 & 7-7), the Water Safety Index scale ranged from 0 to 100. A target safety index of 70 has been set as an acceptable risk level. As described in Table 7-3, this would equate to a system that has low risk and be considered generally safe with monitoring required. This target safety level is similar to the performance threshold of 0.7 (Cannon et al, 2022). The variables are simulated as individual levers to assess their impact.

Table 7-3: Descriptions of water safety index numbers

Water Safety Index	Description	Risk Score
0-20	Unacceptable risk, immediate action required	Very High
21-40	High risk, controls failing	High
41-60	Marginal safety, elevated risk	Medium
61-80	Generally safe, monitoring required	Low
81-100	Controls effective, low residual risk	Very Low

Constants used in the model such as Truck Capacity and Max Operator Capacity were estimated from previous studies, grey literature, lived experience, and other SD models (Stantec, 2018; Nunavut Water Board, 2020; Associated Engineering, 2025; Duncan, Chalmers & Gora, 2025; Duncan, Slowey & Gora, 2025; Duncan et al, 2026; Cannon et al, 2021; Daniel et al, 2021; Loo et al, 2022; Loo et al, 2025). The equations used in the model are provided in Appendix I. Initial values for the stock variables and base flows are listed in Table 7-4. The model was simulated for 120 months (10 years).

Table 7-4: Initial values of variables in the baseline conditions

Variable	Unit	Value	Variable	Unit	Value
Initial Safety Level	Safety Index	50	Base Infrastructure Upgrade	Safety Index/ Month	0.3
Initial Source Quality	Dmnl	2	Base Treatment Impact	Safety Index/ Month	0.6
Initial Watershed Knowledge	Dmnl	0.3	Base Community Change	Safety Index/ Month	0.1
Initial Infrastructure Condition	Dmnl	0.5	Base Contamination	Safety Index/ Month	0.2
Initial Operatory Capacity	Dmnl	0.4	Base Seasonal Degradation	Safety Index/ Month	0.4
Initial Regulatory Capacity	Dmnl	0.3	Base System Failure	Safety Index/ Month	0.4
Initial Community Trust	Dmnl	0.3	Base Source Improvement	1/Month	0.15
Base Trained	1/Month	0.4	Base Capacity	1/Month	0.1
Base Turnover	1/Month	0.01	Base Capacity Loss	1/Month	0.005
Base Trust	1/Month	0.05	Base Knowledge Gain	1/Month	0.1
Base Erosion	1/Month	0.1	Base Knowledge Loss	1/Month	0.01
Base Maintenance	1/Month	0.05	Base Source Degradation	1/Month	0.03
Base Deterioration	1/Month	0.03	Base Service Disruption	Safety Index/ Month	0.2

*Dmnl = Dimensionless

7.3.5 Model Verification and Validation

Model structure verification was carried out following Barlas guidelines, which included structure confirmation tests – i.e., debugging (Forrester & Senge, 1980; Barlas, 1996. This process involved identifying and fixing errors that prevented the model from functioning correctly. In the present study, the Barlas guidelines were used to identify errors such as incorrect equations, which were subsequently corrected. Validation also included unit consistency checks. The model proved to be functional, with no errors in equations or inconsistent units. A sensitivity analysis was conducted on the mentioned exogenous variables, varying parameters by ±10% across 100 runs using a Monte Carlo sampling method in Vensim (Fiddaman, 2002) (Appendix I).

Water quality data from Duncan, Chalmers, & Gora (2025) and Duncan et al. (2026) were used to validate the model's behaviour with respect to turbidity and THMs. Since data was available over multiple years for turbidity and THMs from the treatment plant and trucks from 2022–2024, these hazards were used for validation. This was done to ensure that the model behaved consistently with documented historical patterns prior to simulation (Appendix I). Although the model's projections align with historical trends, discrepancies exist across all three parameters. For example, THM data ranges vary by time of year, indicating that the model does not account for large seasonal fluctuations. Nonetheless, the model captures the dynamics of real-world behaviour; however, caution should still be exercised when interpreting its projections.

For parameters without specific community data, assumptions were made to reflect real-world conditions. For example, regarding the stock Building Water Supply, variables included Water Demand, Truck Frequency, Delivery Efficiency, and Truck Capacity. Truck Capacity was set to 12.5 m^3 in line with Aurora Manufacturing specifications. Truck Frequency was estimated using a community map that divided the community into sections, with trucks delivering to different sections on different days. Based on discussions with GN-TIN stakeholders in Cambridge Bay, it was estimated that trucks made four to five trips daily to the community (M.Cole, private communication). Assuming all four trucks operated, an average of 500 trips per month was used. Delivery Efficiency takes into account factors such as maintenance, holidays, vacations, and sickness that affect driver availability, so a dimensionless value of 0.7 was used to represent variability in truck trips. Water Demand, or Base Water Demand, was estimated at an average of 110 litres per person per day in Nunavut (Daley et al., 2014). For simplicity, an average household size of four people was used, multiplied by 30 days, and then by the number of residential buildings (500). Homes were rounded up to account for larger households, consistent with Cambridge Bay's estimated 2026 population of 2,090, calculated using a 1.36% population growth rate based on 2021 and 2016 data from Statistics Canada (Statistics Canada, 2021).

7.3.6 Simulation Analysis

Scenario analyses were performed to explore the pattern of WSL in relation to the selected hazard variables. Changes were made to the six hazard-related model parameters (Table 7-5). These modifications were implemented one at a time, and the results were compared to the baseline conditions in Table 7-4. Changes were made manually to the variables, and the results were compared for the KPI stock 'Water Safety Level'. All parameters are endogenous except for Regulatory Framework Strength, which is exogenous. Therefore, exogenous variables that influence these endogenous parameters must be manually adjusted for the simulation instead. Many variables have a baseline input, such as Base Capacity Building for Regulatory Capacity. We manually adjusted this baseline to simulate the impact of having a fully operational regulatory team (0.9 dmnl) versus having no regulator (0.1 dmnl). During the study period, there was no dedicated Environmental Health Officer (EHO) for the Kitikmeot Region, so a baseline value of 0.1 was used.

Three variables related to regulatory needs influence each other: Regulatory Framework Strength, Regulatory Standard Strength, and Regulatory Capacity. These represent the human and institutional ability to oversee drinking water systems. For simulation purposes, Regulatory Framework Strength, Funding Level, and Base Capacity are used. Simulating Watershed Knowledge and Unknown Environmental Contaminants, the following exogenous variables are used: Initial Watershed Knowledge and Unknown Contamination Risk. The increasing demand for Water Lake is simulated using Base Service Disruption.

Table 7-5: Manual changes made to variables for the simulation of scenarios

Scenarios	Base Knowledge (Dmnl)	Unknown Contaminant Risk (Dmnl)	Base Capacity (Dmnl)	Funding Level (Dmnl)	Base Service Disruption (Dmnl)	Regulatory Framework (Dmnl)
Baseline	0.1	0.4	0.1	0.9	0.2	0.3
1	0.05	0.1	0.05	0.1	0.1	0.1
2	0.15	0.25	0.25	0.25	0.25	0.25
3	0.2	0.5	0.5	0.5	0.5	0.5
4	0.25	0.75	0.75	0.75	0.75	0.75
5	0.3	0.9	0.9	1.0	0.9	0.9

The interpretation of dimensionless values is outlined in Tables 7-6 & 7-7. For Initial Knowledge, Base Capacity, Funding Level, and Regulatory Framework, a zero indicates an absence, and a one indicates optimal. Conversely, the interpretation is reversed for Unknown Contaminant Risk and Base Service Disruption, where zero signifies no contaminant risk and no service disruption.

Table 7-6: Interpretation of dimensionless values used in scenario analysis for Base Watershed Knowledge, Regulatory Framework Strength, Base Capacity, Funding Level

Dimensionless Value	**Interpretation of Value**
0 – 0.1	Complete absence of regulatory oversight, total failure of infrastructure, no knowledge
0.1 – 0.3	Very low regulatory oversight, frequent failures of infrastructure, limited knowledge of watershed
0.3 – 0.5	Low to moderate regulatory oversight, moderate number of failures of infrastructure, limited knowledge of watershed
0.5 – 0.7	Moderate regulatory oversight, low number of failures of infrastructure, limited knowledge of watershed
0.7 – 0.9	High regulatory oversight, limited failures of infrastructure, high level of knowledge of watershed
0.9 - 1	Near optimal, optimal conditions

Table 7-7: Interpretation of dimensionless values used in scenario analysis for Unknown Contaminant Risk and Base Service Disruption

Dimensionless Value	**Interpretation of Value**
0 – 0.1	Complete absence of contaminants, no disruptions to delivery service
0.1 – 0.3	Minimal contaminants unknown and minimal disruptions
0.3 – 0.5	Low amount of contaminants unknown and low disruptions
0.5 – 0.7	Low amount of contaminants unknown and low disruptions
0.7 – 0.9	High level of unknown contaminant risk and continuous disruption to delivery
0.9 - 1	No secondary water source, no consistent water deliveries and no detection methods for potential contaminants

7.3.7 Limitations

This model has been developed using information collected through stakeholder engagement sessions described in Duncan, Slowey & Gora (2025), water quality data from Duncan, Chalmers & Gora (2025) and Duncan et al., (2026), and the author's personal expertise developed while working in a part time engineering support role at TIN (November 2022 – November 2023) and later as a part-time consultant with ArcticEdge Consulting (March 2025 – Current). Due to funding limitations, in-person modelling workshops were not feasible. Because of the remoteness of Cambridge Bay and the limited availability of stable internet access at homes in the communities, these workshops could not be conducted online. The development of the system dynamics model was carried out primarily by the lead author, and variable values reflect their perspective on the water system at the time of model development. A conceptual model was shared with the community for feedback in June 2025, and the stock and flow model was created based on this diagram.

7.4 Results and Discussion

7.4.1 Model and Feedback Loops

Many exogenous variables influence the model's core components. To improve readability, these variables are hidden in Figure 7-1. This diagram shows the model's overall structure, with 7 primary stocks influenced by inflows and outflows that describe improvement and degradation rates at each time step. In the model, water safety is primarily affected by monitoring the source water, improving operator capacity, building community trust, and effective reporting and regulation, as identified in the feedback loops.

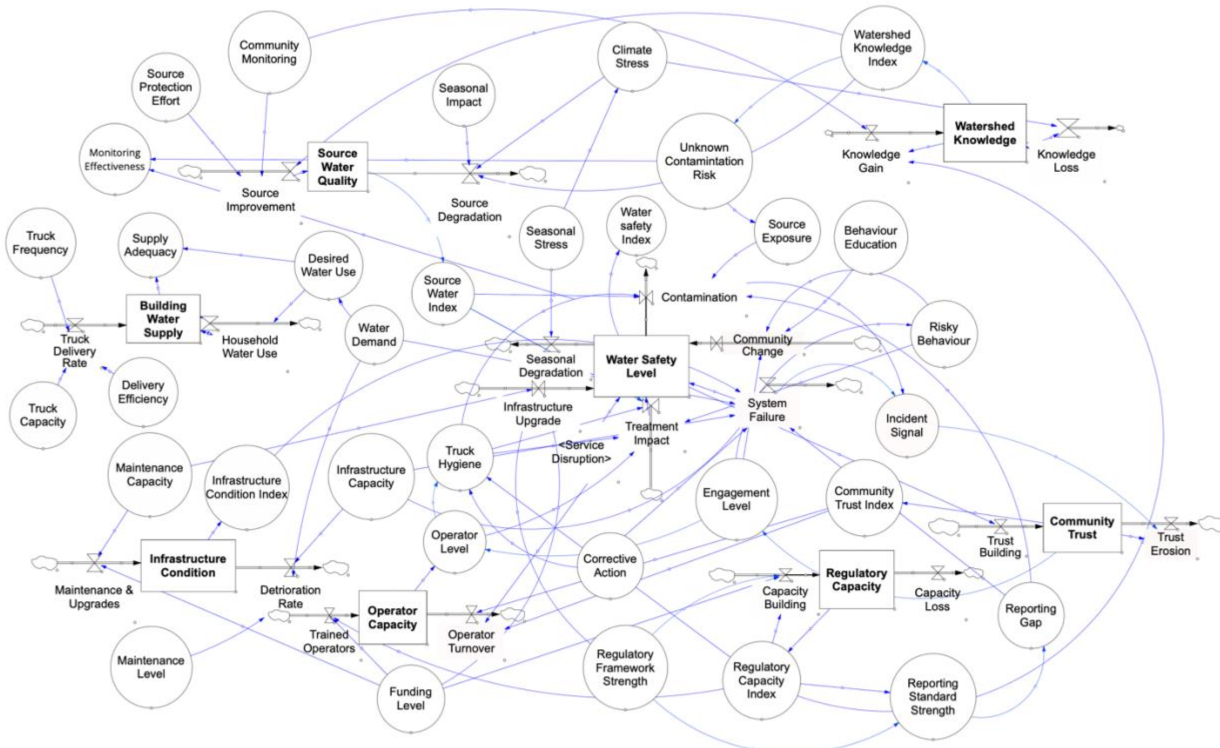

Figure 7-1:The main structure of model with Stocks (Rectangles), Flows (No shape) and Auxiliaries/Constants (Circles).

Feedback Loops

A reinforcing feedback loop amplifies a behaviour and can lead to rapid growth or decline(Meadows, 2008). A balancing feedback loop counteracts this, maintaining stability and balance within the mode (Meadows, 2008). There are three reinforcing loops and one balancing loop (Figures 7-2 to 7-5) in the final PSD model developed in this project. The reinforcing loops illustrate the potential to gain or lose environmental knowledge and community trust. These are countered by corrective actions, for example the proper response to contamination events within trucks, as well as efforts to strengthen regulatory capacity and improve treatment response performance.

Reinforcing oops

R1: This signifies an increase in effective monitoring, which enhances place-based knowledge of the water supply and built water infrastructure, thereby reducing the amount of unknown contamination and potentially vital information for improving water safety. This feedback loop can also be negative: a decrease in effective monitoring may increase unknown contaminants, reducing water treatment efficiency and contributing to a decline in overall water safety in the community.

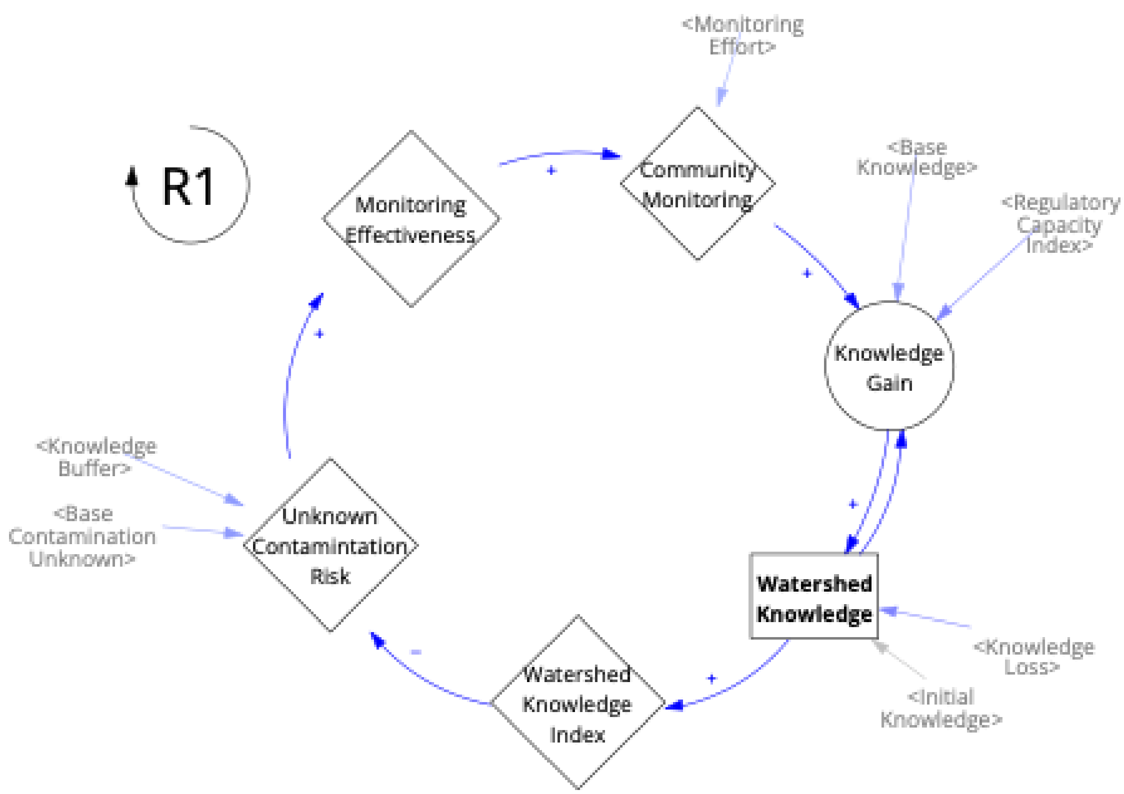

Figure 7-2: Reinforcing *feedback loop R1*. A rectangle represents the stock, a circle represents flows, and a diamond represents auxiliary variables. The + and – signs on the arrows indicate if the value of the variable is increasing or decreasing.

R2: This feedback loop illustrates how, when contamination events happen, community trust decreases, which can lead to a reduction in operator capacity. Operator capacity takes into account the level of training and the number of operators available. With fewer trained staff available, this may potentially affect truck hygiene, increasing the risk of more contamination events. However, if operator capacity improves, truck hygiene also improves, reducing the risk of contamination events and helping build public trust in the water supply.

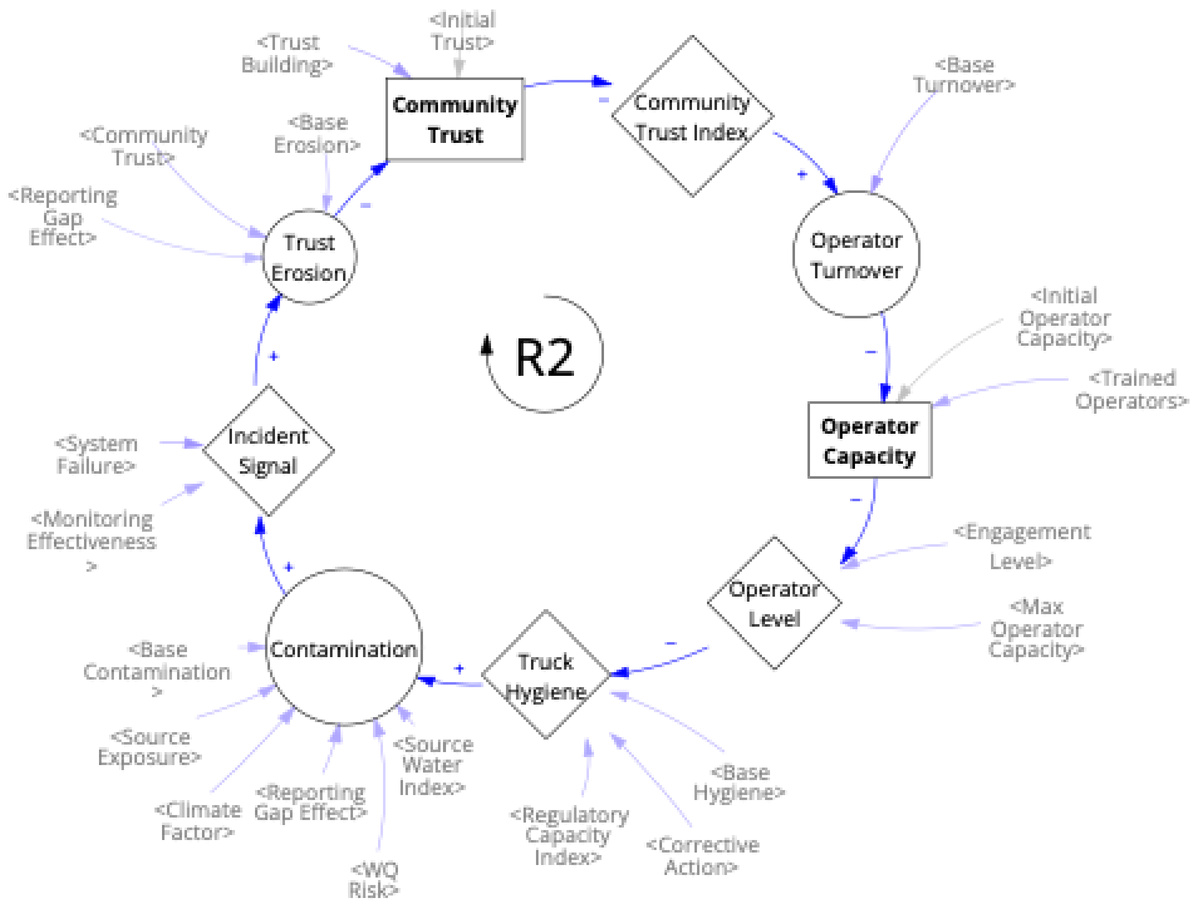

Figure 7-3: Reinforcing *feedback loops* R2. A rectangle represents the stock, a circle represents flows, and a diamond represents auxiliary variables. The + and – signs on the arrows indicate if the value of the variable is increasing or decreasing.

R3: Represents the increase in water safety from a reduction in risky behaviour, and thus community change from increased levels of trust with improved regulatory framework. This feedback loop can also be negative with a decrease in community trust from contamination, can increase the level of risky behaviour and seeking alternative sources and decreasing water safety for community members.

