UNDERSTANDING WATER QUALITY INTERACTIONS WITHINA DECENTRALIZED DRINKING WATER SYSTEM IN A COMMUNITY IN NUNAVIK, CANADA

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Abstract

This study examined microbial water quality in a subarctic Canadian community reliant on a decentralized truck-to-cistern system. Samples were collected from 40 residential cisterns and various stages of the local water treatment plant (WTP) to measure adenosine triphosphate (ATP), an indicator of microbial activity. Non-parametric statistical tests addressed five research questions related to spatial variation, building age, WTP effectiveness, correlations with water quality parameters, and cistern configuration. No significant differences were found between cisterns across different zones or construction periods. However, ATP levels varied significantly across WTP stages, and cleaning had a measurable impact on microbial activity. Moderate correlations between ATP and turbidity were also identified. While results support improved monitoring practices, the study's limited sampling and single-community focus restrict broader generalization. Future work should expand sampling duration, include biofilm analysis, and utilize pilot cisterns and digital twins to better understand and manage microbial risks in truck-to-cistern systems.

Dedication

I’d like to dedicate this report to my friends and family who have been a huge source of inspiration. Your encouragement has carried me through the hardest moments and lifted me higher during the best ones. I’d also like to particularly mention my mother, who’s been a cornerstone in my life throughout. Her strength, sacrifice, and unwavering belief in me has shaped who I am and pushed me to keep going, even when it was difficult. Thank you from the bottom of my heart.

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Additionally, I would like to express my gratitude to York University and Université Laval for providing access to vital resources, mentorship, funding and facilities during this research. I am especially grateful to the civil Engineering department at both institutions that made this project possible.

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Glossary

Adenosine Triphosphate (ATP)	The energy carrier within a sample that can be indicative of microbiological activity. This was the main test used in this study to investigate microbiological activity in the sampled water.
Cistern	A moderate size water tank that is generally used for domestic purposes.
Digital Twin	A virtual replica of a physical object.
Drinking Water Advisory	A preventative measure that is issued when the water in a local area is suspected or known to be unsafe for consumption or usage. There are three types of water advisories; boil the water, do not use, and do not consume. (Canada, 2018)
Decentralized Water Systems	Drinking water that is not delivered through a continuous, centralized network of underground pipes.

Chapter 1: Introduction

In Canada's Arctic and northern regions, access to safe and reliable drinking water remains a critical public health and infrastructure challenge. Northern Indigenous communities often rely on decentralized water systems, where water is drawn from local natural sources such as lakes or rivers, treated at small-scale community water treatment plants, and then delivered by truck to household cisterns. Across this entire pathway—from source to tap—multiple water quality and safety hazards have been documented (Gora, et al., 2020; Daley, et al., 2015). The source water is particularly vulnerable to contamination both natural and human activities. Climate changes continue to impact these water systems in terms of water supply and quality. The annual increase in global temperature contributes to melting glaciers, shifting seasonal precipitation, rising river flows and thawing permafrost that affects groundwater flow, all of which add significantly stress to these water systems (Hoegh-Guldberg, et al., 2018).

Furthermore, Indigenous communities have emphasized that drinking water safety extends beyond regulated parameters and should include social, cultural and economic factors (Bharadwaj, 2013). By considering the perspective of the residents within these communities in this context, the importance of holistic water stewardship, trust in local water management practices, and meaningful involvement in water governance decisions are highlighted.

This thesis focuses on the microbial and physicochemical quality of cistern-stored drinking water in a northern Arctic community, with particular attention to the relationships between specified water quality parameters. Adenosine triphosphate (ATP) was used as an indicator of overall microbial activity, while turbidity, pH, dissolved oxygen, free and total chlorine, and ultraviolet absorbance at 254 nm (UV254) were measured to assess physical and chemical water quality characteristics. Previous studies have shown that elevated turbidity can shield microorganisms from disinfection, while increased UV254 values are indicative of higher levels of dissolved organic matter, both of which are factors that may promote microbial regrowth within cistern systems (Gora, et al., 2020; Wright, et al., 2018).

In the studied Arctic community, drinking water undergoes several treatment processes at the local water treatment plant (WTP) before distribution to households. These processes are designed to remove physical, chemical, and microbiological contaminants to ensure the water meets Canadian drinking water quality guidelines prior to delivery.