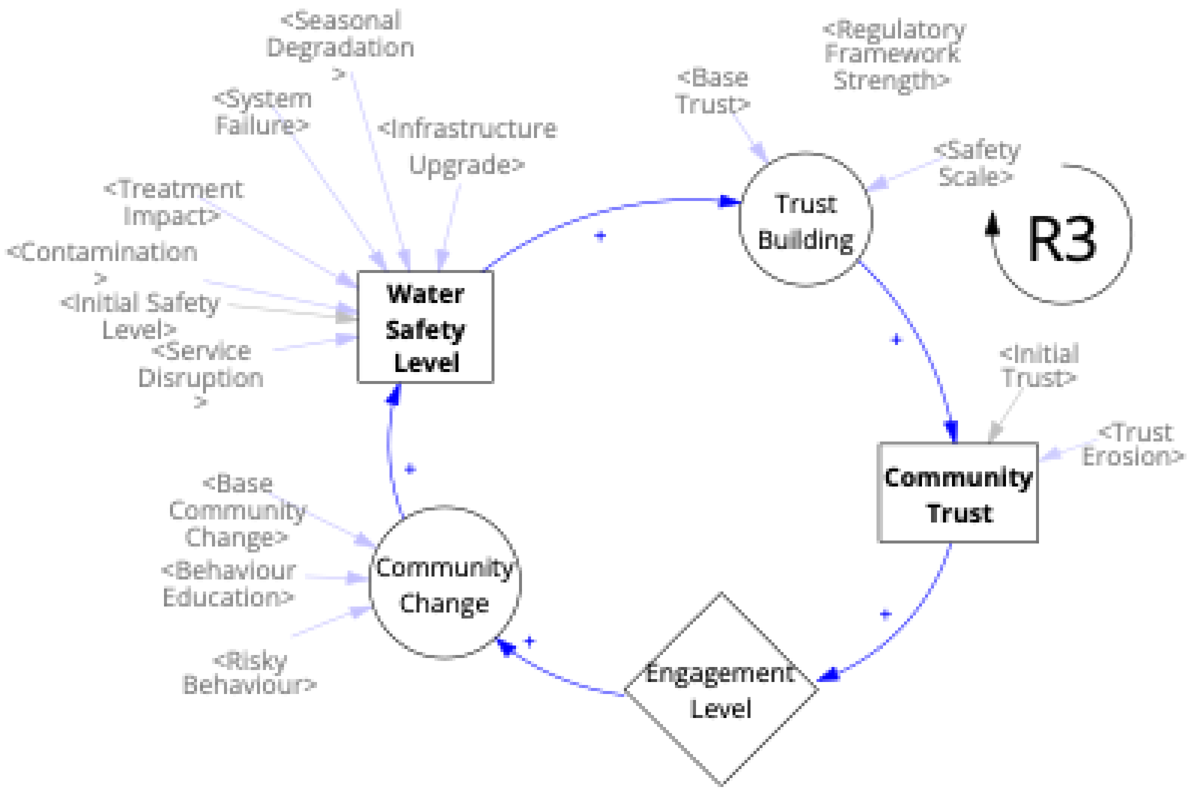

Figure 7-4: Reinforcing *feedback loops* R3. A rectangle represents the stock, a circle represents flows, and a diamond represents auxiliary variables. The + and – signs on the arrows indicate if the value of the variable is increasing or decreasing.

Balancing Loops

B1: When a contamination event occurs, if monitoring is effective, an incident signal occurs. This triggers a response that prompts corrective action. For example, decision trees are used by operators in Nunavut when *E. coli* and turbidity exceedances occur. If an exceedance is detected, chlorine levels are increased, and a boil-water advisory is issued to reduce the risk of public health impacts and near term contamination events. This feedback loop helps calibrate the reinforcing feedback loops if contamination begins to escalate exponentially.

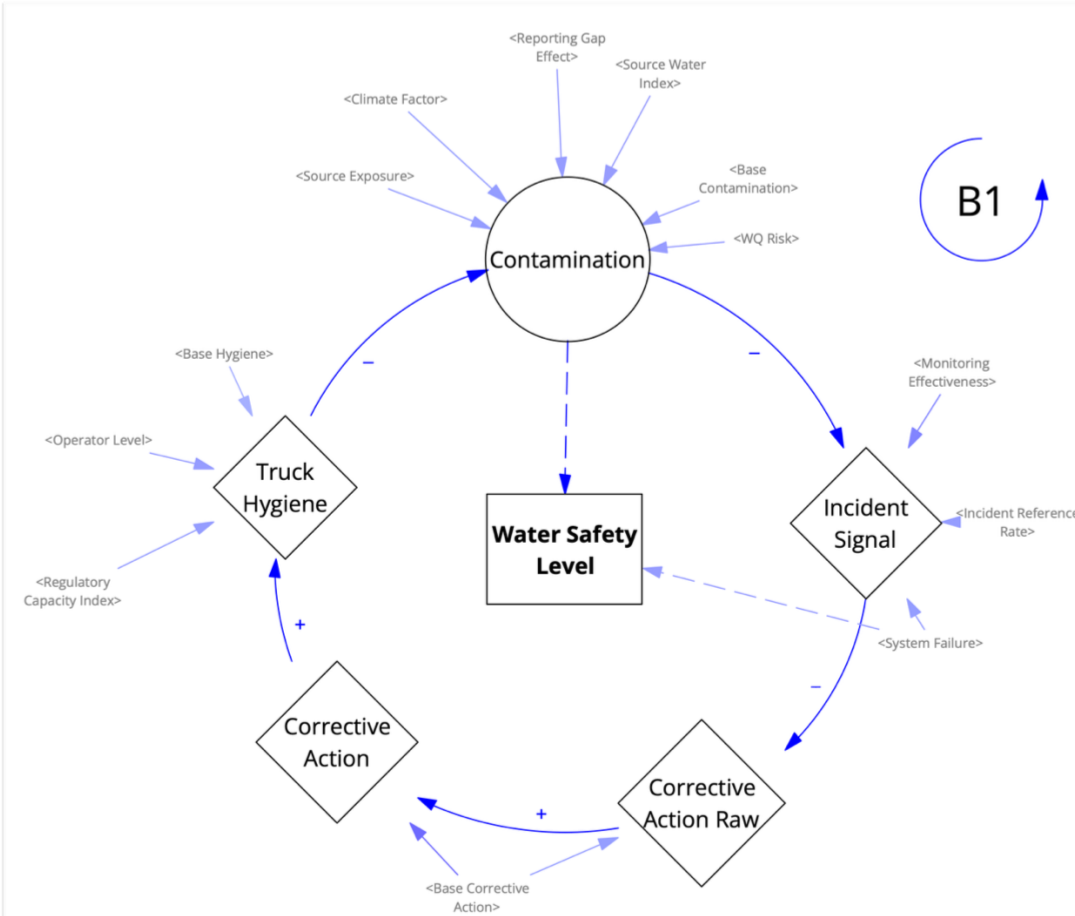

Figure 7-5: B*alancing feedback loops* B1. A rectangle represents the stock, a circle represents flows, and a diamond represents auxiliary variables. The + and – signs on the arrows indicate if the value of the variable is increasing or decreasing. This diagram shows how an increase in corrective action can reduce contamination and, therefore, require less corrective action in the future.

7.4.2 Simulations

Increasing Watershed Knowledge

As in real-world dynamics, time delays also occur in system dynamics, as shown in Figures 7-6 to 7-11. Most casualties involve some form of time delay or lag between cause and effect (Hamilton, 1980; Kunc, 2016). Additionally, dips are a common phenomenon that occurs early in the system, prior to a ramp-up or stabilizing growth (Kunc, 2016). As the model is predominantly reinforcing, the dip indicates that the balancing loop temporarily takes over before the reinforcing loops take effect (Inghels, 2020). This can be common when new policies are implemented. There may be a decrease in water safety as new regulations take effect and mistakes occur, before a stable increase in water safety units.

Like most communities in Nunavut, knowledge of the watershed is primarily local and, in some cases, is becoming less reliable due to climate change. Studies conducted in Nunavut are documented in annual compendiums on the Nunavut Research Institute website (Nunavut Research Institute, 2025). However, much of this research has not been effectively disseminated, especially to communities (Pedersen et al., 2020). Therefore, a baseline knowledge level of 0.1 was set in the model, reflecting participants' belief that too little is known about the watershed and how the source, Water Lake, is fed. The knowledge level was then increased in increments of 0.05, recognizing that research can take years from initiation to publication and community dissemination, which causes a time delay in the water safety units before increasing as the information is implemented. The maximum value used is 0.3, which results in the watershed knowledge stock reaching 71 water safety units after 10 years (Figure 7-6). This is reasonable, as increased watershed knowledge can reduce the risk of unknown contaminants and spur interventions elsewhere, such as modernized water treatment. This growth results from community monitoring, engagement, and field studies. The model shows that when little information is available about the watershed, the water safety level can be further reduced, particularly when the impacts of climate stress are unknown.

Key variables that increase Watershed Knowledge are Community Monitoring, Reporting Standard Strength and Funding Level. This allows for a digital trial of information about the watershed from multiple avenues. A significant variable that could reduce watershed knowledge is Climate Stress, which is associated with environmental change and seasonal shifts and can render historical knowledge unreliable for predicting watershed behaviour.

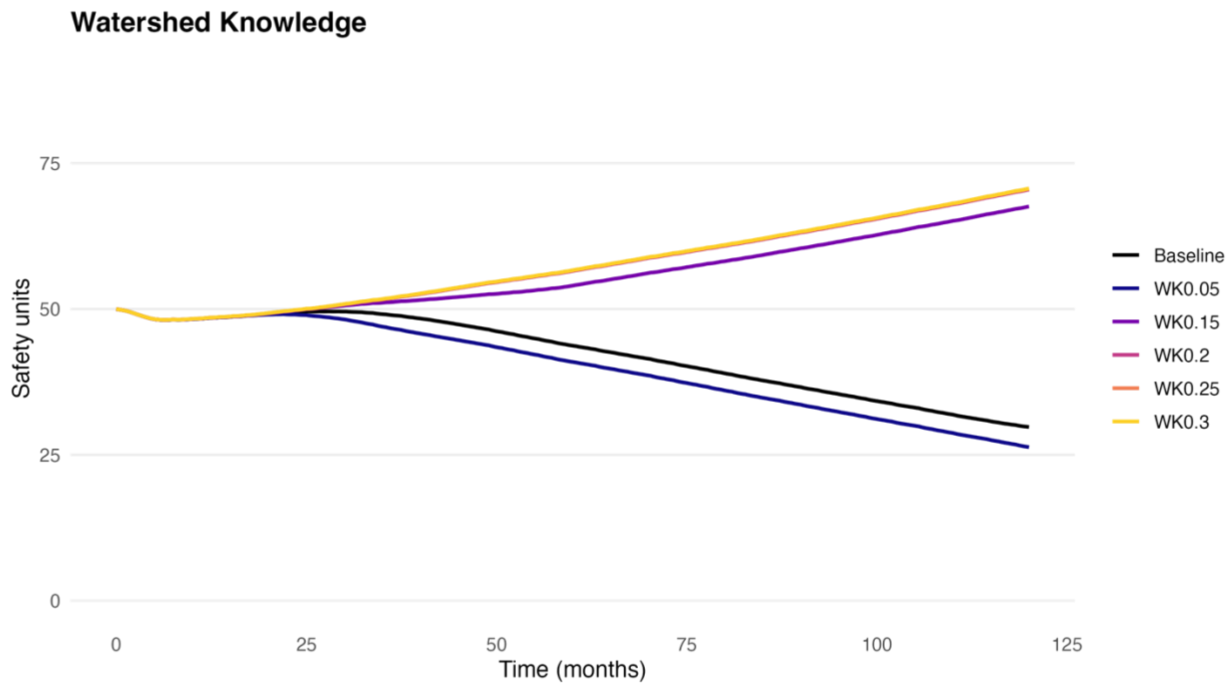

Figure 7-6: Change in water safety units over 120 months with changes to Base Watershed Knowledge. Pink and orange lines are hidden under yellow line.

Reducing Unknown Contaminant Risk

Reducing the unknown contaminant risk (UCR) is strongly linked to increased watershed knowledge. UCRs can include, but are not limited to, permafrost thaw of microorganisms and viruses, unmonitored and unregulated parameters (such as PFAS), and potential undocumented industrial legacies. Unknown Contaminant Risk is linked to Source Exposure, which in turn links to Contamination. Stakeholders raised concerns that they don't know what potential contaminants are in the freshwater, there has been numerous studies regarding the marine environment, mostly apart of the Arctic Monitoring and Assessment Programme (AMAP, 2026). However, little to no monitoring has occurred in drinking water sources.

An increase in UCRs indicates that source degradation could accelerate faster than we currently realize and, in turn, reduce the efficacy of water treatment. However, by collecting valuable information through regulation and monitoring, and increasing our knowledge of the watershed, UCR can be reduced. When the value is reduced to 0.25-0.1 in UCR we see a similar result to increasing watershed knowledge in WSL.

Reducing the risk of unknown contaminants over the next 10 years brings the WSL to 71 safety units (Figure 7-7). When the risk of unknown contamination is high, the WSL decreases quite quickly in the simulation, reaching a critical level within 10 years. Outside of the WSL, we would also see a decrease in community trust in their drinking water. This can lead to other problems, such as seeking untreated water sources, increased contamination, and gastrointestinal illnesses that could be prevented with clean drinking water.

We do not know exactly what contamination events are happening; however, a systematic review by Lee et al. (2023) examining the burden of poor water quality in high-income countries estimated a median annual rate of 2,720 gastrointestinal illnesses per 100,000 people. (Lee, Gibson, Brown, Habtewold, & Murphy, 2023). Both *Giardia* and *Cryptosporidium* have been found in untreated surface waters in Iqaluit, Nunavut (Masina, et al., 2019), and seasonal changes in surface water, minimal treatment, or regulatory oversight may be linked to infectious gastrointestinal illnesses in Northern communities (Harper, Edge, Schuster-Wallace, Berke, & McEwen, 2011). For example, cases of gastrointestinal illnesses were observed to increase during spring and summer in two communities in Nunatsiavut (Harper, Edge, Schuster-Wallace, Berke, & McEwen, 2011).

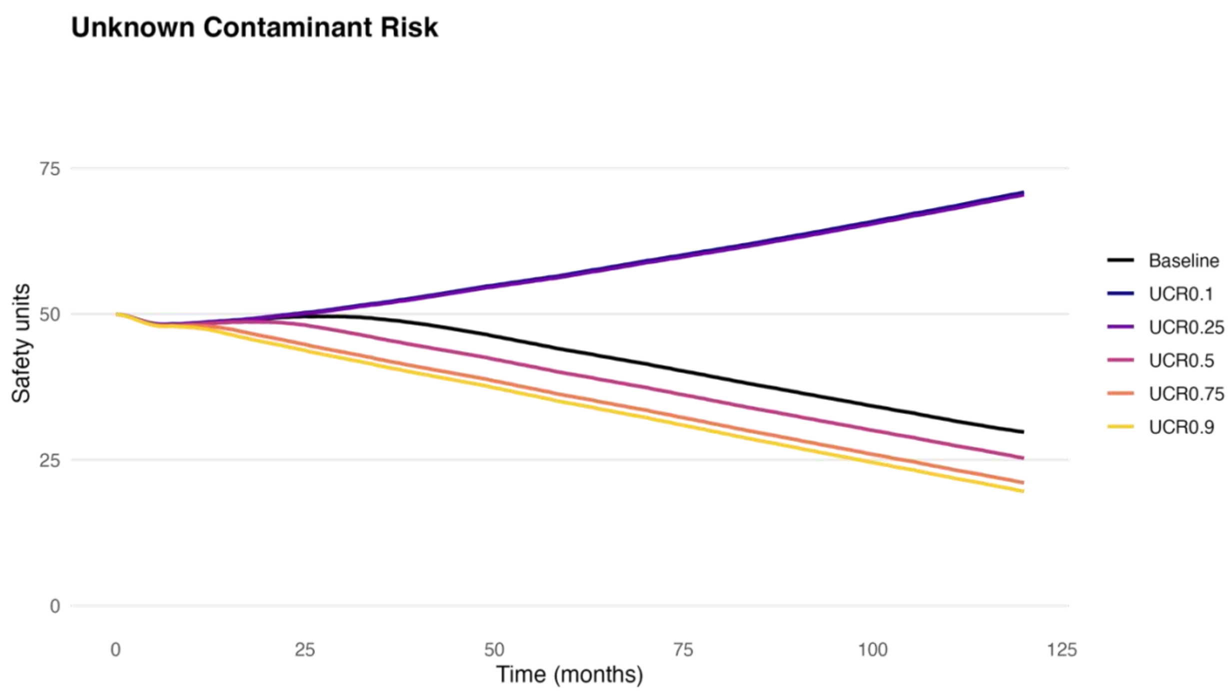

Figure 7-7: Unknown contamination risk simulated over 120 months (10 years)

Strengthening the Regulatory Framework

There were several risk drivers identified in the workshops related to the regulatory framework which outlined when gaps remained. The regulatory framework in Nunavut is outdated and has many gaps that need to be addressed. This is outlined in the Government of Nunavut Drinking Water Strategic Framework. The Government of Nunavut's Department of Health has revised the 1990 *Public Water Supply Regulations*, including the addition of monitoring for all parameters in Health Canada's *Guidelines for Canadian Drinking Water Quality* (GCDWQ) and decision trees for *E. coli* samples and high turbidity. Additionally, the Department of Transport and Infrastructure Nunavut has contributed to the provision of annual operator training and a certification program specifically for water treatment plant operators in Nunavut. However, these efforts only address the treatment and distribution of drinking water. Most communities in Nunavut rely on truck-to-cistern systems, where the water in the cistern is neither monitored nor regulated, unless it is considered federal jurisdiction, such as the RCMP, which follows different guidelines. Furthermore, EHO's in the territory are often overstretched with managing numerous policies, have limited expertise in drinking water safety, and only ensure that water delivered complies with the outdated *Public Water Supply Regulations of 1990*.

The Regulatory Framework Strength (RFS) variable measures how enforceable water regulations are and the impacts of non-compliance, regardless of staffing or funding. In the baseline model trajectory, the WSL decreases to 30 safety units. When the regulatory framework is robust (0.9), capacity building within the agency becomes more effective, compliance improves, and reporting gaps are fewer. This results in safety units rising to 86 after 10 years. The graph shows that implementing strong regulations may take up to two years, after which reporting standards gradually improve and gaps close. Stronger regulations enhance safety even with moderate capacity. A 2019 study evaluated the successes and challenges of implementing affordable, professionalized maintenance services through different approaches, such as ad hoc, structured, or guaranteed maintenance provided by external professionals (Lockwood, 2019). In a simulation model, worse-before-better behaviour, especially in maintenance costs, is to be expected when first implementing a shift to preventive maintenance (Sterman J. D., 2000). To improve reporting standards, a stricter framework is needed initially, which should then be enforced by the regulatory authority. Conversely, if RFS is weak, increasing funds will have a limited impact on drinking water safety.

By strengthening the regulatory framework in Nunavut and implementing a proactive, risk-based approach through accreditation and training, along with improved monitoring and reporting from source to tap, asset management, and source protection, drinking water safety can be significantly enhanced over 10 years.

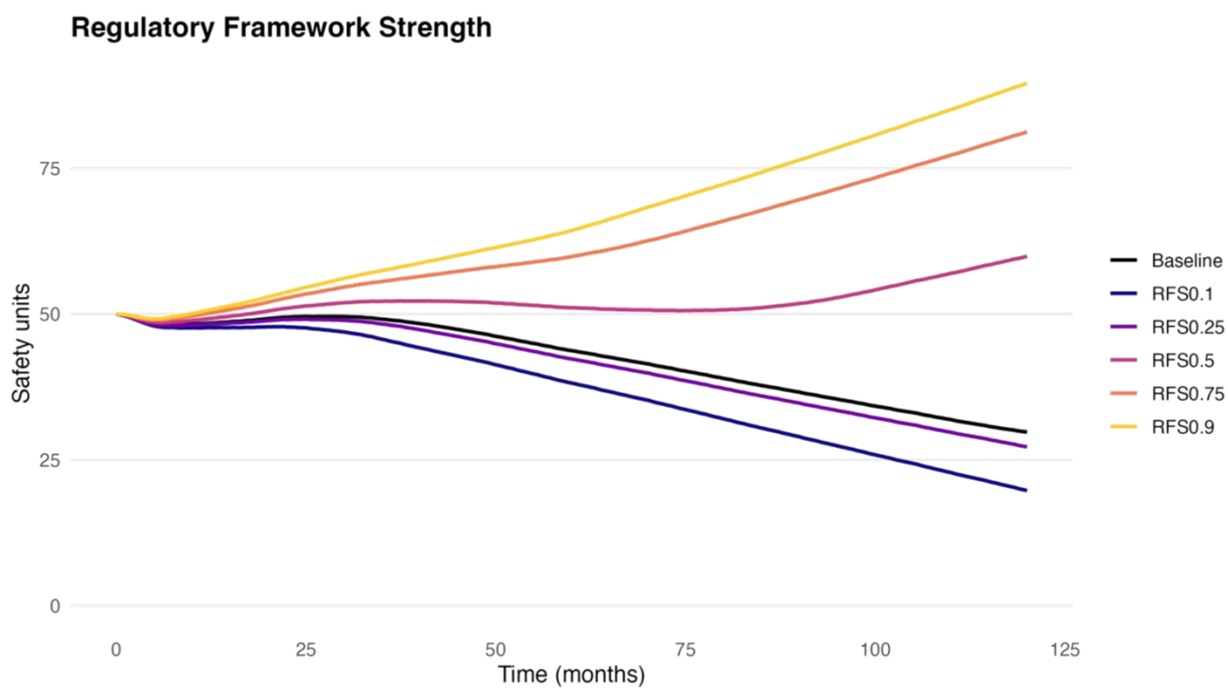

Figure 7-8: Implication of regulatory framework strength variation on Community Trust Stock and safety units in Water Safety Level Stock between 0.1 and 0.9 (dmnl). Simulation is for 120 months (10 years).

Enhanced Regulatory Capacity

Base Capacity and Funding Level

These variables represent the regulator's personnel, financial, and institutional capacity to oversee the drinking water system. The higher values correspond to more inspections, improved enforcement, faster corrective actions, and enhanced operator oversight.

During the study period, there was no dedicated EHO for the Kitikmeot Region; we started with a baseline of 0.1. As capacity increases, truck hygiene compliance improves, and the time needed for corrective actions decreases. The risk of contamination in treated water is reduced through routine regulatory oversight, thereby strengthening the community's trust in the water system. The Kitikmeot Region now has a dedicated EHO, which is simulated in the model as an increase in regulatory capacity and compliance, leading to a snowball effect that reduces the time required for corrective actions when thresholds are exceeded. With regulatory capacity between 0.75 and 0.9—indicating high regulatory oversight or near-optimal conditions—these simulations show the safety units at 77 and 78 after 10 years. Within 8 years, the water safety level target is achieved in the simulation.

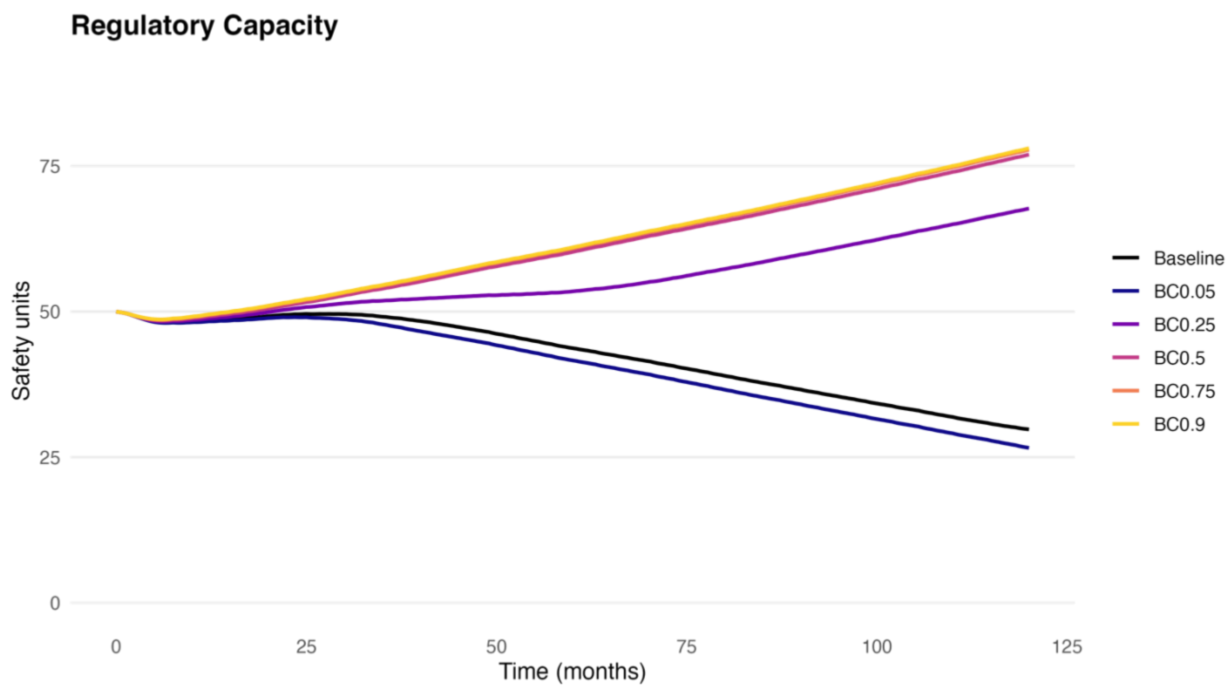

Figure 7-9: Implications of simulating different values in Base Regulatory Capacity on Regulatory Capacity and Water Safety Level. Values range between 0.05 to 0.9 (dmnl). Simulation for 120 months (10 years).

Funding plays a vital role in providing clean drinking water worldwide. In Nunavut, most infrastructure funding originates from the Federal Government. In January 2026, the Government of Canada announced an investment of over $277 million for Nunavut and Yukon. Some of these funds were specifically for constructing new water treatment plants in three Nunavut communities (Government of Canada, 2026). Water infrastructure funding has become a top priority for the territory. All treatment plants are undergoing upgrades, and additional funds are allocated to increase the number of water trucks in communities. Funding has also been allocated to address the housing crisis, supporting both the renovation of existing homes and the construction of new ones with modern infrastructure. The baseline funding level is set at 0.9, which sustains the current system over the next 10 years.

Although the funding level is connected to regulatory capacity, it does not significantly improve water safety units. This is because the Base Capacity variable has not increased within the "Funding Level" simulation. Therefore, although funds are allocated to regulatory capacity, there is no personnel to ensure compliance. Conversely, a decrease in funding would lead to substantial reductions in water safety units. Without funding for regulatory oversight, plant maintenance and operations, and municipal employee salaries to deliver water, safety units could decline to a high-risk level (40 units) within two years as controls fail.

Funding is often a major constraint on ensuring water safety. However, in simulations, improving financial support scenarios has been documented as one of the least effective areas for intervention in the system (Meadows, 1999). Funded interventions commonly target water quality parameters or engineering standards that are considered easier to manage (Meadows, 1999; Neely, 2019). Although this is important, it is also shifting the burden by focusing on symptoms rather than the root causes of the problem.

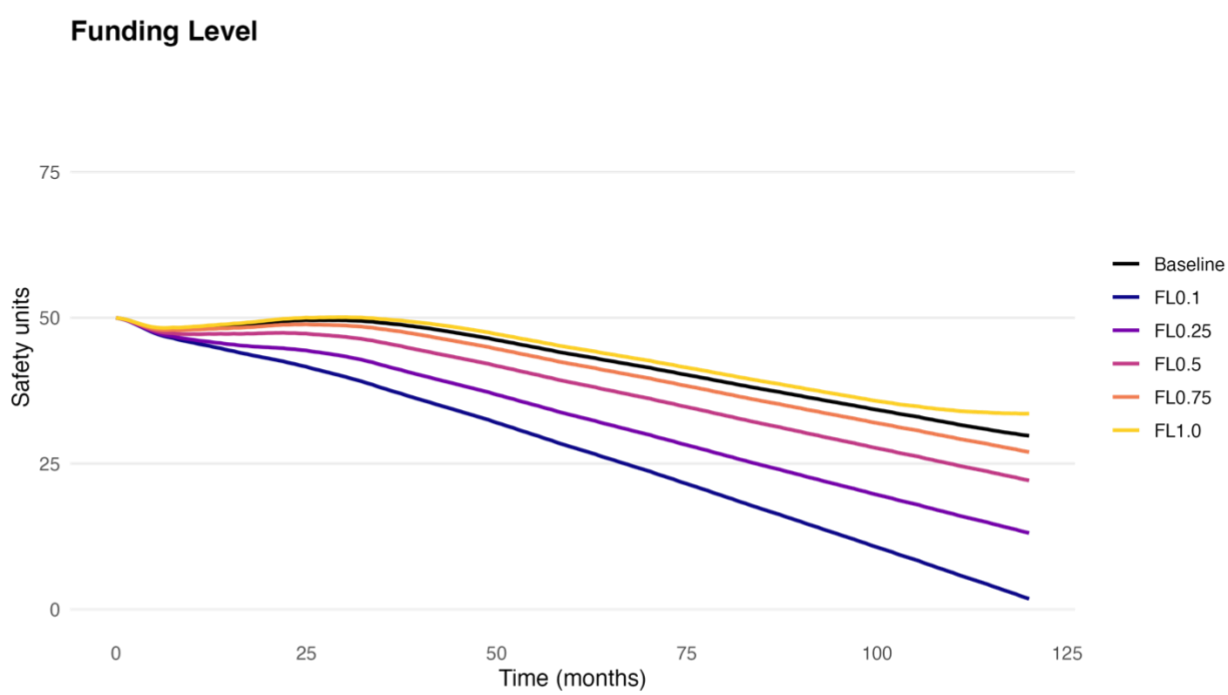

Figure 7-10: Funding Level represented by Infrastructure Condition. Simulation runs for 120 months (10 years).

Evaluating Adequate Water Supply

Service Disruption

This variable indicates major long-term disruptions to water delivery in the community, such as shortages of source water. The sharp drops in safety units symbolize water rationing, the need to ship bottled water, and community members going out onto the land to find their own water sources.

The changes to Base Service Disruption are intended to indicate the severity of safety loss during extreme shortages or when Water Lake is no longer a viable primary source. This hazard was identified by stakeholders and the community during the public consultation. Increasing the values shows safety degradation increasing more rapidly over the ten-year period. Safety units decline fairly sharply with increasing service disruption, reaching critically low levels (20 safety units) within 50 months in the worst-case scenario (Yellow line). A 2021 study conducted a hydrological analysis of municipal source water availability across Nunavut and found that the Municipality of Cambridge Bay was vulnerable to water shortages over the next 50 years (Hayward, Johnston, Jackson, & Jamieson, 2021). This simulation shows how quickly changes in water quantity can adversely affect water safety; however, the baseline aligns with the hydrological study while still accounting for other business-as-usual factors that could negatively impact the system over the next 10 years.

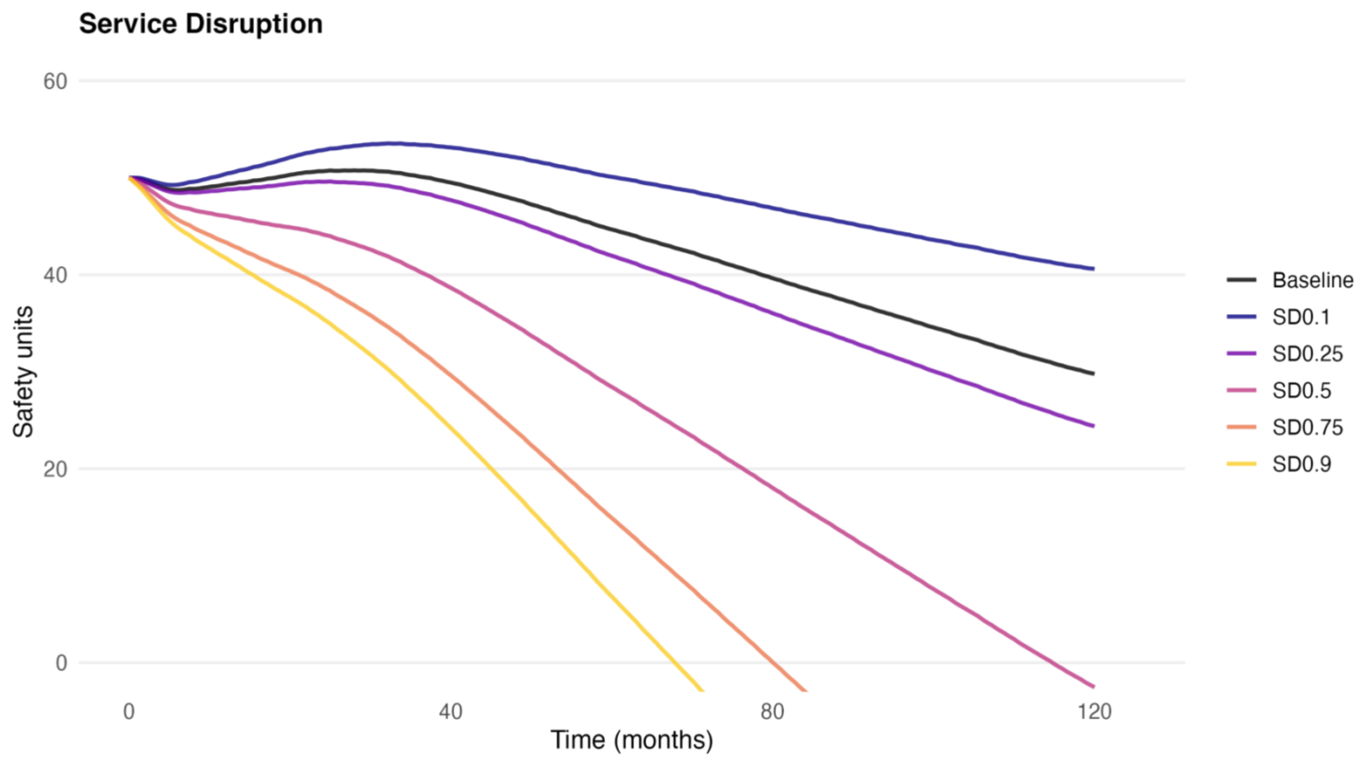

Figure 7-11: Water safety level simulations with different service disruption levels to represent water shortage at a source level. Simulation runs for 120 months (10 years)

7.4 Conclusion

Six variables were simulated with different values to evaluate their impact on water safety levels in Cambridge Bay. Of these, four variables met the 70 safety unit threshold within a 10-year period under strong and optimal conditions. Watershed Knowledge and monitoring significantly reduce Unknown Contaminant Risk, thereby improving corrective actions when contaminant levels exceed thresholds. Furthermore, reducing the level of Unknown Contaminant Risk can improve treatment and infrastructure conditions by ensuring the proper treatment technology is in place for the source water.

Strengthening the Regulatory Framework can enhance Regulatory Capacity. This is achievable through implementing a strategic action plan to boost regulatory capabilities. Although the Funding Level is already high, as noted, it had minimal effect on expanding water safety units because there was no clear allocation plan, and without an increase in baseline regulatory capacity, additional funds resulted in limited improvements. Service Disruption was used to illustrate the worst-case scenario of Water Shortage vulnerability concerning Water Lake. Community members have voiced concerns about Water Lake's water capacity, especially given future population growth. While Water Lake has the capacity to continue supplying water, a secondary source must be identified, and infrastructure options assessed before Water Lake's capacity reaches a point where it cannot support the community.

The simulated model aligns conceptually with the water safety planning framework. However, it lacks sufficient detail across the various stocks to provide meaningful insights for improving water safety in Cambridge Bay. For example: Watershed Knowledge provides an overview of all knowledge related to the watershed, not a specific measure of a single phenomenon. In the future, stakeholders' knowledge of specific environmental and biological variables and data and their influences on water safety level would need to be considered, which are outside the scope of this research.

Recommendations

The model developed in this study has drawn upon various studies including information collected in workshop activities. Due to workshop activities not being completed in the time allocated, much of the development of the stock and flow model is bias to the author's view of the water system. It is recommended that an additional workshop with stakeholders be held to agree upon the model structure and initial values of variables. This will provide the opportunity to: 1) make the model potentially more accurate, and 2) allow for discussion around others' mental models and perceptions of the water system and safety. For example, water truck operators may believe that the model currently assigns a Truck Hygiene value that is too low and should be reevaluated.

The community made various suggestions about what they would like to be simulated. Unfortunately, some of these fell outside the scope of the research. For example, having a utilidor deliver water to the new residential developments. This would be an interesting comparison to see if utilidors in Arctic settings improve water safety with increased water supply.

Next steps also could include further analysis of how each intervention impacts water safety level in other communities in Nunavut or other Arctic jurisdictions to determine if there are similar findings. For policy use, a user-friendly model interface could be built for communities to show how investment in training, monitoring or in-house compliance officer would benefit their community over a set time period.

The mixed methods participatory research activities used to gather input data produced a rich dataset that can guide future approaches to water safety management and research in the territory and in other regions with decentralized water distribution systems. Including multiple stakeholder groups, such as representatives from various levels of government, technical staff in Cambridge Bay, and water system users, proved crucial for understanding the complexity and interconnections among hazards.

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8 Conclusions

8.1 Summary

This thesis presents the findings of a study on water quality, the application of a risk management tool, Water Safety Plans, and the use of the dynamic modelling tool System Dynamics to assess, at the system level, what is necessary to enhance overall drinking water safety in a community in Nunavut. The process of conducting this study highlighted and addressed gaps in Cambridge Bay, Nunavut, that are also evident in many Arctic communities, especially those in Nunavut, Canada.

Three questions posed in Chapter One were addressed by this study. As a result, extensive data has been collected from water quality sampling, interviews, and workshops with drinking water stakeholders and community members. This research has provided crucial information on drinking water quality in the Territory of Nunavut and has identified additional recommended areas for further study. It has also worked closely with many stakeholders, fostering collaborative efforts to improve drinking water safety not only in Cambridge Bay but also in the Kitikmeot Region and the broader Territory.

To address the first question: "*What are the water safety hazards in Cambridge Bay*?", a review of historical data was carried out. Chapter Four provides a desktop review to identify initial water quality hazards and evaluates the risk matrices created by Chalmers et al. (2025) for feasibility using real data. This analysis offers background information and points out gaps that need further investigation. A total of five hazards were identified through a desktop review of water policy regulations, water quality data, and operational data available in Cambridge Bay (Government of Nunavut, 1999; Stantec, 2018; Dillon Consulting & Outcome Consultants, 2021; Government of Nunavut, 2023). It also highlights the limitations of risk matrices that rely on past frequency as a main factor in scoring, especially in areas with limited data. Chapter Five builds on the information from Chapter Four and other studies conducted in Nunavut and Arctic jurisdictions, and conducts a large-scale sampling campaign to collect additional information on potential hazards from source to tap. A total of eight hazards were identified through the water sampling campaigns, several of which were mentioned in Chapter Four; however, with a more extensive sampling effort, a more accurate risk assessment could be achieved. Qualitative methods used with stakeholders, outlined in Chapter Six, identified 204 actual and perceived water safety hazards. Many of these hazards lacked quantitative data; however, multiple stakeholder groups identified similar hazards, indicating they may be present in this community. The qualitative data collected provides a baseline of actual and perceived hazards for future analysis. The full list of hazards identified is available in Appendix H.

Question two asked, "*Can water safety planning be used to characterize water safety risk in Cambridge Bay?"* Data collected in Chapters Four and Five were both evaluated using the risk matrices developed for Nunavut by Chalmers et al. (2026). In Chapter Four, hazards in Cambridge Bay were identified by reviewing territory-wide hazards documented in Chalmers et al. (2026), hazards identified in other Nunavut or Arctic communities (Martin et al., 2007; Harper et al., 2011; Guilherme & Rodriguez, 2014; Daley et al., 2018; Wright et al., 2018; Masina et al., 2019; Gora et al., 2020; Cassivi et al., 2024; Mahgoub et al., 2025), and historical monitoring data from the Government of Nunavut. Due to limited information on water quality in the territory, it was determined that the risk matrix based on past frequency underestimated the risk level for hazards in Cambridge Bay, and that a system readiness score was more suitable for assessing risk. In Chapter Five, hazards were evaluated solely using the risk matrix, which required system readiness as a likelihood score. Water Safety Planning effectively assesses risks associated with quantifiable hazards, such as those related to water quality data. However, when it involves political, social, and behavioural hazards, water safety planning sometimes falls short due to limited data and the challenge of quantifying qualitative risks. WSPs benefit from considering each hazard independently and proposing mitigation strategies to reduce the risk for that specific hazard; nonetheless, they have limited capacity to view the water system as a whole and to understand how its components are interconnected.

Finally, in addressing question three: "*Can system dynamics be used to characterise water safety risk in Cambridge Bay?*", Chapter Six provides details on participatory methods used to gather information on water safety hazards in Cambridge Bay. It then, in collaboration with participants, examines how each risk influences others and whether there are causal links between hazards. This information is translated into a stock and flow simulation model to assess how these hazards affect water safety in the community (Chapter Seven). The study concludes that, on a broad level, system dynamics can provide an overview of how compounding hazards can affect water safety. It also highlights potential improvements for each simulated variable; however, a new iteration is needed to better estimate the necessary degree of change for each variable to enhance water safety, as indicated in this study. A limitation of this study is that, although it draws on water quality data and workshop materials, it is heavily influenced by the lead author's mental model. For further evaluation, experts and stakeholders would need to verify and reach consensus on the values included in the model.

In summary, this research represents the first study to assess water safety risks in Cambridge Bay, Nunavut, using water safety planning and system dynamics modelling. Water quality data from source to tap in Inuit regions are scarce, and this study provides critical information to the Municipality of Cambridge Bay and the Territorial Government. Through stakeholder engagement activities, the study identified both actual and perceived water safety hazards, which can be used to evaluate risks across the territory.

Both WSP risk matrices and PSD modelling are affected by the dynamics within communities at the time they are developed. This highlights the importance of regularly updating both tools to ensure they accurately represent the current state of the water system. For instance, during research activities in 2024, there were fewer geopolitical pressures in the Arctic, especially in the Canadian Arctic (BBC, January 2026). Now, the Canadian Arctic has become a geopolitical hotspot for both the U.S. and China (Springer, 2025). Additionally, drugs are becoming more common in the Canadian Arctic, with increases in the seizure of Class A drugs seen in 2025 (CBC, 2025). Although not directly affecting the water system, risk drivers like these were discussed during the workshops.

With shifts in society and geopolitical interests, stakeholders may indeed view the importance of these risks differently now to the drinking water system.

8.2 Relevance to Government and Industry

Combining WSP with PSD is useful for government and industry because it provides detailed information about hazards and hazardous events within a community, and also offers a high-level view of the complex system to include risk drivers. Involving stakeholders and local community members in the process enhances understanding of the system and helps evaluate the potential consequences of policies aimed at mitigating hazards and hazardous events. This study provides government and industry with solid evidence to incorporate into drinking water safety strategies in Nunavut.

8.3 Limitations

Limitations are to be expected when undertaking studies in remote areas. First, water sampling and workshops only occurred in one community in Nunavut over the course of one year. This limits the water quality hazards and water safety hazards and risk drivers identified in the workshops to Cambridge Bay. Expanding both the workshop activities and water sampling program to other communities in Northern Canada and other Arctic jurisdictions could facilitate key priority areas for governments to focus on in reducing water safety hazards across the North, particularly in jurisdictions that rely on truck-to-cistern water systems.

The remoteness of the study location sometimes caused logistical and shipping issues. For instance, sample bottles from equipment suppliers to Cambridge Bay often experienced delays of weeks or months, and occasionally, filled sample containers were not received at the accredited laboratory due to loss or mishandling by shipping companies.

The limited time and resources for the workshops restricted the activities to just developing a polarity matrix. Because of these constraints, it wasn't feasible to hold additional workshops for in-person modelling activities or to evaluate the polarity matrix with stakeholders. Such workshops would have enhanced understanding of how risk drivers interact and encouraged discussion among stakeholders to build collective knowledge. Furthermore, due to the remoteness of Cambridge Bay and the limited availability of stable internet at community homes, online workshops were not possible. This limited participation in building the model, which was primarily carried out by the lead author with minimal input from others after the workshop activities.

Furthermore, there are still very few formal datasets available on water quality and safety in Nunavut. Much of the information used in Chapters 6 and 7 is subjective. Although various stakeholder groups and community members raised similar risk drivers, this information has not been quantified.

8.4 Research Costs

Conducting research in Nunavut can be expensive. Overall, this study was just shy of $400,000. Approximately $100,000 of Dr. Stephanie Gora's NERSC Discovery Grant was allocated to this project and to cover international tuition fees. Two years of the Dahdaleh Institute Graduate Scholarship contributed $50,000 towards my tuition and living expenses. The Canada Capacity Building Fund provided $180,000 to support the Nunavut Youth Operator Program and to cover expenses for water sample transit, analysis, flights, food, and accommodation. Hotels in Cambridge Bay generally cost around $400 per night, but with in-kind support of free lodging, this saved the project roughly $32,000; additional accommodation support was provided by CHARS during the first week of the youth program. Various other forms of in-kind support were given and have been essential for this project's success. Future researchers planning work in Nunavut should prioritize securing funding for logistics and translation services to ensure project success and appropriate knowledge dissemination. For meaningful engagement, multiple trips and longer stays should be expected.

8.5 Recommendations for Future Researchers

For those interested in conducting research in Nunavut, there are several hurdles to overcome before the research begins. In fact, unless your supervisor or community already has ties to Nunavut communities, this will be the most time-consuming aspect of your research. Relationship-building in the territory is critical, and learning to build trust quickly is equally important. The fastest way to do this is to ensure your research aligns with the objectives of the territory and/or communities, and, secondly, to truly believe in the research you set out to conduct. Numerous studies and reports can inform your project design to ensure it aligns with best practice. However, the most critical piece of advice I can offer is: if you can't meet in person, pick up the phone and don't be afraid to call multiple times.

The following are a small selection of platforms and articles that can assist in the development of your project:
Nunavut Research Institute – Scientific Research Licensing Guidelines
National Inuit Strategy on Research (ITK, 2018)
The Sikumiut Model (Wilson, 2022)
Indigenous Arctic Research Ethics Guidelines and Protocols: Reflections from a Master's thesis. (Lingner, 2025)
ScIQ: an invitation and recommendation to combine science and Inuit Qaujimajatuqangit for meaningful engagement of Inuit communities in research (Pedersen et al, 2020)

8.6 Recommended Directions for Future Research

Based on Chapter Four (identifying water safety hazards based on historical data), Chapter Five (identifying water safety hazards based on community-based water quality sampling), Chapter Six (identifying water safety hazards using participatory methods) and Chapter Seven (Integrating WSP risk assessment and System Dynamics to evaluate water safety) the following recommendations are made:

Water quality sampling: Carrying out comprehensive metals sampling in Cambridge Bay and other Arctic communities. Specifically, lead and copper sampling campaigns in Nunavut and other Arctic jurisdictions that use truck-to-cistern water distribution to analyze lead and copper corrosion in buildings, particularly older residential buildings built before 1995. Additionally, evaluating the composition of NOM in water supplies used in Cambridge Bay and other Arctic communities to ensure that new WTPs are equipped with technologies that can effectively prevent the formation of disinfection byproducts.