The treatment process begins with the intake of raw surface water from a nearby natural source, which is then subjected to treatment. The first treatment step involves a sand filtration unit, where water passes through layers of fine sand and gravel. This step primarily targets the removal of suspended solids and turbidity, reducing particulate matter and improving water clarity. Following sand filtration, the water undergoes nano-filtration, a membrane-based treatment process that uses semi-permeable membranes to further remove fine particles, organic matter, and microbial contaminants, including bacteria and viruses. Nano-filtration also contributes to reducing color and potential taste or odor issues associated with organic compounds. The final stage of treatment involves disinfection, commonly achieved through the addition of chlorine to ensure microbial inactivation and provide a residual disinfectant effect during distribution. The treated water is then directed to a distribution system where it is delivered by truck to household cisterns. Throughout these stages, key water quality parameters such as turbidity, chlorine residual, and microbial activity are monitored to verify treatment performance and water safety prior to consumption.

1.1 – Motivation

Northern Arctic communities in Canada rely on small water treatment systems and decentralized drinking water systems to distribute water to end users. Some of the challenges that remote Arctic communities experience are relying heavily on trucked water, frequent boil water advisories and potential for major public health concerns due to the risk for microbial hazardous parameters in their water through the influence of system-wide and building specific concerns (Gora, et al., 2020). Although significant progress is being made by the government of Canada, there are still many northern communities that continue to face drinking water access challenges and are often left without safe & reliable drinking water services. This study aims to investigate the challenges faced by northern Arctic communities with regards to accessing safe drinking water for end users, with the goal of provide vital information to community members and other stakeholders about water quality management in truck and cistern drinking water systems in the Arctic.

1.2 - Research objectives

The overall objective of this research is to investigate the microbial and physicochemical quality of drinking water stored in household cisterns in a northern Arctic community. To achieve this aim, the following specific objectives were established:

1. To evaluate the influence of geographical location within the community and the age of residential buildings on microbial activity levels in cistern water prior to cleaning. This was achieved by subdividing the community into distinct geographical zones based on the location of households. Water samples were collected from each zone before cistern cleaning, and microbial activity was measured using ATP analysis. Building age data was collected from local housing records, and statistical comparisons was performed to determine if spatial factors or building age are associated with variations in microbial activity.
2. To assess the variation in microbial activity at different stages of the water treatment process by comparing samples collected from the raw water intake, intermediate treatment points, and final treated water. Water samples were collected at four key locations along the water treatment pathway: the raw water intake, the sand filter inlet, the nano-filter inlet, and the final distribution point. ATP measurements, along with supporting physicochemical parameters (e.g., turbidity, pH, chlorine residuals), were used to quantify the reduction or fluctuation of microbial activity through each treatment stage.

3. To determine the effect of cistern cleaning on microbial activity by analyzing changes in water quality before and after the cleaning process. This involved conducting a before-and-after comparison by sampling cistern water directly prior to cleaning and immediately after refilling with treated water post-cleaning. Statistical tests were used to assess significant differences in microbial activity and other water quality parameters, providing insight into the immediate effectiveness of the cleaning process.
4. To examine potential correlations between microbial activity (ATP levels) and other physicochemical water quality parameters, including turbidity, pH, dissolved oxygen, free chlorine, total chlorine, and UV254 absorbance. Spearman and Kendall non-parametric correlation tests were conducted to evaluate the strength and direction of relationships between ATP and the measured water quality parameters. This objective aimed to identify which parameters are most strongly associated with microbial activity and could serve as useful indicators of water quality deterioration in stored cisterns.
5. To investigate the relationship between cistern-specific characteristics—such as tank dimensions, construction materials, piping configurations, and installation conditions—and microbial activity levels in stored drinking water. Field inspections were performed to document cistern features, including material type (e.g., polyethylene), dimensions, age, presence of insulation, and piping setup. This information was recorded alongside microbial activity measurements, and statistical analyses were used to determine if any cistern design or installation factors contribute to higher or lower microbial activity levels.

By focusing on a northern community where water is delivered and stored under unique logistical and environmental constraints, this research aimed to fill a critical knowledge gap and inform future strategies for monitoring and improving water safety in similar underserved regions.

1.3 – Thesis outline

The structure of this thesis report is as follows; Chapter 1 provides a brief introduction to the need for microbial testing of the water quality in the Canadian Arctic and provides the key research questions that were investigated in this study. Chapter 2 provides a detailed literature review on the existing background information on various topics about water quality/stored water in decentralized as trucked systems, boil water advisories and climate change impacts in Arctic and subarctic communities in Canada. Chapter 3 presents a summary of the datasets collected and the statistical analysis conducted in this research project. Chapter 4 presents the results of study on the microbial activity in 40 water storage cisterns and at different water treatment plant stages, including raw water, sand filter and stored water located in a small village in Nunavik. The final chapter summarizes discusses the findings and limitations of the study. Potential future research directions are also identified including a biofilm study and the design of a digital model of a cistern and the implementation of a pilot water cistern and water quality monitoring system located at York University to simulate cisterns used in truck-and-cistern drinking water systems and identify ways to improve cistern operation and maintenance.