Assessing water cisterns: A knowledge gap exists regarding cistern water quality, particularly from a microbial perspective. To date, only one study has examined the microbial content of water cisterns in an Arctic community (Gora et al, 2020). It is advisable to explore solutions to enhance water quality in cisterns.
Integrating drinking water quality research in cisterns to water epidemiology to gain a better understanding of the impacts of contamination from water cisterns impacts on public health.

Investigate legacy and emerging hazards: Although there is a substantial amount of data on marine waters and freshwater species, and the impact of legacy and emerging hazards on these environments and flora and fauna, there is limited understanding of how hazards such as hydrocarbons, microplastics, and cyanobacteria influence water treatment and water safety in cold climates. As Nunavut works to upgrade all their water treatment facilities, gaining a better understanding of these hazards would benefit the operational capabilities of these facilities.

Collaborative research methods: Using approaches like water safety planning and participatory system dynamics to work effectively with stakeholders in Arctic jurisdictions. The goal is to identify and understand community-specific and regional water safety hazards and hazardous events. This includes exploring how individual hazards interact and gaining a clearer understanding of the complexities of drinking water systems in Arctic regions. These methods can help collaboratively assess culturally important alternative water sources and storage techniques outside municipal systems, raise community awareness of water quality, and work with communities to develop Water Safety Plans (WSPs). This enhances their understanding of watersheds, water systems, and home-based strategies to reduce contamination risks. These approaches can be time-consuming and require building strong relationships with various stakeholders. Success depends on commitment from operational staff, community members, local organizations, and regulators to support a collaborative approach. Ultimately, there remains an urgent need to better understand and incorporate social, cultural, and economic factors affecting drinking water safety in remote communities, especially those serving vulnerable populations.

8.7 References

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9 Appendices

Appendix A

Ethics approvals and NRI licenses for research activities.

YORK U
UNIVERSITÉ
UNIVERSITY

OFFICE OF RESEARCH ETHICS (ORE)
2nd Floor,
Kaneff Tower

4700 Keele St.
Toronto ON
Canada M3J 1P3
ore@yorku.ca
www.research.yorku.ca

Certificate #:	**2024-004**
Approval Period:	**01/05/24-01/05/25**

ETHICS APPROVAL

To: **Caroline Duncan – Graduate Student**
Civil Engineering
Faculty of Lassonde
cd1224@yorku.ca

From: Alison M. Collins-Mrakas, Director, Research Ethics
(on behalf of You-ta Chuang, Chair, Human Participants Review Committee)

Date: **Thursday, March 7, 2024**

Title: **Optimize Water Safety in Cambridge Bay using Participatory System Dynamics**

Risk Level: ☒ Minimal Risk ☐ More than Minimal Risk

Level of Review: ☒ Delegated Review ☐ Full Committee Review

I am writing to inform you that this research project, **"Optimize Water Safety in Cambridge Bay using Participatory System Dynamics"** has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines.

We have received the following: Natural Sciences Licence & Nunavut Research Institute Licence and appended both to your file.

Note that approval is granted for one year. Ongoing research – research that extends beyond one year – must be renewed prior to the expiry date.

Any changes to the approved protocol must be reviewed and approved through the amendment process by submission of an amendment application to the HPRC prior to its implementation.

Any adverse or unanticipated events in the research should be reported to the Office of Research ethics (ore@yorku.ca) as soon as possible.

For further information on researcher responsibilities as it pertains to this approved research ethics protocol, please refer to the attached document, **"RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE".**

Should you have any questions, please feel free to contact me at: ore@yorku.ca

Yours sincerely,

Alison M. Collins-Mrakas M.Sc., LLM
Director, Office of Research Ethics

YORK U UNIVERSITÉ UNIVERSITY

Certificate #:	**2024-004**
Initial Approval:	**01/05/24-01/05/25**
Amendments:	**Amendment approved: 08/01/24, 2nd Amendment appproved: 04/25/25**
Renewals:	**04/25/25-04/25/26**
Current Approval Period:	**04/25/25-04/25/26**

OFFICE OF RESEARCH ETHICS (ORE)

4700 Keele St.
Toronto ON
Canada M3J 1P3
ore@yorku.ca
www.research.yorku.ca

ETHICS AMENDMENT APPROVAL

To: **Professor Caroline Duncan**
Department of Civil Engineering
Lassonde School of Engineering
cd1224@yorku.ca

From: Alison M. Collins-Mrakas, Director, Research Ethics
(on behalf of Gillian Parekh, Chair, Human Participants Review Committee)

Date: Friday, April 25, 2025

Title: **Optimize Water Safety in Cambridge Bay using Participatory System Dynamics**

Risk Level: ☒ Minimal Risk ☐ More than Minimal Risk

Level of Review: ☒ Delegated Review ☐ Full Committee Review

With respect to your research project entitled, **"Optimize Water Safety in Cambridge Bay using Participatory System Dynamics",** the committee notes that, as there are no substantive changes to either the methodology employed or the risks to participants in and/or any other aspect of the research project, a renewal of approval re the proposed amendment(s) to the above project is granted.

Any further changes to the approved protocol must be reviewed and approved through the amendment process by submission of an amendment application to the HPRC prior to its implementation.

Ongoing research – research that extends beyond one year – must be renewed prior to the expiry date.

Any adverse or unanticipated events in the research should be reported to the Office of Research ethics (ore@yorku.ca) as soon as possible.

For further information on researcher responsibilities as it pertains to this approved research ethics protocol, please refer to the attached document, **"RESEARCH ETHICS: PROCEDURES to ENSURE ONGOING COMPLIANCE".**

Should you have any questions, please feel free to contact me at: acollins@yorku.ca.

Yours sincerely,

Alison M. Collins-Mrakas M.Sc., LLM
Director, Office of Research Ethics

Nunavut Research Institute / ᓄᓇᕗᒻᒥ ᖃᐅᔩᓴᖅᑐᓕᕆᔩᒃᑯᑦ
Box 1720, Iqaluit, NU X0A 0H0 phone:(867) 979-7279 fax: (867) 979-7109 e-mail: mosha.cote@arcticcollege.ca

SCIENTIFIC RESEARCH LICENSE

LICENSE NUMBER 04 001 24N-A

ISSUED TO: Caroline Duncan
Lassonde School of Engineering
York University
134 Adelaide St.E, 308
Toronto, Ontario
M5C 1K9 Canada

TEAM MEMBERS: S.Gora,E.Chalmers,A.Tam

TITLE: Optimizing Drinking Water Safety in Cambridge Bay using Participatory System

OBJECTIVES OF RESEARCH:

My research is based on optimizing water safety in Cambridge Bay using participatory system dynamics. Part of this will require water sampling at various stages in the water treatment and distribution process. Water will be collected from Water Lake, the pumphouse, various places within the treatment plant, the distribution line (and trucks) and private residents. These samples will be used for research purposes and will add the quantitative data required for building a model with the community members.

TERMS & CONDITIONS:
The holder of the licence will be bound by the terms and conditions of the Nunavut Impact Review Board Screening Decision Report and the Department of Culture & Heritage archaeological sites terms and conditions. These terms and conditions will form part of this licence.

DATA COLLECTION IN NU:
DATES: January 20,2024 to December 31,2024
LOCATION: Cambridge Bay

Scientific Research License 04 001 24N-A expires on December 31,2024
Issued at Iqaluit, NU on November 10,2023

Jamal Shirley
Science Advisor

NUNAVUT SCIENTISTS ACT
SCIENTIFIC RESEARCH LICENCE

Nunavut Research Institute / ᓄᓇᕘᒻᒥ ᖃᐅᔨᓴᖅᑐᓕᕆᓂᕐᒧᑦ

959A Nunavut Dr. Iqaluit, NU X0A 3H0 phone:(867) 979-7279 email:mosha.cote@arcticcollege.ca

SCIENTIFIC RESEARCH LICENSE

LICENSE NUMBER 04 022 25R-M

ISSUED TO: Caroline Duncan
Lassonde School of Engineering
York University
134 Adelaide St.E, 308
Toronto, Ontario
M5C 1K9 Canada

TEAM MEMBERS: S.Gora,E.Chalmers

TITLE: Optimizing Drinking Water Safety in Cambridge Bay using Participatory System

OBJECTIVES OF RESEARCH:

My research is based on optimizing water safety in Cambridge Bay using participatory system dynamics. Part of this will require water sampling at various stages in the water treatment and distribution process. Water will be collected from Water Lake, the pumphouse, various places within the treatment plant, the distribution line (and trucks) and private residents. These samples will be used for research purposes and will add the quantitative data required for building a model with the community members. We will gather this input during public forums, workshops, and targeted interviews to help identify problems in the way that drinking water is managed in Cambridge Bay and to build and validate a computer model that will help community members, water system workers, and government workers to work together to find solutions to drinking water problems in the community.

TERMS & CONDITIONS:
The holder of the license will be bound by the terms and conditions of the Nunavut Impact Review Board Screening Decision Report (NIRB File # 23YN037) and the Department of Culture & Heritage archaeological sites terms and conditions. These terms and conditions will form part of this license.

DATA COLLECTION IN NU:
DATES: June 1,2025 to December 6,2025
LOCATION: Cambridge Bay

Scientific Research License 04 022 25R-M expires on December 31,2025
Issued at Iqaluit, NU on May 12,2025

James Shirley
Science Advisor

SCIENTIFIC RESEARCH LICENCE

Appendix B

Consent forms for research activities

Informed Consent Form Public Forum

Date:

Study Name: Optimizing Water Safety in Cambridge Bay using Participatory System Dynamics

Researchers: Caroline Duncan (cd1224@yorku.ca), a doctoral student in Civil Engineering at Lassonde School of Engineering, York University. (Toronto, ON). Dr Stephanie Gora, Assistant Professor, Civil Engineering at Lassonde School of Engineering, York University.

Purpose of the Research: The goal of this work is to explore how different water treatment and water policy changes could help to improve access to clean and safe drinking water in the community of Cambridge Bay, Nunavut. The research intends to use participatory system dynamics modelling, an approach that incorporates technical information, policy, and professional and personal experience into a computer model, to optimize water safety in Cambridge Bay. Input will be sought from different stakeholders such as water system users, people who work with the drinking water system (operators, truck drivers, etc.), and people who regulate and inspect the drinking water system (GN Department of Community and Government Services, GN Department of Health, CIRNAC, etc.). We will gather this input during public forums, workshops, and targeted interviews to help identify problems in the way that drinking water is managed in Cambridge Bay and to build and validate a computer model that will help community members, water system workers, and government workers to work together to find solutions to drinking water problems in the community.

What You Will Be Asked to Do in the Research: Participating in the public forum, you will be asked to attend all 3 meetings that will be held throughout the project to provide your thoughts and stories related to drinking water in Cambridge Bay. You will be asked something following the below questions in the first public forum:

What is the most common problem in the drinking water system?
Where do you see where the problems lie within the drinking water system?
What do you think the top 5 water safety hazards are in the Cambridge Bay drinking water system?

For participating in this research, you will receive a $50 gift card to the local Co-op.

Risks and Discomforts: "We do not foresee any risks or discomfort from your participation in the research."

Benefits of the Research and Benefits to You: The research will allow you to be involved with the discussions to improve water safety in Cambridge Bay. The public forum will allow you and other stakeholders to come together collectively to discuss and share possible ways forward on water safety. The long-term goal of this research is to improve access to clean and safe drinking water in Cambridge Bay, Nunavut. In the short term, the benefits of this research to participants will include a better understanding of the Cambridge Bay drinking water system and new and renewed relationships with other people who interact with the drinking water system.

Voluntary Participation and Withdrawal: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the *[treatment you may be receiving] [nature of the ongoing relationship you may have with the researchers or study staff]* nature of your relationship with York University either now, or in the future.

"If you stop participating, you will still be eligible to receive the inducement of $50 gift card to the local Co-op for agreeing to be in the project, even if you withdraw without completion of the research." In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. *[or, if applicable, "Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete"].*

Confidentiality: *Unless you choose otherwise.* All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research.

The principal investigator will keep a link that identifies you to your coded information, but this link will be kept secure and available only to the principal investigator and/or selected members of the research team. Any information that can identify you will remain confidential.

It is acknowledged that anonymity cannot be guaranteed during public forums. If you choose to participate, it is asked that you respect the privacy of others and not share information outside of the public forums. Information such as photographs of workshop outputs will be provided to the Municipality in accordance with OCAP and keeping research within the community. This will not have any of your personal information.

Data will be collected in the form of handwritten notes and photographs. Your data will be safely stored in a locked facility *until digitized and then stored on a password-protected personal repository belonging to the PI,* and only research staff/research team members will have access to this information. *This information will be stored indefinitely.* Confidentiality will be provided to the fullest extent possible by law.

> *The data collected in this research project may be used – [indicate whether it will be in an anonymous, or anonymized, or de-identified form] - by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.*

Please note that at the end of the study, anonymized may be deposited into one or more publicly accessible scientific repositories, such as York University Dataverse, an institutional research data repository, managed by York University Libraries and provided by Scholars Portal on behalf of the Ontario Council of University Libraries (OCUL), through which researchers from around the world will have access to these data for future research, through a [CC, CC-BY, CC-BY-NC, or other] standard data sharing license.

York University Dataverse does NOT accept content that contains confidential or sensitive information. Dataverse can be used to share de-identified and non-confidential data only. Contributors are required to remove, replace, or redact such information from datasets prior to upload. Scholars Portal makes backup copies of the uploaded data regularly in the event of a server or system malfunction, malicious attack, or other technical issues.

"This study will use the video/audio conferencing software Zoom to collect data, which is an externally hosted cloud-based service. When information is transmitted over the internet privacy cannot be guaranteed. There is always a risk your responses may be intercepted by a third party (e.g., government agencies, hackers). Further, while York University researchers will not collect or use IP addresses or other information which could link your participation to your computer or electronic devices without informing you, there is a small risk with any platform such as this of data that is collected on external servers falling outside the control of the research team. If you are concerned about this, we would be happy to make alternative arrangements (where possible) for you to participate, perhaps via telephone. Please contact Caroline Duncan for further information.

Recordings (audio/video) will be saved in a password protected file to research team members' local computer, not the cloud-based service.

Please note that it is the expectation that participants agree not to make any unauthorized recordings of the content of a meeting / data collection session."

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Caroline Duncan, either by telephone at (437) 328 3009 or by email cd1224@yorku.ca or Dr. Stephanie Gora by e-mail (stephanie.gora.lassonde.yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Director, Research Ethics in the Office of Research Ethics, York University (e-mail ore@yorku.ca).

Legal Rights and Signatures:

I *(fill in your name here)*, consent to participate in (*insert study name here*) conducted by *(insert investigator name here)*. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature ______________________________ **Date** ________________________
Participant

Signature _____________________________ **Date ___________________________**
Principal Investigator

Additional consent (where applicable)

You must seek additional consent by including check boxes or requesting additional signatures for the following:

1. Audio recording

☐ I consent to the audio-recording of my interview(s).

2. Photographs

I _______________________ consent to the use of images of me, my environment and property in the following ways (please check all that apply):

In academic articles	☐ N	☐ Y
In print, digital and slide form	☐ N	☐ Y
In academic presentations	☐ N	☐ Y
In media	☐ N	☐ Y
In thesis materials	☐ N	☐ Y

3. Consent to waive anonymity

I, <<insert participants name>>, consent to the use of my name in the publications arising from this research.

4. Consent to data deposit

I understand that my identifiable data will be placed into an open research data repository. Y / N

5. Consent to use of quotes

I consent to the use of quotations in any final reports/ publications of the research? Y / N

Informed Consent Water Sampling

Date:

Study Name: Optimizing Water Safety in Cambridge Bay using Participatory System Dynamics

Researchers: Caroline Duncan (cd1224@yorku.ca), a doctoral student in Civil Engineering at Lassonde School of Engineering, York University. (Toronto, ON). Dr Stephanie Gora, Assistant Professor, Civil Engineering at Lassonde School of Engineering, York University.

Purpose of the Research: The goal of this work is to explore how different water treatment and water policy changes could help to improve access to clean and safe drinking water in the community of Cambridge Bay, Nunavut. The research intends to use participatory system dynamics modelling, an approach that incorporates technical information, policy, and professional and personal experience into a computer model, to optimize water safety in Cambridge Bay. Input will be sought from different stakeholders such as water system users, people who work with the drinking water system (operators, truck drivers, etc.), and people who regulate and inspect the drinking water system (GN Department of Community and Government Services, GN Department of Health, CIRNAC, etc.). We will gather this input during public forums, workshops, and targeted interviews to help identify problems in the way that drinking water is managed in Cambridge Bay and to build and validate a computer model that will help community members, water system workers, and government workers to work together to find solutions to drinking water problems in the community.

What You Will Be Asked to Do in the Research: If you're volunteering for water sampling, expect requests to access your cistern and kitchen tap. You'll need to provide a convenient time through phone, Facebook, or in-person of your availability. Researchers may need to visit your home four times during the project, taking around 30 minutes for the sampling process.

Risks and Discomforts: We do not foresee any risks or discomfort from your participation in the research.

Benefits of the Research and Benefits to You: The research will allow you to access data about your home's plumbing and better understand the water quality coming from your tap. You will have the chance to ask the researcher any questions you might have to increase your own understanding of the drinking water you receive by the municipality. If you use alternative sources, you will have the opportunity to have these sources also tested for various water quality parameters, which will provide you with information to make informed decisions on your drinking water.

Voluntary Participation and Withdrawal: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the *nature of the ongoing relationship you may have with the researchers or study staff]* nature of your relationship with York University either now, or in the future.

Confidentiality: *Unless you choose otherwise*. All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research.

The principal investigator will keep a link that identifies your house number to your coded information, but this link will be kept secure and available only to the principal investigator and/or selected members of the research team. Any information that can identify you will remain confidential.

Water quality data collected from your home will be safely stored in a password-protected repository, and only research staff/research team members will have access to this information. Should data indicate that you are exposed to a health hazard, this information will be shared with community leaders and the Department of Health; otherwise, anonymized data will be provided to the Department of Community and Government Services to increase baseline data for the community. All raw data will be provided to the community for storage; additionally, this data will be stored indefinitely as an archive on the researcher's personal password-protected repository unless the community decides to destroy all raw data. Confidentiality will be provided to the fullest extent possible by law.

> *The data collected in this research project may be used in an anonymized form by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use*

of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.

Please note that at the end of the study, anonymized data may be deposited into one or more publicly accessible scientific repositories, such as York University Dataverse, an institutional research data repository, managed by York University Libraries and provided by Scholars Portal on behalf of the Ontario Council of University Libraries (OCUL), through which researchers from around the world will have access to these data for future research, through a [CC, CC-BY, CC-BY-NC, or other] standard data sharing license.

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Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact the researcher, Caroline Duncan, either by telephone at (437) 328 3009 or by email cd1224@yorku.ca or Dr. Stephanie Gora by e-mail (stephanie.gora.lassonde.yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Director, Research Ethics in the Office of Research Ethics, York University (e-mail ore@yorku.ca).

Legal Rights and Signatures:

I ___________________________, consent to participate in *Optimizing water safety in Cambridge Bay* conducted by Caroline Duncan. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature____________________________ **Date**________________________
Participant

Signature____________________________ **Date**________________________
Principal Investigator

Additional consent (where applicable)

You must seek additional consent by including check boxes or requesting additional signatures for the following:

6. Audio recording

☐ I consent to the audio-recording of my interview(s).

7. Photographs

I ____________________ consent to the use of images of me, my environment and property in the following ways (please check all that apply):

In academic articles	☐ N	☐ Y
In print, digital and slide form	☐ N	☐ Y
In academic presentations	☐ N	☐ Y
In media	☐ N	☐ Y
In thesis materials	☐ N	☐ Y

8. Consent to waive anonymity

I, , consent to the use of my name in the publications arising from this research.

9. Consent to data deposit

I understand that my identifiable data will be placed into an open research data repository. Y / N

10. Consent to use of quotes

I consent to the use of quotations in any final reports/ publications of the research? Y / N

Informed Consent Form Workshops

Date:

Study Name: Optimizing Water Safety in Cambridge Bay using Participatory System Dynamics

Researchers: Caroline Duncan (cd1224@yorku.ca), a doctoral student in Civil Engineering at Lassonde School of Engineering, York University. (Toronto, ON). Dr Stephanie Gora, Assistant Professor, Civil Engineering at Lassonde School of Engineering, York University.

Purpose of the Research: The goal of this work is to explore how different water treatment and water policy changes could help to improve access to clean and safe drinking water in the community of Cambridge Bay, Nunavut. The research intends to use participatory system dynamics modelling, an approach that incorporates technical information, policy, and professional and personal experience into a computer model, to optimize water safety in Cambridge Bay. Input will be sought from different stakeholders such as water system users, people who work with the drinking water system (operators, truck drivers, etc.), and people who regulate and inspect the drinking water system (GN Department of Community and Government Services, GN Department of Health, CIRNAC, etc.). We will gather this input during public forums, workshops, and targeted interviews to help identify problems in the way that drinking water is managed in Cambridge Bay and to build and validate a computer model that will help community members, water system workers, and government workers to work together to find solutions to drinking water problems in the community.

What You Will Be Asked to Do in the Research: If you participate in this research, you will be asked to contribute your knowledge on drinking water in focus group workshops. You will be working alongside other participants half-day workshops both in-person in Iqaluit or Cambridge Bay or remotely via Zoom to come to a consensus on identifying problems for water safety in Cambridge Bay through multiple activities. Between workshops you will be provided with a report of the findings from the previous workshop with information from other groups or water quality data. You will be expected to read this prior to the workshop and provide an opinion. E.g. if you have changed your mind on something.

Activities include working in teams to answer questions.

1. Problem articulating through answer questions and risk factor mapping
   In teams, you'll identify core factors for system analysis that will then be refined into priority factors. You'll assess each factor for its influence, considering whether it affects other factors, it's direction (positive/negative), and the strength of influence.

2. Modelling activities to test various treatment and policy change hypotheses identified in the problem articulation stage. Example questions at this stage will be something like:
   What changes would you make?
   What policy recommendations would you make?
   How do you think water safety could be improved in CB?

3. You will be provided with the report from the problem identification and modelling workshops to weigh in on details you believe should be included for the researcher to test in the model.

For participating in this research, you will receive a $50 gift card to the local Co-op.

Risks and Discomforts: There is no anticipated risk with participating in this research; however, should discussions in the workshop get too heated, the researcher will intervene and ask for a time-out. You will have the choice to express your opinion alone with the researcher, or you can withdraw from the research if you are too uncomfortable or upset to continue. You are not obligated to share your opinion or knowledge with the group or me.

Benefits of the Research and Benefits to You: The research will allow you to be involved with the discussions to improve water safety in Cambridge Bay. The workshop will allow you and other stakeholders to come together collectively to discuss possible ways forward on water safety. The long term goal of this research is to improve access to clean and safe drinking water in Cambridge Bay, Nunavut. In the short term, the benefits of this research to participants will include a better understanding of the Cambridge Bay drinking water system and new and renewed relationships with other people who interact with the drinking water system.

Voluntary Participation and Withdrawal: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the *nature of the ongoing relationship you may have with the researchers or study staff or the* nature of your relationship with York University either now, or in the future.

"If you stop participating, you will still be eligible to receive the inducement of a $50 gift card to your local Co-op for agreeing to be in the project, even if you withdraw without completion of the research." In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. *[or, if applicable, "Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete"].*

Confidentiality: *Unless you choose otherwise.* All information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. Information such as photographs of workshop outputs will be provided to the Municipality in accordance with OCAP and keeping research within the community. This will not have any of your personal information.

The principal investigator will keep a link that identifies you to your coded information, but this link will be kept secure and available only to the principal investigator and/or selected members of the research team. Any information that can identify you will remain confidential.

It is acknowledged that anonymity cannot be guaranteed during group work. If you choose to participate, it is asked that you respect the privacy of others and not share information outside of the workshops.

Data will be collected in the form of handwritten notes, photographs and audio tapes. Your data will be safely stored in a locked facility *until digitized and then stored on a password-protected personal repository belonging to the PI,* and only research staff/research team members will have access to this information. *This information will be stored indefinitely.* Confidentiality will be provided to the fullest extent possible by law.

> *The data collected in this research project may be used in an anonymized form by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.*

Please note that at the end of the study, anonymized may be deposited into one or more publicly accessible scientific repositories, such as York University Dataverse, an institutional research data repository, managed by York University Libraries and provided by Scholars Portal on behalf of the Ontario Council of University Libraries (OCUL), through which researchers from around the world will have access to these data for future research, through a [CC, CC-BY, CC-BY-NC, or other] standard data sharing license.

York University Dataverse does NOT accept content that contains confidential or sensitive information. Dataverse can be used to share de-identified and non-confidential data only. Contributors are required to remove, replace, or redact such information from datasets prior to upload. Scholars Portal makes backup copies of the uploaded data regularly in the event of a server or system malfunction, malicious attack, or other technical issues.

"This study will use the video/audio conferencing software Zoom to collect data, which is an externally hosted cloud-based service. When information is transmitted over the internet privacy cannot be guaranteed. There is always a risk your responses may be intercepted by a third party (e.g., government agencies, hackers). Further, while York University researchers will not collect or use IP addresses or other information which could link your participation to your computer or electronic devices without informing you, there is a small risk with any platform such as this of data that is collected on external servers falling outside the control of the research team. If you are concerned about this, we would be happy to make alternative arrangements (where possible) for you to participate, perhaps via telephone. Please contact Caroline Duncan for further information.

Recordings (audio/video) will be saved in a password protected file to research team members' local computer, not the cloud-based service.

Please note that it is the expectation that participants agree not to make any unauthorized recordings of the content of a meeting / data collection session."

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Caroline Duncan, either by telephone at (437) 328 3009 or by email cd1224@yorku.ca or Dr. Stephanie Gora by e-mail (stephanie.gora.lassonde.yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Director, Research Ethics in the Office of Research Ethics, York University (e-mail ore@yorku.ca).

Legal Rights and Signatures:

I ___________________________, consent to participate in *the workshops for Optimizing Water Safety in Cambridge Bay* conducted by Caroline Duncan. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature ______________________________ **Date** ________________________
Participant

Signature ______________________________ **Date** ________________________
Principal Investigator

Additional consent (where applicable)

You must seek additional consent by including check boxes or requesting additional signatures for the following:

11. Audio recording

☐ I consent to the audio-recording of my interview(s).

12. Photographs

I ____________________ consent to the use of images of me, my environment and property in the following ways (please check all that apply):

In academic articles	☐ N	☐ Y
In print, digital and slide form	☐ N	☐ Y
In academic presentations	☐ N	☐ Y
In media	☐ N	☐ Y
In thesis materials	☐ N	☐ Y

13. Consent to waive anonymity

I, ___________________________ consent to the use of my name in the publications arising from this research.

14. Consent to data deposit

I understand that my identifiable data will be placed into an open research data repository. Y / N

15. Consent to use of quotes

I consent to the use of quotations in any final reports/ publications of the research? Y / N

Informed Consent Form Interview

Date:

Study Name: Optimizing Water Safety in Cambridge Bay using Participatory System Dynamics

Researchers: Caroline Duncan (cd1224@yorku.ca), a doctoral student in Civil Engineering at Lassonde School of Engineering, York University. (Toronto, ON). Dr Stephanie Gora, Assistant Professor, Civil Engineering at Lassonde School of Engineering, York University.

Purpose of the Research: The goal of this work is to explore how different water treatment and water policy changes could help to improve access to clean and safe drinking water in the community of Cambridge Bay, Nunavut. The research intends to use participatory system dynamics modelling, an approach that incorporates technical information, policy, and professional and personal experience into a computer model, to optimize water safety in Cambridge Bay. Input will be sought from different stakeholders such as water system users, people who work with the drinking water system (operators, truck drivers, etc.), and people who regulate and inspect the drinking water system (GN Department of Community and Government Services, GN Department of Health, CIRNAC, etc.). We will gather this input during public forums, workshops, and targeted interviews to help identify problems in the way that drinking water is managed in Cambridge Bay and to build and validate a computer model that will help community members, water system workers, and government workers to work together to find solutions to drinking water problems in the community.

What You Will Be Asked to Do in the Research: You will either complete tasks similar to the workshops alongside the PI and assistant researcher if you have chosen to participate in the study but not in group work or you will be asked questions to clarify further information provided in the workshops help with the improvement of the model accuracy, for both conversations may be recorded for precise transcripts and quotes.

For those that wish to have one to one workshops with the PI the following can be expected:

You will be asked to contribute your knowledge on drinking water in focus group workshops. You will be working alongside the PI and research assistant both in-person in Iqaluit or Cambridge Bay or remotely via Zoom to come to a consensus on identifying problems for water safety in Cambridge Bay through multiple activities. Between workshops you will be provided with a report of the findings from the previous workshop with information from other groups or water quality data. You will be expected to read this prior to the workshop and provide an opinion. E.g. if you have changed your mind on something.

Activities include working in teams to answer questions.

4. Problem articulating through answer questions and risk factor mapping
   In teams, you'll identify core factors for system analysis that will then be refined into priority factors. You'll assess each factor for its influence, considering whether it affects other factors, it's direction (positive/negative), and the strength of influence.

5. Modelling activities to test various treatment and policy change hypotheses identified in the problem articulation stage. Example questions at this stage will be something like:
   What changes would you make?
   What policy recommendations would you make?
   How do you think water safety could be improved in CB?

6. You will be provided with the report from the problem identification and modelling workshops to weigh in on details you believe should be included for the researcher to test in the model.

For participating in this research, you will receive a $50 gift card to the local Co-op.

Risks and Discomforts: We do not foresee any risks or discomfort from your participation in the research.

Benefits of the Research and Benefits to You: The research will allow you to be involved with the discussions to improve water safety in Cambridge Bay. This research aims to improve access to clean and safe drinking water in

Cambridge Bay, Nunavut. In the short term, the benefits of this research to participants will include a better understanding of the Cambridge Bay drinking water system and new and renewed relationships with other people who interact with the drinking water system.

Voluntary Participation and Withdrawal: Your participation in the study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the *[treatment you may be receiving] [nature of the ongoing relationship you may have with the researchers or study staff]* nature of your relationship with York University either now, or in the future.

"If you stop participating, you will still be eligible to receive the inducement of a $50 gift card to your local Co-op for agreeing to be in the project, even if you withdraw without completion of the research." In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. *[or, if applicable, "Should you wish to withdraw after the study, you will have the option to also withdraw your data up until the analysis is complete"].*

Confidentiality: *Unless you choose otherwise* All information you supply [through interviews and recordings] during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research.

The principal investigator will keep a link that identifies you to your coded information, but this link will be kept secure and available only to the principal investigator and/or selected members of the research team. Any information that can identify you will remain confidential.

Data will be collected in the form of handwritten notes and audio tapes. Your data will be safely stored in a locked facility *until digitized and then stored on a password-protected personal repository belonging to the PI,* and only research staff/research team members will have access to this information. *This information will be stored indefinitely.* Confidentiality will be provided to the fullest extent possible by law.

> *The data collected in this research project may be used – [indicate whether it will be in an anonymous, or anonymized, or de-identified form] - by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.*

Please note that at the end of the study anonymized may be deposited into one or more publicly accessible scientific repositories, such as York University Dataverse, an institutional research data repository, managed by York University Libraries and provided by Scholars Portal on behalf of the Ontario Council of University Libraries (OCUL), through which researchers from around the world will have access to these data for future research, through a [CC, CC-BY, CC-BY-NC, or other] standard data sharing license.

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"This study will use the video/audio conferencing software Zoom to collect data, which is an externally hosted cloud-based service. When information is transmitted over the internet privacy cannot be guaranteed. There is always a risk your responses may be intercepted by a third party (e.g., government agencies, hackers). Further, while York University researchers will not collect or use IP addresses or other information which could link your participation to your computer or electronic devices without informing you, there is a small risk with any platform such as this of data that is collected on external servers falling outside the control of the research team. If you are concerned about this, we would be happy to make alternative arrangements (where possible) for you to participate, perhaps via telephone. Please contact Caroline Duncan for further information.

Recordings (audio/video) will be saved in a password protected file to research team members' local computer, not the cloud-based service.

Please note that it is the expectation that participants agree not to make any unauthorized recordings of the content of a meeting / data collection session."

Questions About the Research? If you have questions about the research in general or about your role in the study, please feel free to contact Caroline Duncan, either by telephone at (437) 328 3009 or by email cd1224@yorku.ca or Dr. Stephanie Gora by e-mail (stephanie.gora.lassonde.yorku.ca). This research has received ethics review and approval by the Human Participants Review Sub-Committee, York University's Ethics Review Board and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Director, Research Ethics in the Office of Research Ethics, York University (e-mail ore@yorku.ca).

Legal Rights and Signatures:

I ___________________________, consent to participate in *the workshops for Optimizing Water Safety in Cambridge Bay* conducted by Caroline Duncan. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by signing this form. My signature below indicates my consent.

Signature ______________________________ **Date** ________________________
Participant

Signature ______________________________ **Date** ________________________
Principal Investigator

Additional consent (where applicable)

You must seek additional consent by including check boxes or requesting additional signatures for the following:

16. Audio recording

☐ I consent to the audio-recording of my interview(s).

17. Photographs

I ____________________ consent to the use of images of me, my environment and property in the following ways (please check all that apply):

In academic articles	☐ N	☐ Y
In print, digital and slide form	☐ N	☐ Y
In academic presentations	☐ N	☐ Y
In media	☐ N	☐ Y
In thesis materials	☐ N	☐ Y

18. Consent to waive anonymity

I, ____________________ consent to the use of my name in the publications arising from this research.

19. Consent to data deposit

I understand that my identifiable data will be placed into an open research data repository. Y / N

20. Consent to use of quotes

I consent to the use of quotations in any final reports/ publications of the research? Y / N

Appendix C

Public consultation poster


WATER SAFETY
in
CAMBRIDGE BAY
PUBLIC CONSULTATION ON COMMUNITY-CENTRIC DRINKING WATER SAFETY RESEARCH
WHO: Caroline Duncan, PhD Candidate at York University
WHAT: Public Consultation for Community Water Safety Research
WHEN: November 30th, 5:30-6:30
WHERE: Luke Novoligak Community Hall
Join Caroline Duncan, as she seeks your valuable feedback on how best to connect with community members on topics related to water safety in Cambridge Bay.
Snacks will be provided.
For inquires, please contact:
cd1224@yorku.ca or +1 437 328 3009
Let's make Cambridge Bay's water safer together.
LASSONDE
SCHOOL OF ENGINEERING
YORK U

Appendix D

Blog post on Nunavut Youth Water Operator Program

Nunavut Youth Water Operator Program Nominated for Water Canada Awards

In early 2024, a pilot program was initiated to address a gap in the water sector by providing a sucession plan encouraging youth interested in water treatment to get hands on experience and insight into the profession.

In acknowledgment of its innovative approach to tackling water sector challenges, the Nunavut Youth Water Operator Pilot Program was nominated as a finalist for the Downstream category at the Water Canada Awards. This nomination highlights the program's commitment to fostering diversity and addressing critical skills shortages within Canada's water sector.

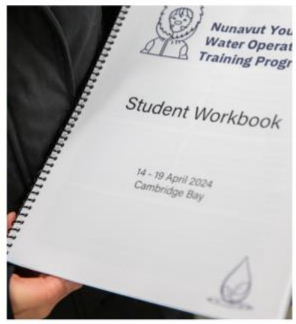
Funding through the Community Capacity Building Fund for the pilot was approved in October 2023, and is a collaborative effort between the Nunavut Association of Municipalities (NAM) and a team of researchers from York University. Caroline Duncan, a PhD student at York University led the program, alongside Dr. Stephanie Gora, Audrey Tam and Victoria Carroll from the Safe and Sustainable Water Research Group at the Lassonde School of Engineering.

This pilot program is designed to create a pipeline for future water operators in Nunavut by providing valuable training opportunities for local youth. The initiative represents a crucial first step toward rolling out a comprehensive technical program across the Territory.

The program consisted of two intensive two-week sessions, the first held in April and the second in June 2024. During these sessions, youth participants gained hands-on experience by engaging with experienced water operators, conducting a mini water sampling project, and exploring various water quality parameters from source to tap. They also delved into the impacts of climate change on water sources, basic mathematical skills, and data analysis.

The students involved in the pilot program will have the opportunity to present their feedback at this year's Annual General Meeting (AGM) in Iqaluit. Their insights will be instrumental in determining the future of the program and whether it should be expanded to other communities across Nunavut.

This nomination underscores the program's potential to make a lasting impact on the water sector in Nunavut, promoting not only technical skills but also local capacity building and sustainability in water management. The recognition at the Water Canada Awards is a testament to the program’s innovative approach and its role in shaping the future of water operations in the Territory.



Appendix E

Instructions for workshop activities

Instructions for factor mapping water safety hazards

Step 1: Prioritizing hazards

Using the handout provided to you, identify your top 10 hazards for each location in the below tables. Each hazard will be numbered so you are able to write down the number of the hazard if preferred on this form.

Step 2: Polarity Analysis

Using the Step two scoring system below, each of you will indicate the polarity of influence between the hazard/hazardous event factors. Using symbols from the table below you will select an option regarding how Hazard 1 would influence Hazard 2, either: (+), and increase in Hazard 1 will cause on increase in Hazard 2; (0), there is little or no influence between Hazard 1 and Hazard 2 or; (−), an increase in Hazard 1 will cause a decrease in Hazard 2.

If you are unsure about the impact of the hazard then you can use DK for “Do not know”

STEP TWO
Impact of hazard
(-) Negative
(0) Neutral
(+) Positive
Do not know

Step 3**: **Cross Impact Assessment

In step three you will be evaluating the strength of the impact of the analysis performed in Step 2, using the scoring system below. This number will be put in the same box as the impact chosen in Step 2.

For example, hazard 1 has a weak strength with hazard 2 as it is an indirect influence. Hazard 3 has a strong influence on hazard 4 as it is direct and there is a clear link between the two hazards.

STEP THREE
Strength of influence
0 - Non-existent
1 – Weak
2 - Medium
3 - Strong

Top 10 hazards for each location:
Use the blank space below to either write out the hazard or write down the number assigned to the hazard in the hand out.

Source Water Hazards	
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Treatment Plant	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	
Distribution	

21	
22	
23	
24	
25	
26	
27	
28	
29	
30	
Buildings	
31	
32	
33	
34	
35	
36	
37	
38	
39	
40	

Source vs Source

	1	2	3	4	5	6	7	8	9	10
1										
2										
3										
4										
5										
6										
7										
8										
9										
10										

Treatment Plant vs Treatment Plant

	11	12	13	14	15	16	17	18	19	20
11										
12										
13										
14										
15										
16										
17										
18										
19										
20										

Distribution vs Distribution

	21	22	23	24	25	26	27	28	29	30
21										
22										
23										
24										
25										
26										
27										
28										
29										
30										

Buildings vs Buildings

	31	32	33	34	35	36	37	38	39	40
31										
32										
33										
34										
35										
36										
37										
38										
39										
40										

Appendix F

Chapter 4 Supplementary Information

Table F4-1: Past frequency scores definitions

Score	Likelihood		Consequence
	Past frequency	***System readiness***	
0	No past evidence of hazard in community	Hazard is not present in community	No impact
1	Has occurred at least once in the past 5 years	All best practices (DWSF) have been implemented and are regularly reviewed	Aesthetic non-compliance (< 1 week)
2	Has occurred at least once a year	Barriers that should address the hazard are in place and are regularly monitored	Aesthetic non-compliance (> 1 week)
3	Has occurred at least once a month	Barriers that should address the hazard are in place but are not regularly monitored	Health – preventative (e.g. low chlorine residual indicative of long-term conditions that could give rise to microbial regrowth)
4	Has occurred at least once a week	No barriers are in place to address the hazard, but the hazard is regularly monitored	Health – chronic illness from long-term exposure
5	Occurs every day	No barriers are in place to address the hazard, and the hazard is not regularly monitored	Health – reactive (e.g. *E. coli* detected in distributed drinking water) and acute illness

Table F4-2: Cambridge Bay potential water system non-compliance in 2021 against federal guidelines [41]

Item or parameter	Requirement	Current condition	Notes
Filtration	Filtration technology approved by Health Canada	Pressure media filter	Not an acceptable type of filtration for pathogen removal
Chlorination	0.7 mg/L as per CT	0.7 mg/L	Pipes and pumps have been upgraded, unknown if CT is being reached at the storage outlet.
Source water turbidity sampling	Daily sampling	Daily sampling	Records not provided
Monitoring of *E.coli* and total coliforms	4 times per month[1] (Government of Nunavut, 1990)	1-2 times per month	Sampling frequency based on population size
Disinfection of water trucks weekly	Weekly (Health Canada, 2021)	Trucks disinfected annually	
Free chlorine measured from truck during delivery	Daily, overnight trucks every morning (Government of Nunavut, 1990)	Sampling results not recorded daily	FC not measured at the point of delivery

[1]This is under the federal guidelines. Under territorial regulations, the communities are only required to test monthly.

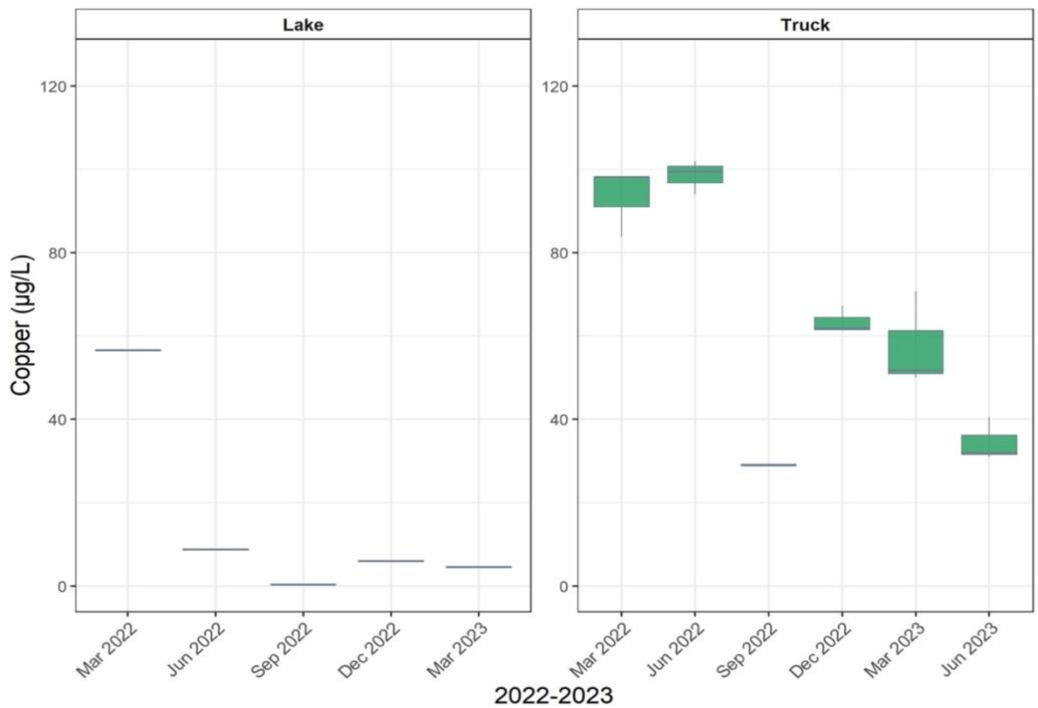


Figure F4-1: Copper levels during 2022-2023 (all sampling events) in Cambridge Bay, NU.

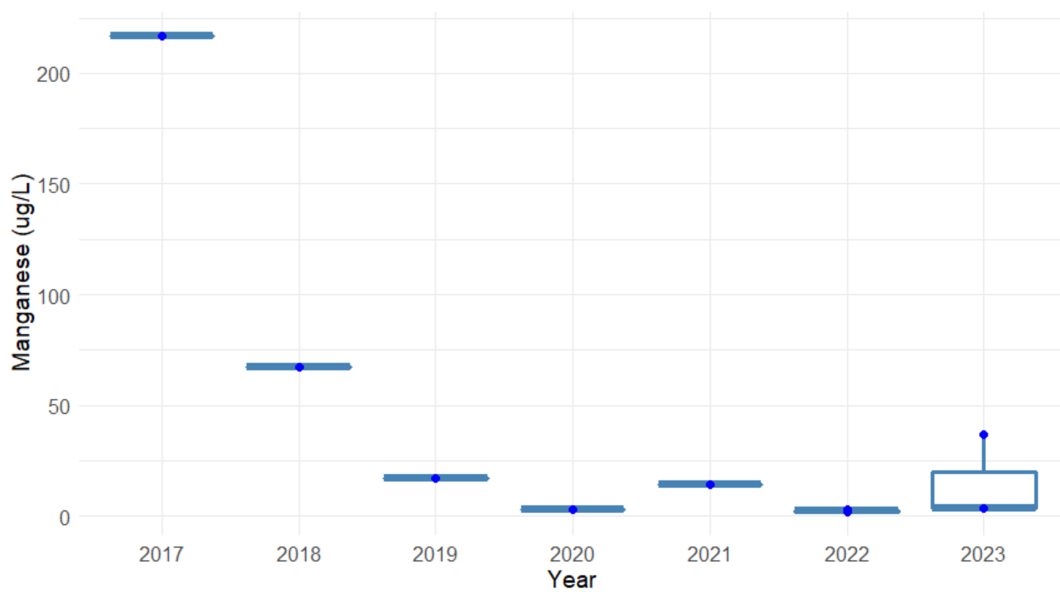


Figure F4-2: Manganese concentrations within trucks between 2017 and 2023 in Cambridge Bay, NU.

Figure F4-3: Continuous monitoring of free chlorine residual during 2022, provided by GN-CGS WaterTrax management system. The black line represents the recommended free chlorine residual level of 0.7 mg/L

Figure F4-4: Temporal and spatial information of sampling events from the historical data set. Blue cells indicate where samples were taken during which sampling campaign.

Table F4-3: Averages, minimums and maximums of parameters 2017 – 2023 – (Spring Freshet)

Parameter	Average	Minimum	Maximum
pH (pH units)	7.58	7.28	7.91
Turbidity (NTU)	0.643	0.21	2.01
Alkalinity (mg/L)	212	139	244
DOC (mg/L)	8.46	6.2	9.7

<u>TOC</u> (mg/L)	8.64	6.7	10
<u>Magnesium</u> (mg/L)	39	32.6	67.2
<u>Aluminium</u> (ug/L)	15.9	0.7	153
<u>Copper</u> (ug/L)	118	0.4	1850
<u>Iron</u> (ug/L)	76.9	18	200
<u>Lead</u> (ug/L)	0.805	0.1	3.7
<u>Manganese</u> (ug/L)	62.4	1.8	277
<u>Zinc</u> (ug/L)	149	15.4	648

Table F4-4: Averages, minimums and maximums of parameters 2022-2023 (All seasons)

Parameter	Average	Minimum	Maximum
<u>pH</u> (pH units)	7.86	7.45	8.21
<u>Turbidity</u> (NTU)	0.495	0.21	2.01
<u>Alkalinity</u> (mg/L)	174	94	241
<u>DOC</u> (mg/L)	7.98	5.4	9.7
<u>TOC</u> (mg/L)	8.06	5.6	10
<u>Magnesium</u> (mg/L)	30.9	17.7	43.1
<u>Aluminium</u> (ug/L)	16.5	0.8	153
<u>Copper</u> (ug/L)	55.6	0.4	127
<u>Iron</u> (ug/L)	54.4	19	101
<u>Lead</u> (ug/L)	0.752	0.1	3.7
<u>Manganese</u> (ug/L)	11.6	1.8	86
<u>Zinc</u> (ug/L)	90.5	0.8	218

Table F4-5: Lake (2017 -2023)

Parameter	Average	Minimum	Maximum

pH (pH units)	7.43	7.28	7.83
Turbidity (NTU)	0.656	0.25	1.62
Alkalinity (mg/L)	216	188	241
DOC (mg/L)	8.28	7.1	9.2
TOC (mg/L)	8.6	7.4	9.7
Magnesium (mg/L)	38.1	33.6	53.6
Aluminium (ug/L)	0.75	0.7	0.8
Copper (ug/L)	10.8	0.4	56.6
Iron (ug/L)	79.2	18	200
Lead (ug/L)	0.636	0.2	1.4
Manganese (ug/L)	83.5	3.5	274
Zinc (ug/L)	95.3	15.4	259

Table F4-6: Trucks (2017 – 2023)

Parameter	Average	Minimum	Maximum
pH (pH units)	7.75	7.5	7.91
Turbidity (NTU)	0.495	0.21	1.22
Alkalinity (mg/L)	210	139	244
DOC (mg/L)	8.81	7.5	9.7
TOC (mg/L)	8.92	7.4	10
Magnesium (mg/L)	39.5	33.2	67.2
Aluminium (ug/L)	27.6	2.5	153
Copper (ug/L)	69.1	11.8	123
Iron (ug/L)	71.1	36	130
Lead (ug/L)	0.667	0.1	3.7

Manganese (ug/L)	25.2	1.8	217
Zinc (ug/L)	130	92.5	205

Table F4-7: Spearman's Correlation for water quality parameters in data sets 2017-2023 and 2022-2023

Parameters	Spearman's Correlation **(ρ)** Lake (2017-2023)	Spearman's Correlation **(ρ)** Trucks (2017-2023)	Spearman's Correlation **(ρ)** (Trucks 2022-2023)
Iron ~ Turbidity	0.64	0.26	0.07
Manganese ~ Turbidity	0.46	0.52	0.01
Iron ~ Manganese	0.73	0.599	0.32
Iron ~ Copper	-0.63	-0.39	0.23
Zinc ~ Copper	0.69	0.20	0.85
Copper ~ Lead	0.16	0.05	0.09
Turbidity ~ Magnesium	0.14	0.58	0.20
Aluminium ~ Copper	-0.48	0.15	0.26
Iron - Zinc	-0.67	0.26	0.54
DOC-THM	N/A[1]	0.63	0.911
Copper – Manganese	-0.42	-0.64	0.3

Appendix G

Chapter 5 Supplementary Information

Table G5-1: Summary of methods and number of buildings sampled.

Parameter	Sampling Method	Volume of sample	Campaign 1 No of samples | No of locations		Campaign 2 No of samples | No of locations		Campaign 3 No of samples | No of locations		Total of samples
Free and total chlorine	Grab	250 mL	73 100[1]	24 2[1]	62	29	64	33	199 100
			Source, truck fill, trucks 1-3, buildings 1,**2**,**3**,**4**,**5**,6, 9 (tap and cistern)[2]		Trucks 1-3, buildings 1,**3**,**4**,**5**,6,**7**,9,**10**,**11**,**12**,**13**,**14**,**16**,**18** (tap and cistern)[2]		Source, truck fill, core service, trucks 1-3, buildings 21- 51 (taps)		
ATP	Grab	50 mL	32 100[1]	13 2[1]	29	13	66	33	127 100
			Source, truck fill, buildings 1,**2**,**3**,**4**,**5**,6, 9 (tap and cistern)[2]		Trucks 1-3, buildings 1,**3**,**4**,**5**,6,**7**,**10**,**13**,14,16 (tap and cistern)[2]		Source, truck fill, core service, trucks 1-3, buildings 21- 51 (taps)		
Anions	Grab	500 mL	33	17	16	8	26	13	75
			Source, treatment plant, trucks, buildings 1,**2**,**3**,**4**,**5**,6, 9 (taps and cisterns)		Buildings 2,3,**4**,**5**,9 (tap and cistern)[2]		Source, before filter, core service, truck fill, trucks 1-3, buildings 1,2,3[3]		
Organics	Grab	200 mL	33	17	16	8	26	13	75
			Source, treatment plant, trucks, buildings 1,**2**,**3**,**4**,**5**,6, 9 (taps and cisterns)		Buildings 2,3,**4**,**5**,9 (tap and cistern)[2]		Source, before filter, core service, truck fill, trucks 1-3, buildings 1,2,3[3]		
THM	Grab	40 mL	33	17	16	8	26	13	75

			Trucks 1-3, buildings 1,**<u>2</u>**,**<u>3</u>**,**<u>4</u>**,**<u>5</u>**,6, 9 (tap and cistern)[2]		Buildings 2,3,**<u>4</u>**,**<u>5</u>**,9 (tap and cistern)[2]	Source, before filter, core service, truck fill, trucks 1-3, buildings 1,<u>2</u>,<u>3</u>[3]		
Total metals	RDT	1 L	41	21	-	70	35	111
			Buildings 1-20 (taps)			Source , core service, truck fill, buildings 1, 21-51 (taps)		
Total metals	6HRS	5 X1 L	20	2	-	30	3	50
			Buildings 1, 5 (taps)			Buildings 1,24, 29 (taps)		

[1:] *Spring freshet sample number and location number*

[2]*Bold underlined number indicates both the cistern and the tap were tested at this location*

[3]*Underlined number means that samples were only taken from the cistern at this location*

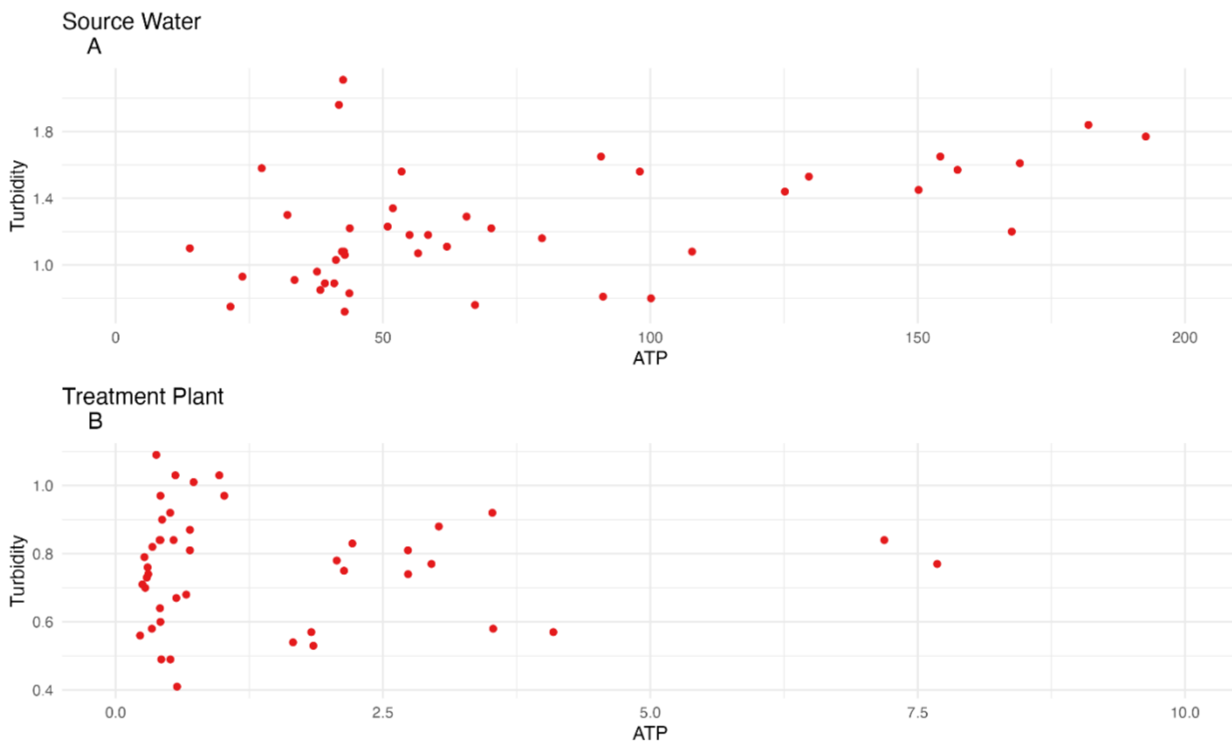


Figure G5-1: Correlations between turbidity and ATP in the source water (top) and the treatment plant (bottom) in Cambridge Bay, NU, during the spring freshet..

Table G5-2: System readiness score for NU-WSP framework (adapted from Chalmers et al., 2025)

System readiness score	Description
0	Hazard not present in community
1	All best practices from the Nunavut Drinking Water Strategic Framework have been implemented and are regularly reviewed
2	Barriers that should address the hazard are in place and are regularly monitored
3	Barriers that should address the hazard are in place but are not regularly monitored
4	No barriers are in place to address the hazard but the hazard is regularly monitored
5	No barriers are in place to address the hazard and the hazard is not regularly monitored

Table G5-3: Consequence score for NU-WSP framework (adapted from Chalmers et al., 2025)

Consequence score	Description
0	No impact
1	Aesthetic non-compliance (< 1 week)
2	Aesthetic non-compliance (> 1 week)
3	Health – preventative (e.g. low free chlorine residual in tap water)
4	Health – chronic (e.g. lead in tap water)
5	Health – acute (e.g. *E. coli* in tap water)

Table G5-4: Water safety risk levels for NU-WSP framework (adapted from Chalmers et al., 2025)

Water safety risk score	Water safety risk level
0	No risk
1-5	Low risk
6-10	Moderate risk
11-9	High risk
20-25	Very high risk

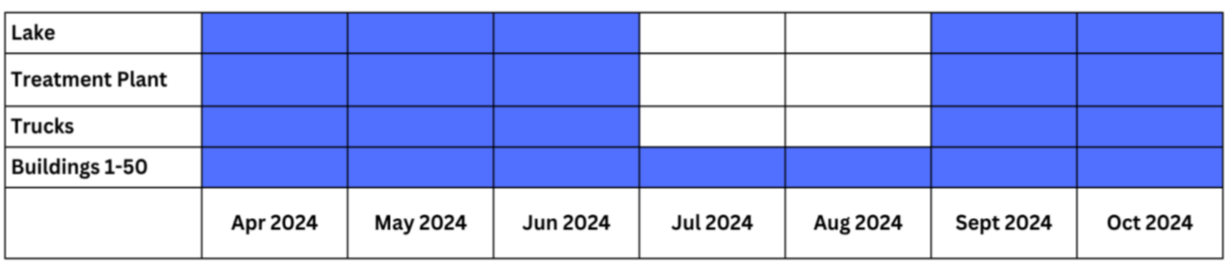


Table G5-5: Temporal and spatial information of sampling events from the study period. Blue cells indicate where samples were taken during which month of the study period.

Appendix H

Chapter 6 Supplementary Information

Table H6-1: Source Water Priority Risk Drivers from all Stakeholder Groups

Stakeholder Group 1	
Source Water Top 10	
Oxygen depletion	annual ice formation
Sewage lagoon	sewage outlet polluting alternative sources at river
Fuel spill	direct contamination of water from spilled fuels
Access road	Blizzard reduces condition of road, hindering maintenance and emergency response if required
Lack of signage	increased risk of accidental contamination or improper use of water resources
Solid waste fires	windblown ash and pollutants could contaminate water supply
Sewage lagoon	infiltration to water table, connected to Water Lake
Proximity of incinerator to drinking water source	Risk of contamination with toxins from the incinerator emissions
Nutrification from climate change and development	increased algal bloom, treatment plant unable to treat
Camping around the lake	possible pollution from waste, chemicals and human activity
Stakeholder Group 2	
Lack of knowledge of watershed	Unknown contamination of lakes that feed into source water
Microbial contamination	cross contamination of birds migrating from lagoon or solid waste site to source water
Access road	run off and sedimentation from road during heavy precipitation
Spring runoff	Increased run off during spring thaw carrying sediments, potential pollutants into the source
Inadequate water supply	increased demand of Water Lake
Lack of signage	increased risk of accidental contamination or improper use of water resources
Global warming	Altered aquatic ecosystem due to changes in water quality and potential introduction of new contaminants
Global warming	Altered precipitation patterns potential for increased run off and contamination of water sources
Sewage lagoon	sewage outlet polluting alternative sources at river

No fence	unrestricted access to water source increasing chance of unauthorized activities and contamination
Stakeholder Group 3	
Microbial contamination	Local and migratory animals defecating into the lake
Microbial contamination	Swimmers introducing faecal contamination
Insufficient testing of surrounding lakes	Lack of monitoring of water quality in watershed, unknown risks of contamination
Inadequate water supply	increased demand of Water Lake
Inadequate water supply	Lower precipitation from climate change reducing flow from other surrounding lakes into Water Lake
Inadequate water supply	drought conditions from reduced snow melt/ longer summers
Lack of signage	increased risk of accidental contamination or improper use of water resources
Legacy contamination	long-term risk of residual contaminants in soils
No fence	unrestricted access to water source increasing chance of unauthorized activities and contamination
Global warming	Altered aquatic ecosystem due to changes in water quality and potential introduction of new contaminants
Stakeholder Group 4	
Snow coverage	snow cover patterns causing change in water patterns and quality
Insufficient testing of surrounding lakes	Lack of monitoring of water quality in watershed, unknown risks of contamination
Garbage	Accumulation of garbage in the water source from lack of containment and solid waste site
Microbial contamination	Local and migratory animals defecating into the lake
Inadequate water supply	Lower precipitation from climate change reducing flow from other surrounding lakes into Water Lake
Microbial contamination	swimmers introducing faecal contamination
High turbidity	spring freshet reducing clarity and reducing UV lights efficacy
Fuel spill	direct contamination of water from spilled fuels
No Water Safety Plan	increased risk of unaddressed risk and inadequate response measures

Sewage lagoon	sewage outlet polluting alternative sources at river
Stakeholder Group 5	
Recreational vehicle activity	Accidental or intentional entry of vehicles into the lake, causing potential contamination
Microbial contamination	Swimmers introducing faecal contamination
Microbial contamination	Local and migratory animals defecating into the lake
Lack of knowledge of watershed	Unknown contamination of lakes that feed into source water
Microbial contamination	cross contamination of birds migrating from lagoon or solid waste site to source water
Solid waste fires	windblown ash and pollutants could contaminate water supply
No fence	unrestricted access to water source increasing chance of unauthorized activities and contamination
Dust	Dust from roads deposited into water source, carrying potential contaminants
Microbial contamination	ineffective communication during animal migration causing potential exposure to unsafe water due to lack of timely advisories for boil water
Proximity of incinerator to drinking water source	Risk of contamination with toxins from the incinerator emissions
Stakeholder Group 6	
Lack of knowledge of watershed	Unknown contamination of lakes that feed into source water
Microbial contamination	cross contamination of birds migrating from lagoon or solid waste site to source water
Garbage	Accumulation of garbage in the water source from lack of containment and solid waste site
No fence	unrestricted access to water source increasing chance of unauthorized activities and contamination
Dust	Dust from roads deposited into water source, carrying potential contaminants
Legacy contamination	long-term risk of residual contaminants in soils
No Water Safety Plan	increased risk of unaddressed risk and inadequate response measures

No source water protection	increased risk of contamination from external sources
Microbial contamination	direct contamination of sources with pathogens or pollutants from urination
Pollution from various sources (Growth of community, vehicle emissions, lack of bylaw for dog waste, poor yard maintenance)	Degradation of environmental quality through various sources of pollution leading to contamination of local water source
Stakeholder Group 7	
Garbage	Accumulation of garbage in the water source from lack of containment and solid waste site
Sewage lagoon	infiltration to water table, connected to Water Lake
Dust	Dust from roads deposited into water source, carrying potential contaminants
Global warming	Altered aquatic ecosystem due to changes in water quality and potential introduction of new contaminants
Global warming	Altered precipitation patterns potential for increased run off and contamination of water sources
No Water Safety Plan	increased risk of unaddressed risk and inadequate response measures
Microbial contamination	ineffective communication during animal migration causing potential exposure to unsafe water due to lack of timely advisories for boil water
Proximity of incinerator to drinking water source	Risk of contamination with toxins from the incinerator emissions
Sewage lagoon	sewage outlet polluting alternative sources at river
Pollution from various sources (Growth of community, vehicle emissions, lack of bylaw for dog waste, poor yard maintenance)	Degradation of environmental quality through various sources of pollution leading to contamination of local water source
Stakeholder Group 8	
Lack of knowledge of watershed	Unknown contamination of lakes that feed into source water
Solid waste fires	windblown ash and pollutants could contaminate water supply

Spring runoff	Increased run off during spring thaw carrying sediments, potential pollutants into the source
Inadequate water supply	Lower precipitation from climate change reducing flow from other surrounding lakes into Water Lake
High turbidity	spring freshet reducing clarity and reducing UV lights efficacy
Inadequate water supply	permafrost degradation - less feeding from other lakes into Water Lake
Legacy contamination	long-term risk of residual contaminants in soils
Global warming	Altered precipitation patterns potential for increased run off and contamination of water sources
No Water Safety Plan	increased risk of unaddressed risk and inadequate response measures
phosphorus and nitrogen pollution from climate change and development	increased algal bloom, treatment plant unable to treat
Stakeholder Group 9	
High turbidity	spring freshet reducing clarity and reducing UV lights efficacy
Inadequate water supply	increased demand of Water Lake
Global warming	Altered precipitation patterns potential for increased run off and contamination of water sources
Fuel spill	direct contamination of water from spilled fuels
Insufficient testing of surrounding lakes	Lack of monitoring of water quality in watershed, unknown risks of contamination
Legacy contamination	long-term risk of residual contaminants in soils
Inadequate water supply	drought conditions from reduced snow melt/ longer summers
Global warming	Altered aquatic ecosystem due to changes in water quality and potential introduction of new contaminants
Global warming	damage to infrastructure from frost heave

Pollution from various sources (Growth of community, vehicle emissions, lack of bylaw for dog waste, poor yard maintenance)	Degradation of environmental quality through various sources of pollution leading to contamination of local water source
Stakeholder Group 10	
Insufficient testing of surrounding lakes	Lack of monitoring of water quality in watershed, unknown risks of contamination
Urban and industrial development	risk of contamination of source due to poor planning and risk assessment of municipal development
Access road	Blizzard reduces condition of road, hindering maintenance and emergency response if required
Lack of knowledge of watershed	Unknown contamination of lakes that feed into source water
No Water Safety Plan	increased risk of unaddressed risk and inadequate response measures
Inadequate water supply	permafrost degradation - less feeding from other lakes into Water Lake
Inadequate water supply	increased demand of Water Lake
Economic benefits preferred over holistic community needs	Neglect of essential water safety due to economic concerns

Table H6-2: Treatment Plant Priority risk drivers for all stakeholders

Stakeholder Group 1	
Treatment Plant Top 10	
No training after upgrades	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Equipment failure	Failure to address maintenance issues in a timely fashion
Inadequate treatment	Disinfection by-products exceeding regulatory limits, posing health risk
Freezing temperatures	Burst pipes, water leaks, contamination from outside sources
Electrical malfunction	Disruption of water treatment processes through electrical failure
excessive chlorine levels	Causing taste and odour issues, formation of DBPs
Power outage	Risk in water treatment system failure during outage
Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination
Deliberate damage to infrastructure	Tampering with water supply systems leading to contamination
High staff turnover	Reduced operational effectiveness and increased risk of error
Stakeholder Group 2	
Inconsistent sampling procedures	Irregular sampling locations, potential failure to detect water quality issues
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Lack of continuous training	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Absence of clear standard operating procedures	Misinterpretation of SOPs leading to operational inefficiencies
No training after upgrades	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
No standardization	Potential inefficiencies and increased risk of system failures
Equipment failure	System failure due to aging infrastructure
High staff turnover	Reduced operational effectiveness and increased risk of error

Limited capacity of regulatory agencies	Neglect of water safety concerns due to overextended resources
Insufficient funding	Aging infrastructure and reduced capacity to improve water quality
Stakeholder Group 3	
Lack of equipment redundancies	Dependence on a single intake pump for water supply until lake has defrosted
Insufficient storage	Running out of media or chlorine during peak demand and compromising water treatment as no storage
Equipment failure	Failure to address maintenance issues in a timely fashion
Extreme weather	Infrastructure damage causing potential contamination
Deliberate damage to infrastructure	Tampering with water supply systems leading to contamination
excessive chlorine levels	Causing taste and odour issues, formation of DBPs
Limited capacity of regulatory agencies	Neglect of water safety concerns due to overextended resources
Insufficient funding	Aging infrastructure and reduced capacity to improve water quality
Limited asset management	Inadequate management of water system assets
Snow coverage	snow cover patterns causing change in water patterns and quality
Stakeholder Group 4	
Lack of equipment redundancies	Dependence on a single intake pump for water supply until lake has defrosted
Lack of continuous training	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Insufficient storage	Running out of media or chlorine during peak demand and compromising water treatment as no storage
Unclear or inadequate reporting requirements for regulatory compliance	Failure to report incidents or exceedances promptly, resulting in regulatory non-compliance and potential public health risks
Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination

Inaccurate measurement from testing equipment	Misleading data leading to incorrect decisions in water treatment processes, potentially compromising water quality and public safety
Freezing temperatures	Burst pipes, water leaks, contamination from outside sources
excessive chlorine levels	Causing taste and odour issues, formation of DBPs
Electrical malfunction	Disruption of water treatment processes through electrical failure
Power outage	Risk in water treatment system failure during outage
Stakeholder Group 5	
Inadequate treatment	Disinfection by-products exceeding regulatory limits, posing health risk
Inaccurate measurement from testing equipment	Misleading data leading to incorrect decisions in water treatment processes, potentially compromising water quality and public safety
Equipment failure	Failure to address maintenance issues in a timely fashion
Extreme weather	Infrastructure damage causing potential contamination
Freezing temperatures	Burst pipes, water leaks, contamination from outside sources
Insufficient maintenance	Clogging of intake screens, potential contamination due to blocked screens
excessive chlorine levels	Causing taste and odour issues, formation of DBPs
No standardization	Potential inefficiencies and increased risk of system failures
Vacation time of water operators	No trained staff available for daily operation, increasing risk to effective treatment of water
Lack of continuous training	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Stakeholder Group 6	
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Lack of continuous training	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Unclear or inadequate reporting requirements for regulatory compliance	Failure to report incidents or exceedances promptly, resulting in regulatory non-compliance and potential public health risks

Inaccurate measurement from testing equipment	Misleading data leading to incorrect decisions in water treatment processes, potentially compromising water quality and public safety
Equipment failure	Failure to address maintenance issues in a timely fashion
Freezing temperatures	Burst pipes, water leaks, contamination from outside sources
Equipment maintenance and cleanliness	Analytical equipment not cleaned contributing to contamination of samples and potentially inaccurate test results
Insufficient maintenance	Clogging of intake screens, potential contamination due to blocked screens
No standardization	Potential inefficiencies and increased risk of system failures
Power outage	Risk in water treatment system failure during outage
Stakeholder Group 7	
Inadequate treatment	Disinfection by-products exceeding regulatory limits, posing health risk
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Lack of continuous training	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
No training after upgrades	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Unclear or inadequate reporting requirements for regulatory compliance	Failure to report incidents or exceedances promptly, resulting in regulatory non-compliance and potential public health risks
Equipment failure	Failure to address maintenance issues in a timely fashion
Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination
Inconsistent sampling procedures	Irregular sampling locations, potential failure to detect water quality issues
High staff turnover	Reduced operational effectiveness and increased risk of error
Plants too technical for current staff knowledge	Ineffective use and maintenance of treatment plant technology
Stakeholder Group 8	

Lack of equipment redundancies	Dependence on a single intake pump for water supply until lake has defrosted
Inadequate treatment	Disinfection by-products exceeding regulatory limits, posing health risk
Absence of clear standard operating procedures	Misinterpretation of SOPs leading to operational inefficiencies
Unclear or inadequate reporting requirements for regulatory compliance	Failure to report incidents or exceedances promptly, resulting in regulatory non-compliance and potential public health risks
Equipment failure	Failure to address maintenance issues in a timely fashion
Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination
International interference or cyber attack	Lock out of SCADA causing potential supply or quality concerns
Insufficient maintenance	Accumulation of manganese over Health Canada MAC
Unclear roles and responsibilities	Ineffective water management and response from departments
Limited capacity of regulatory agencies	Neglect of water safety concerns due to overextended resources
Stakeholder Group 9	
Equipment failure	Failure to address maintenance issues in a timely fashion
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Freezing temperatures	Burst pipes, water leaks, contamination from outside sources
Equipment failure	System failure due to aging infrastructure
High staff turnover	Reduced operational effectiveness and increased risk of error
Insufficient funding	Aging infrastructure and reduced capacity to improve water quality
Inadequate treatment	Disinfection by-products exceeding regulatory limits, posing health risk
Lack of equipment redundancies	Dependence on a single intake pump for water supply until lake has defrosted
Extreme weather	Infrastructure damage causing potential contamination

Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination
Stakeholder Group 10	
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
No training after upgrades	Staff lacking necessary skills and knowledge to operate the treatment plant, increasing the risk of operational errors
Unclear or inadequate reporting requirements for regulatory compliance	Failure to report incidents or exceedances promptly, resulting in regulatory non-compliance and potential public health risks
Unclear roles and responsibilities	Ineffective water management and response from departments
Equipment maintenance and cleanliness	Analytical equipment not cleaned contributing to contamination of samples and potentially inaccurate test results
Inconsistent sampling procedures	Irregular sampling locations, potential failure to detect water quality issues
Insufficient testing of water quality	Lack of monitoring of water quality unknown risks of contamination
Lack of equipment redundancies	Dependence on a single intake pump for water supply until lake has defrosted
Absence of clear standard operating procedures	Misinterpretation of SOPs leading to operational inefficiencies
Equipment failure	System failure due to aging infrastructure

Table H6-3: Distribution Priority Risk Drivers from all Stakeholders

Stakeholder Group 1	
Distribution Top 10	
Radios malfunction	Ineffective communication during emergencies
Microbial contamination	Potential contamination of water due to unclean hoses
Harassment of drivers	Safety of drivers compromised from locals harassing for water deliveries
Water main break	Contaminants into water supply from improper practice while repairing
Lack of redundant parts	Trucks remain broken and unavailable for water delivery
Insufficient water supply	Interpersonal conflict between workers and tenants causing disruption in water and sewage services
Microbial contamination	Cross-contamination from swampers using the same gloves for sewage trucks and water trucks
Equipment failure	Inadequate storage for water trucks, exposing trucks to extreme weather
Supply chain interruption/delays	Delays in equipment repairs impacting operations and water safety
Lack of redundant parts	Risk of prolonged downtime and operational disruptions
Stakeholder Group 2	
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Cross contamination during filling of building	Transfer of contaminants from the fill point
Microbial contamination	Potential microbial contamination of water during delivery due to inadequate sterilization procedures
Poor inter-departmental communication	Inefficient coordination increasing risk of compliance failures
Microbial contamination	Potential contamination of water due to unclean trucks

Equipment failure	Failure to address maintenance issues in a timely fashion
Inadequate reporting standards	Water truck sanitation practices not standardized or documented, potential risk of supplying contaminated water
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Equipment failure	Breakdown of trucks due to aging
Microbial contamination	Potential introduction of contaminants in the soil to the water truck through tracking
Stakeholder Group 3	
Insufficient workforce	Payday reducing available drivers causing delays in delivery as truck drivers unavailable after payday
Growth of community	Overwhelmed municipal services leading to inadequate water deliveries increasing water security issues
Blizzards	Individuals bypassing protocols, putting those in need more at risk of receiving no water
Insufficient space for vehicle storage	Exposure to environmental conditions and potential vandalism leading to wear and tear
Microbial contamination	Potential contamination of water hoses due to unsanitary garage flooring
Equipment failure	Failure to address maintenance issues in a timely fashion
Equipment failure	Breakdown of trucks due to aging
Insufficient water supply	Interpersonal conflict between workers and tenants causing disruption in water and sewage services
Substance abuse	Potential neglect of proper water management increasing risk of contamination
Insufficient number of water trucks	Increased strain on existing water delivery infrastructure
Stakeholder Group 4	
Changes in delivery routes	Disruptions in water deliveries to homes
Water main break	Contaminants into water supply from improper practice while repairing

Corrosion	Excess chlorine due to degradation
Equipment failure	Breakdown of trucks due to aging
Gaps in regulation oversight in public health concerns	Lack of coordination in water management
Equipment failure	Inadequate storage for water trucks, exposing trucks to extreme weather
Lack of redundant parts	Risk of prolonged downtime and operational disruptions
Insufficient resources for water system maintenance	Prioritization of well-being needs over basic right needs leading to bottleneck in delivery for staff and trucks
Insufficient water supply	Lack of sewage pump out halting access to water supply
Supply chain interruption/delays	Delays in equipment repairs impacting operations and water safety
Stakeholder Group 5	
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Cross contamination during filling of building	Transfer of contaminants from the fill point
Harassment of drivers	Safety of drivers compromised from locals harassing for water deliveries
Microbial contamination	Potential contamination of water hoses due to unsanitary garage flooring
Microbial contamination	Potential contamination of water due to unclean hoses
Corrosion	Excess chlorine due to degradation
Equipment failure	Water line exposed to extreme weather
Microbial contamination	Cross contamination from truck nozzle to building fill intakes
Insufficient water supply	Interpersonal conflict between workers and tenants causing disruption in water and sewage services

Insufficient water supply	Lack of sewage pump out halting access to water supply
Stakeholder Group 6	
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Microbial contamination	Potential microbial contamination of water during delivery due to inadequate sterilization procedures
Equipment failure	Failure to address maintenance issues in a timely fashion
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Equipment failure	Water line exposed to extreme weather
Supply chain interruption/delays	Delays in equipment repairs impacting operations and water safety
Changes in delivery routes	Disruptions in water deliveries to homes
Lack of redundant parts	Trucks remain broken and unavailable for water delivery
Insufficient workforce	Decreased number of drivers due to vacation reducing water deliveries
Insufficient number of water trucks	Increased strain on existing water delivery infrastructure
Stakeholder Group 7	
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Microbial contamination	Potential microbial contamination of water during delivery due to inadequate sterilization procedures
Inadequate training in hazardous environments	Increased risk of accidents during confined space entry and truck cleaning

Limited capacity of regulatory agencies	Inadequate enforcement of regulations, potential risks to public health
Microbial contamination	Potential contamination of water due to unclean trucks
Inadequate reporting standards	Water truck sanitation practices not standardized or documented, potential risk of supplying contaminated water
Microbial contamination	Cross-contamination from swampers using the same gloves for sewage trucks and water trucks
Road maintenance	Potholes in the road increase wear and tear in delivery vehicles
No formal training	Increased likelihood of errors in water management and operations
Growth of community	Overwhelmed municipal services leading to inadequate water deliveries increasing water security issues
Stakeholder Group 8	
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Microbial contamination	Potential microbial contamination of water during delivery due to inadequate sterilization procedures
Lack of monitoring at building intakes	Inadequate disinfection levels in truck at point of delivery, potential reintroduction of microbial contamination
Inadequate monitoring of water trucks for turbidity	Potential microbial contamination of water during delivery
Inadequate training in hazardous environments	Increased risk of accidents during confined space entry and truck cleaning
Outdated regulatory framework	Ineffective oversight of water distribution practices due to regulatory gaps
Poor inter-departmental communication	Inefficient coordination increasing risk of compliance failures
Limited capacity of regulatory agencies	Inadequate enforcement of regulations, potential risks to public health

Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
Water main break	Contaminants into water supply from improper practice while repairing
Stakeholder Group 9	
Microbial contamination	Potential microbial contamination of water during delivery due to inadequate sterilization procedures
Limited capacity of regulatory agencies	Inadequate enforcement of regulations, potential risks to public health
Equipment failure	Failure to address maintenance issues in a timely fashion
Equipment failure	Breakdown of trucks due to aging
Insufficient resources for water system maintenance	Bottleneck in delivery due to truck shortage
Supply chain interruption/delays	Delays in equipment repairs impacting operations and water safety
Insufficient workforce	Buildings not receiving water and left without access to drinking water and sanitation services
Blizzards	Individuals bypassing protocols, putting those in need more at risk of receiving no water
Lack of redundant parts	Trucks remain broken and unavailable for water delivery
Insufficient water supply	Blizzards/ adverse weather
Stakeholder Group 10	
Insufficient trained staff	Inadequate training leading to errors of inability to respond effectively to emergencies
No formal training	Increased likelihood of errors in water management and operations
Inadequate reporting standards for water truck cleaning	Water truck sanitation practices not documented, potential risk of disturbing contaminated water
Lack of monitoring at building intakes	Inadequate disinfection levels in truck at point of delivery, potential reintroduction of microbial contamination

Inadequate recording	No keeping consistent or correct logbooks to identify when water may require additional disinfection
Inadequate reporting standards	Water truck sanitation practices not standardized or documented, potential risk of supplying contaminated water
Microbial contamination	Potential contamination of water due to unclean hoses
Limited capacity of regulatory agencies	Inadequate enforcement of regulations, potential risks to public health
Poor inter-departmental communication	Inefficient coordination increasing risk of compliance failures
Outdated regulatory framework	Ineffective oversight of water distribution practices due to regulatory gaps

Table H6-4:Buildings Priority Risk Drivers from all Stakeholders

Stakeholder Group 1	
Buildings Top 10	
Copper in treated water	Water in pipes corroding copper piping
Microbial growth	High temperature in mechanical room
Inadequate regulation of home water tank maintenance	No transparency on cleaning requirements leading to potential contamination of household water tanks from unclean water storage practices
Equipment failure	Leaks in pipes from general wear and tear
Insufficient housing	Overburdening of water sources in home
Lack of security	Intake used as ashtray leading to potential contamination of water supply
Ice on steps	Risk of falling and unable to deliver water to house
Occupational health risk	Unsanitary conditions
Insufficient water supply	Swampers won't delivery to homes with steps to inlet not had snow shovelled
Broken intake	De-icing banging breaks intake pipe and home unable to receive water deliveries
Stakeholder Group 2	
Lack of security	Contamination of water supply
Microbial growth	Stagnant water due to occupants on vacation
Inadequate regulation of home water tank maintenance	No transparency on cleaning requirements leading to potential contamination of household water tanks from unclean water storage practices
Equipment failure	Improper installation or repairs of infrastructure
Insufficient personnel	Insufficient maintenance leading to failures in dwelling infrastructure
Unidentified health issues	potential contamination of drinking water contributing to unexplained health problems

Inadequate hygiene practices	Poor hygiene leads to potential microbial contamination and illness
Ice collection	Risk of introducing contaminants into water supply
Lack of security	Contamination of water supply through easy access from intake pipes
Water wasted	Design flaw for fill pipes leading to pooling of water at intake pipe
Stakeholder Group 3	
Water wasted	Design flaw for fill pipes leading to pooling of water at intake pipe
Equipment failure	Breakage of pipes and fittings due to freezing
Power outage	Pumps inside homes stop working due to power outage in community limiting access to water and basic sanitation
Fuel spill	Leaks filling house fuel tanks, causing ground contamination
Insufficient housing	Overburdening of water sources in home
Microbial growth	Extended periods without fresh treated water in tank
Inadequate regulation of home water tank maintenance	No transparency on cleaning requirements leading to potential contamination of household water tanks from unclean water storage practices
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices due to tanks being inaccessible
Lack of security	Contamination of water supply through easy access from intake pipes
Occupational health risk	Unsanitary residents
Stakeholder Group 4	
Copper in treated water	Water in pipes corroding copper piping

No regulation for water tank hygiene	No cleaning occurs for multiple years, risking microbial contamination
Lack of security	Contamination of water supply
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices
Equipment failure	Leaks in pipes from general wear and tear
Microbial contamination	Insects accessing water through intake pipe
Equipment failure	Breakage of pipes and fittings due to freezing
Insufficient water supply	Swampers won't delivery to homes with steps to inlet not had snow shovelled
Use of fresh snow due to taste	Potential exposure to contaminants if fresh snow used for drinking
No WASH education	Poor sanitation and hygiene practices increasing waterborne diseases risk
Stakeholder Group 5	
Copper in treated water	Water in pipes corroding copper piping
Microbial growth	High temperature in mechanical room
Microbial growth	Stagnant water due to occupants on vacation
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices due to tanks being inaccessible
Equipment failure	Breakage of pipes and fittings due to freezing
Airborne microbes	Using contaminated water in humidifier
Ice on steps	Risk of falling and unable to deliver water to house

super conservation of water	Reduced availability, increasing inadequate hygiene and increased risk of contamination from poor sanitation
No WASH education	Poor sanitation and hygiene practices increasing waterborne diseases risk
Contaminated water used in food prep	Contamination of food due to unsafe water sources
Stakeholder Group 6	
Copper in treated water	Water in pipes corroding copper piping
Equipment failure	Leaks in pipes from general wear and tear
Equipment failure	Improper installation or repairs of infrastructure
No education on responsibilities	Staff or residents not understanding the roles leading to errors or mismanagement
Insufficient personnel	Insufficient maintenance leading to failures in dwelling infrastructure
No locking mechanism at intake	Water can end up pooling on ground and forming ice, making harder access to intake pipe
Lead in taps	Acute health hazard especially in homes with young children
Power outage	Pumps inside homes stop working due to power outage in community limiting access to water and basic sanitation
Unclear roles and responsibilities	Conflict arises on who to talk to about water safety concerns
Discoloration of water	High levels of chemical parameters such as iron and manganese in the drinking water
Stakeholder Group 7	
Microbial contamination	Contamination from water tank lid left open
Microbial growth	High temperature in mechanical room
Insufficient personnel	Insufficient maintenance leading to failures in dwelling infrastructure

Water wasted	Design flaw for fill pipes leading to pooling of water at intake pipe
Proximity of water and sewage tanks	Cross contamination
Inadequate hygiene practices	Poor hygiene leads to potential microbial contamination and illness
Discoloration of water	High levels of chemical parameters such as iron and manganese in the drinking water
No WASH education	Poor sanitation and hygiene practices increasing waterborne diseases risk
No education on sanitization	Contamination of water due to improper sanitization of tap
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices due to tanks being inaccessible
Stakeholder Group 8	
Copper in treated water	Water in pipes corroding copper piping
No regulation for water tank hygiene	No cleaning occurs for multiple years, risking microbial contamination
Inadequate water supply	Size and number of tanks insufficient for number of individuals in residents
Microbial growth	Stagnant water due to occupants on vacation
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices due to tanks being inaccessible
Confined space	Personnel exposed to chlorine and poor ventilation during cleaning without proper training
Microbial contamination	Microbial growth due to high temperature in maintenance room

Lead in taps	Acute health hazard especially in homes with young children
Unclear roles and responsibilities	Conflict arises on who to talk to about water safety concerns
Stakeholder Group 9	
Microbial contamination	Contamination from water tank lid left open
Inadequate water supply	Size and number of tanks insufficient for number of individuals in residents
Equipment failure	No delivery of water due to frozen water within intakes
Confined space	Personnel exposed to chlorine and poor ventilation during cleaning without proper training
Microbial growth	Extended periods without fresh treated water in tank
Inadequate hygiene practices	No education on cleaning water storage containers
Equipment failure	Improper installation or repairs of infrastructure
Inadequate regulation of home water tank maintenance	No transparency on cleaning requirements leading to potential contamination of household water tanks from unclean water storage practices
Insufficient personnel	Insufficient maintenance leading to failures in dwelling infrastructure
Equipment failure	Breakage of pipes and fittings due to freezing
Stakeholder Group 10	
Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices
Microbial growth	Degradation of chlorine residual in water tanks
Inadequate regulation of home water tank maintenance	No transparency on cleaning requirements leading to potential contamination of household water tanks from unclean water storage practices
No education on sanitization	Contamination of water due to improper sanitization of tap

Inadequate regulation of home water tank maintenance	Potential contamination of household water tanks from unclean water storage practices due to tanks being inaccessible
No regulation for water tank hygiene	No cleaning occurs for multiple years, risking microbial contamination
Microbial growth	Stagnant water due to minimal use
Inadequate hygiene practices	No education on cleaning water storage containers
No education on responsibilities	Staff or residents not understanding the roles leading to errors or mismanagement
Proximity of water and sewage tanks	Cross contamination

Appendix I

Chapter 7 Supplementary Information

Validation Graphs

Model vs Turbidity Data

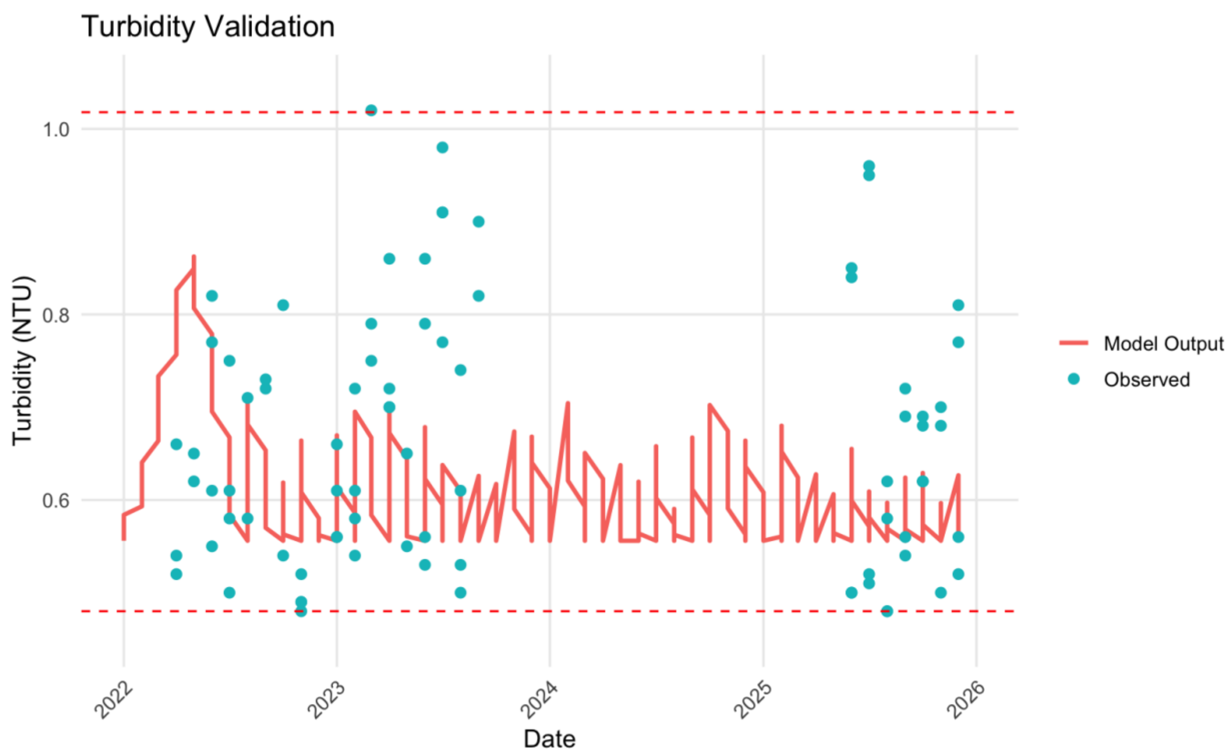


Figure I7-1: Validation of turbidity data observed from 2022-2025 in Cambridge Bay, NU against modelled output. Red dotted lines represent 95% confidence intervals. Model falls within the observed data boundary, although simulated variability is lower than observed

Model vs THM Data

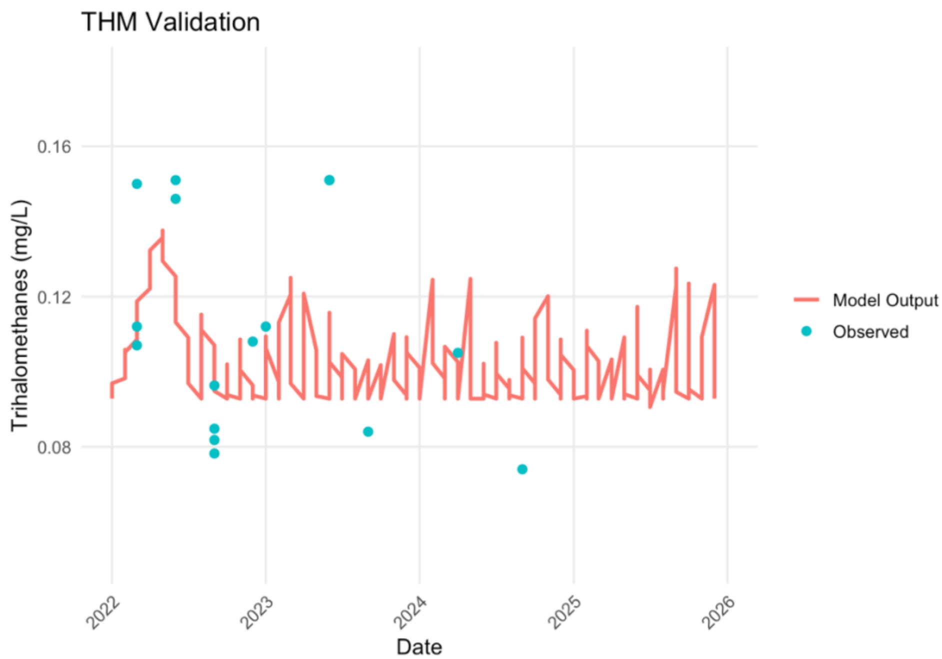


Figure I7-2: Validation of THM observed data from 2022-2025 in Cambridge Bay, NU against modelled output

Model for Chlorine using LOOKUP function

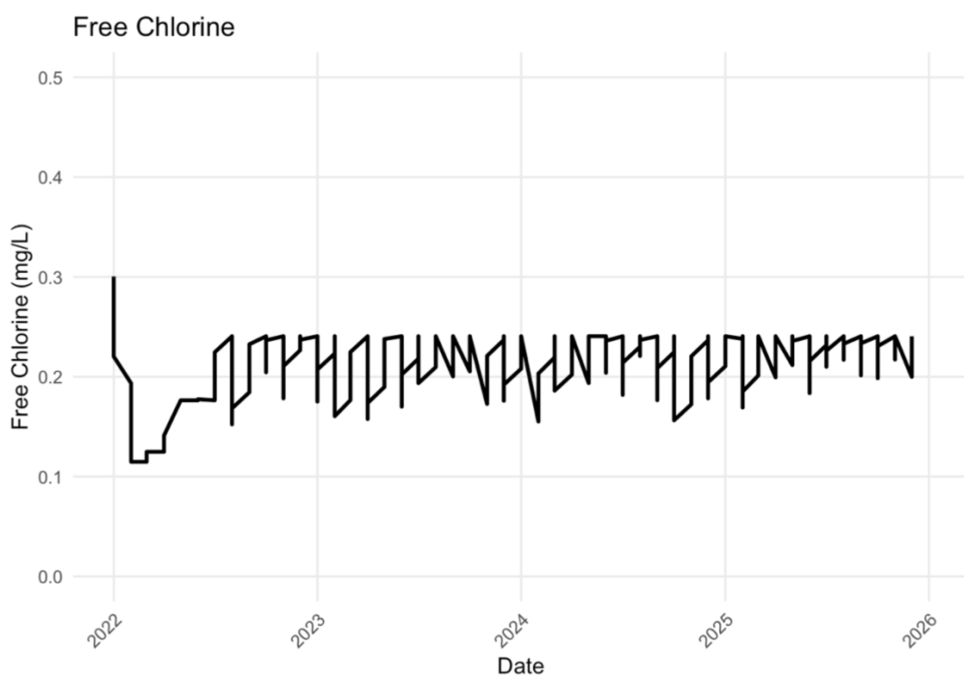


Figure I7-3: Modelled free chlorine to mimic free residual chlorine levels in water cisterns.

Sensitivity analysis

Sensitivity testing of the most critical variables in the water safety model was conducted. Scenarios were tested by adjusting the values of these variables by 10% $\pm$ to observe how the model responded, aligning with the Monte Carlo output on Vensim. The asymmetric variability of the behaviours indicates a reinforcing feedback mechanism, particularly related to the watershed knowledge and source water quality.

The knowledge buffer is a variable used as a convex exponent for unknown contaminants. This introduces a nonlinear amplification to the unknown contaminant risk. When Watershed Knowledge is high, the unknown contaminant risk variable decreases. This suggests that the system (or Water Safety Level) is more responsive to increases in watershed knowledge, making this variable structurally influential. In Figure 4, the Water Safety Level remains around 50 safety units throughout the simulation. However, as watershed knowledge is already low, a decrease in the knowledge buffer has less of an impact on the Water Safety Level

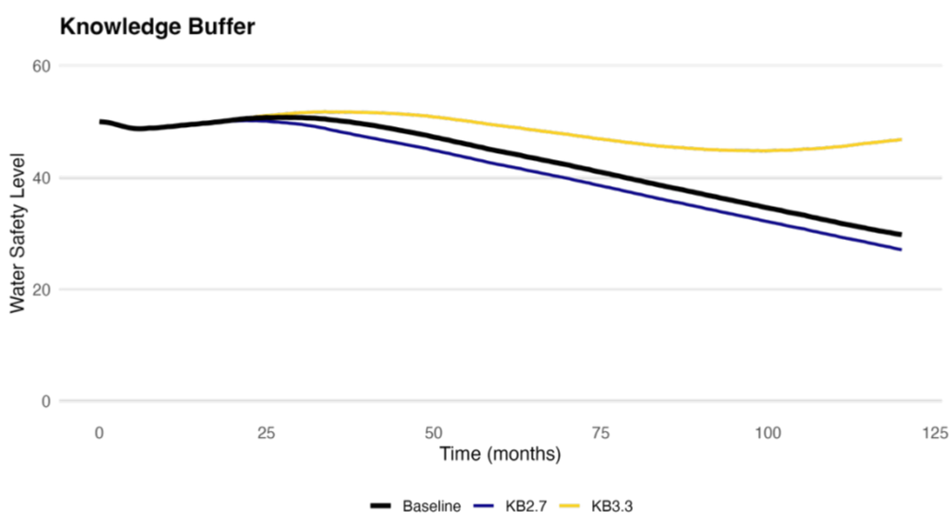


Figure I7-4: Knowledge buffer, one of the most sensitive variables within the system structure. The yellow line is an increase in the knowledge buffer, and the purple line is a decrease in the buffer. The black line represents the baseline for Cambridge Bay's Water Safety Level

Raw monitoring acts as the baseline for community monitoring efforts in the watershed before adjusting other variables. It provides the foundational monitoring activities within the community's watershed. Similarly, with increased knowledge, improved baseline monitoring would keep the Water Safety Level stock around 50 safety units, and any decrease due to limited monitoring activities or undocumented efforts would have minimal effect on the baseline.

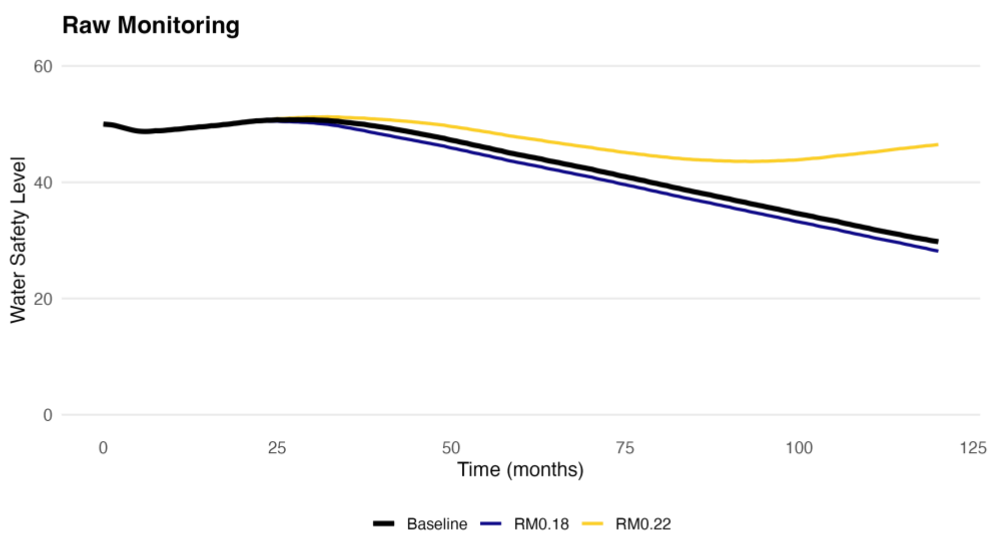


Figure I7-5: The yellow line represents an increase in the raw monitoring, and the purple line represents a decrease in the monitoring. The black line represents the baseline for Cambridge Bay's Water Safety Level

Base unknown contaminants is a constant that links to the auxiliary variable unknown contaminant risk. It provides a baseline value for unknown contaminants in the source water. By decreasing the base value, i.e. reducing the unknown contaminant risk, there is an increase in safety units. While increasing only reduces the safety units slightly over the course of the simulation.

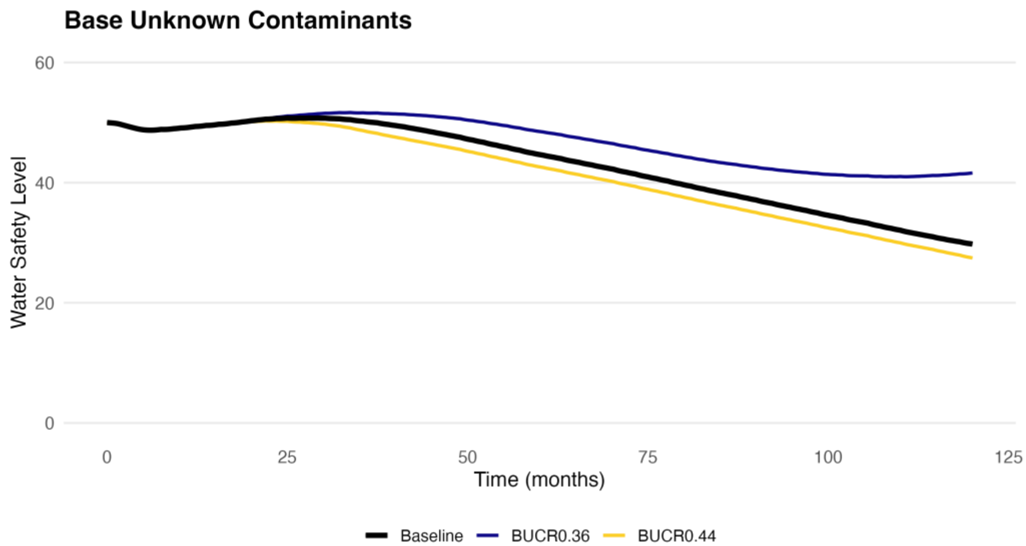


Figure I7-6: Yellow line is an increase in the base unknown contaminants and the purple line is the decrease in the unknown contaminants. The black line represents the baseline for Cambridge Bay's Water Safety Level

Equations for Variables

Table I7-1: Stocks

Stock Name	Equation	Units
Water Safety Level	*INTEG (Community Change+ Infrastructure Upgrade +Treatment Impact -Contamination-Seasonal Degradation-System Failure-Service Disruption, Initial Safety Level)*	Safety index (0–100)
Source Water Quality	*INTEG (Source Improvement-Source Degradation, Initial Source Quality)*	Dmnl (0–1)
Building Water Supply	*INTEG (Truck Delivery Rate-Household Water Use ,Initial Water Supply)*	m^3
Infrastructure Condition	*INTEG ("Maintenance & Upgrades"-Deterioration Rate, Initial Condition)*	Dmnl (0–1)
Operator Capacity	*INTEG (Trained Operators-Operator Turnover, Initial Operator Capacity)*	Dmnl (0–1)
Regulatory Capacity	*INTEG (Capacity Building-Capacity Loss, Initial Regulatory Capacity)*	Dmnl (0–1)
Community Trust	*INTEG (Trust Building-Trust Erosion, Initial Trust)*	Dmnl (0–1)
Watershed Knowledge	*(152) Watershed Knowledge= INTEG (Knowledge Gain-Knowledge Loss, Initial Knowledge)*	Dmnl (0–1)

Table I7-2: Flows

Flow Name	Equation	Units
Treatment Impact	*Base Treatment Rate*Operator Level*Source Water Index *(1-Risky Behaviour)*Truck Hygiene*	Safety Index / month
Community Change	*Base Community Change*Behaviour Education*Engagement Level *(1-Risky Behaviour)*	Safety Index / month
Infrastructure Upgrade	*Base Infrastructure Upgrade*Funding Level*Maintenance Capacity *Regulatory Framework Strength*	Safety Index / month
System Failure	*Base System Failure *(1-Infrastructure Condition Index) *(Water Demand/MAX(1e-06,Infrastructure Capacity)) *(1-Effective Maintenance Level)*	Safety Index / month
Contamination	*Base Contamination *Source Exposure*Climate Factor *(1-Truck Hygiene) *Reporting Gap Effect *(1+Source Contamination Sensitivity*(1-Source Water Index))*	Safety Index / month
Seasonal Degradation	*Base Seasonal Degradation*Seasonal Stress*	Safety Index / month
Service Disruption	*(118) Service Disruption=Base Service Disruption*Supply stress*	Safety Index / month
Source Improvement	*Base Source Improvement*Source Protection Effort*Community Monitoring *Watershed Knowledge Index*	1 / month
Source Degradation	*Base Source Degradation * Climate Stress * Seasonal Impact * Wildlife Activity +Unknown degradation rate*	1 / month
Truck Delivery Rate	*Truck Frequency *Truck Capacity *Delivery Efficiency*	m³ / month
Household Water Use	*MIN(Desired Water Use, Building Water Supply / MAX(Tiny time, Drawdown Time))*	m³ / month
Maintenance and Upgrades	*Maintenance Base*Funding Level*Maintenance Capacity Units: 1/Month*	1 / month
Deterioration Rate	*Deterioration Base * (1 - Maintenance Level) * (Water Demand / MAX(1e-06, Infrastructure Capacity))*	1 / month
Trained Operators	*Base Trained Operator*Funding Level*Regulatory Capacity Index*	1 / month
Operator Turnover	*Base Operator Turnover*(1-Community Trust Index)*	1 / month
Capacity Building	*Base Capacity Building*Funding Level*Regulatory Framework Strength * (1 - Regulatory Capacity Index)*	1 / month
Capacity Loss	*Base Regulatory Capacity Loss*	1 / month
Trust Building	*Base Community Trust*(Water Safety Level/Safety Scale)*	1 / month
Trust Erosion	*Base Trust Erosion *Incident Signal *(1+Trust Erosion Reporting Sensitivity *Reporting Gap Effect) *Community Trust*	1 / month

Knowledge Gain	*Base Knowledge * Community Monitoring * Regulatory Capacity Index * (1 - Watershed Knowledge)*	1 / month
Knowledge Loss	*Knowledge Loss=Base Loss *(1+Climate sensitivity*Climate Stress) * Watershed Knowledge*	1 / month
Phase Advance	*1/Season Length*	Dmnl/month
Phase Reset	*IF THEN ELSE (Seasonal Phase >= 1 , Reset Rate* (Seasonal Phase -1) , 0)*	Dmnl/month

Table I7-3: Auxiliaries

Auxiliary Name	Equation	Units
Water Safety Index	*MIN(100, MAX(0, Water Safety Level))*	Safety Index
Source Water Index	*MIN(1, MAX(0, Source Water Quality))*	Dmnl
Infrastructure Condition Index	*MIN(1, MAX(0, Infrastructure Condition))*	Dmnl
Community Trust Index	*MIN(1, MAX(0, Community Trust))*	Dmnl
Watershed Knowledge Index	*MIN(1, MAX(0, Watershed Knowledge))*	Dmnl
Regulatory Capacity Index	*MIN(1, MAX(0, Regulatory Capacity))*	Dmnl
Engagement Level	*MIN(1, MAX(0, Unbound Engagement Level))*	Dmnl
Risky Behaviour	*MIN(1,MAX(0,Base Risk*Supply stress*(1-Engagement Level)))*	Dmnl
Seasonal Stress	*WITH LOOKUP (Season Phase Bounded, ([(0,0)-(10,10)],(0,0.2), (0.1,0.3), (0.25,0.9), (0.55,1), (0.8,0.6), (1 ,0.2)))*	Dmnl
Incident Signal	*MIN(1, MAX(0, (Contamination + System Failure)/MAX(Tiny Incident ,Incident Reference Rate)))*	Dmnl
Reporting Gap	*1-Reporting Standard Strength*	Dmnl
Base Corrective Action	*MIN(1, MAX(0, Corrective Action Min + (Corrective Action Max - Corrective Action Min) * Regulatory Capacity Index))*	Dmnl
Climate Stress	*Base Climate Stress*Seasonal Stress*	Dmnl
Community Monitoring	*Monitoring Effort*Monitoring Effectiveness*	Dmnl
Corrective Action	*SMOOTHI(Corrective Action Raw, Adjusted Time Action, Base Corrective Action)*	Dmnl
Corrective Action Raw	*MIN(1, MAX(0, Base Corrective Action + Corrective Action Sensitivity * Incident Signal))*	Dmnl
Desired Water Use	*Water Demand*	M3/month
Effect Unknown Decay	*Unknown Contamination Risk * (1 - Watershed Knowledge) ^ Knowledge Buff*	Dmnl
Effective Maintenance Level	*MIN(1, MAX(0, Maintenance Level * (1 + Maintenance Regulatory Boost * Regulatory Framework Strength)))*	Dmnl
Monitoring Effectiveness	*MIN(1, MAX(0, 1 - K unknown * Unknown Contamination Risk))*	Dmnl
Monitoring Effort	*SMOOTHI(Raw Monitoring, Community Monitoring)*	Dmnl
Operator Level	*MIN(1,MAX(0,Operator Capacity/Max Operator Capacity))*	Dmnl
Reporting Gap Effect	*WITH LOOKUP (Reporting Gap, ([(0,0)-(10,10)],(0,0.2), (0.2,0.4), (0.5,1), (0.8,1.4), (1,1.6)))*	Dmnl
Reporting Standard Strength	*Base Regulatory Strength*Regulatory Capacity Index*Regulatory Framework Strength*	Dmnl

Source Exposure	*Base Exposure + Wildlife Activity + KUnknown*Unknown Contamination Risk*	Dmnl
Supply Adequacy	*MIN(1,MAX(0, Building Water Supply/MAX(Tiny demand, Desired Water Use*Storage Buffer)))*	Dmnl
Supply Shortfall	*1 - Supply Adequacy*	Dmnl
Supply Stress	*Supply shortfall ^ Supply sensitivity*	Dmnl
Truck Hygiene	*MIN(1, MAX(0, Base Hygiene +KReg*Regulatory Capacity Index +KTrain*Operator Level +Khygiene * Corrective Action))*	Dmnl
Unknown Contamination Risk	*Base Contamination Unknown *Knowledge Buffer *1-Watershed Knowledge Index*	Dmnl
Unknown Degradation Risk	*Effect Unknown Decay*K Unknown Degradation*	1/month
Water Demand	*Base Demand*Seasonal Demand Factor*	M3/month

Table I7-4: Constants

Parameter Name	Value	Units
Initial Safety Level	50	Safety index
Initial Source Quality	1.0	Dmnl
Initial Water Supply	0.5	m^3
Initial Infrastructure Condition	0.7	Dmnl
Initial Operator Capacity	0.4	Dmnl
Initial Regulatory Capacity	0.4	Dmnl
Initial Trust	0.3	Dmnl
Initial Knowledge	0.3	Dmnl
Initial Condition	0.5	Dmnl
Adjusted Time Monitoring	4	Month
Adjusted Time Action	1	Month
Base Capacity Building	0.01	1/month
Base Capacity Loss	0.005	1/month
Base Community Change	0.1	Safety Index/month
Base Contamination	0.4	Safety Index/month
Base Climate Stress	0.5	Dmnl
Base Contamination Unknown	0.4	Dmnl
Base Water Demand	3500	M3/month
Base Engagement	1	Dmnl
Base Trust Erosion	0.1	1/month
Base Contaminant Exposure	0.5	Dmnl
Base Truck Hygiene	0.4	Dmnl
Base Infrastructure Upgrade	0.3	Safety Index/month
Base Knowledge	0.01	1/month
Base Knowledge Loss	0.005	1/month
Base Risk Behaviour	0.3	Dmnl
Base Seasonal Degradation	0.4	Safety Index/month
Base Source Improvement	0.05	1/month
Base Regulatory Strength	0.3	Dmnl
Base System Failure	0.4	Safety Index/month
Base Trained Operator	0.4	1/month
Base Treatment Rate	0.6	Safety Index/month
Base Community Trust	0.05	1/month
Base Operator Turnover	0.01	1/month
Behaviour Education	0.7	Dmnl
Climate Factor	0.5	Dmnl
Corrective Action Max	0.3	Dmnl

Corrective Action Min	0.05	Dmnl
Corrective Action Sensitivity	0.8	Dmnl
Delivery Efficiency	0.7	Dmnl
Demand Amplitude	0.1	Dmnl
Deterioration Base	0.02	1/month
Drawdown Time	0.25	Month
Funding Level	0.9	Dmnl
Infrastructure Capacity	100000	M3/month
K unknown	0.02	Dmnl
K hygiene	0.3	Dmnl
K Unknown Degradation	0.05	1/month
Knowledge Buffer	1	Dmnl
K regulation	0.2	Dmnl
K training	0.2	Dmnl
K unknown contaminant	0.12	Dmnl
Maintenance Base	0.05	1/month
Maintenance Capacity	0.8	1/month
Maintenance Level	0.5	Dmnl
Max Operator Capacity	1	Dmnl
Raw Monitoring	0.1	Dmnl
Regulatory Framework Strength	0.3	Dmnl
Season Length	7	month
Seasonal Impact	0.3	Dmnl
Source Contamination Sensitivity	0.002	Dmnl
Source Protection Effort	0.3	Dmnl
Stress Reference	0.6	Dmnl
Supply Sensitivity	0.25	Dmnl
Tiny Demand	0.001	M3/month
Tiny Incident	1e-06	Safety Index/month
Tiny Time	1e-06	month
Truck Capacity	12	M3
Truck Frequency	500	Trips/month
Wildlife Activity	0.1	Dmnl