These results of this study were published at the Canadian Society for Civil Engineering Annual Conference (CSCE) 2025 proceedings held in the city of Winnipeg, Manitoba from May 28 – 30, 2025:

Mahgoub, A., Di Falco, P., Guilherme, S. Marecayar, Z., Duval, M., McGregor, A., Gora, S.L. Understanding water quality interactions within storage tanks for decentralized drinking water systems in Canadian Arctic communities. (2025).

Chapter 2: Literature review

A systematic literature review on the status of water quality in the Canadian Arctic was performed. Peer reviewed articles were searched for using Google Scholar, Scopus and Engineering village and a list of search terms was inputted which are highlighted in Table 2-1.

Table 2-1: Search terms used for literature review

Water treatment	Canadian Arctic & subarctic	Drinking water advisories
Microbial activity	Water quality	Storage tanks
Decentralized communities	Water trucking systems	Cisterns

The literature search determined that there was limited reporting on the condition of stored water infrastructure as it relates to microbial activity within remote Canadian Arctic and subarctic communities.

2.1 – How water is managed and stored in remote Arctic and subarctic communities

In many remote Canadian Arctic and subarctic communities' potable water is provided by decentralized truck-to-cistern systems. Harsh weather conditions such as extreme cold temperatures, permafrost and shifting terrains make underground piped systems costly and challenging to maintain (Inuit Tapirit Kanatami, 2020). Many of the household cisterns are made from polyethylene with varying sizes and shapes. They are often found in separate mechanical shed rooms that are attached to the residential homes. Figure 2-1 shows two types of cisterns found in a Canadian subarctic community.

Figure 2-1: Household water storage cisterns (Mahgoub, 2024)

Depending on the number of users, the way the water is used, and the frequency of deliveries, these cisterns are typically sized to supply a few days to a week of potable water (e.g., 700 litres or about 2500 gallons). Based on firsthand observation, the cisterns are typically vertically shaped and several were covered with insulation to help against the freezing conditions.

Furthermore, trucking water as a mode of water transport/supply has its cost implications and sustainability concerns, however it is recommended for short-term water supply, particularly to remote communities. (Coerver, et al., 2021). See Figure 2-2 below for a schematic of water trucking systems in the Arctic. It shows (1) is the WTP, (2) is the trucked water that transports the water, (3) is the truck that fills the storage cistern and (4) is the households that use the stored potable water.

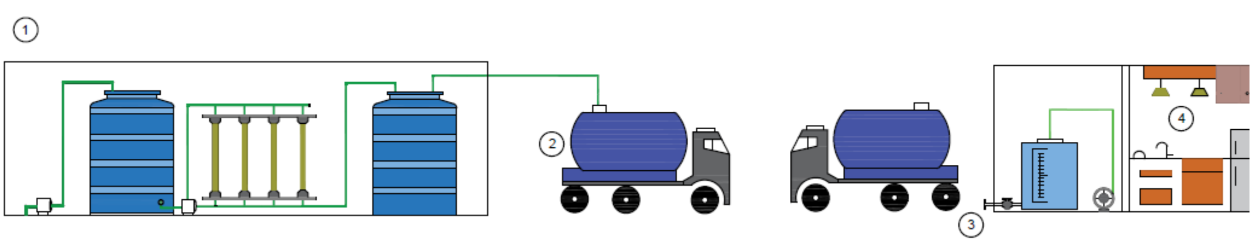

Figure 2-2 Schematic of trucked water journey from treatment plant to tap

The reliance on trucked water provides challenges especially for long durations as they require high ongoing costs and a degree of difficulty in arranging and sustaining (Coerver, et al., 2021). Furthermore, there are several points along the trucking process where the risk of contamination is heightened and water quality may be compromised as it is largely unregulated (Lane, et al., 2023).

2.2 - Microbial contamination in drinking water in Canadian Arctic and subarctic communities

Drinking water safety and reliability continue to be a threat for the residents of remote communities in the Canadian Arctic and subarctic due to limited guidelines on water quality safety, limited monitoring procedures and lower funding to build advanced water treatment methods (Lane, et al., 2017; Klasing, 2016). For water to be safe for consumption, it needs to be free of pathogenic microorganisms and chemical toxins and have good aesthetic properties such as no colour, taste or odour (Health Canada, 2002). While this is possible to obtain in major cities due to the piped networks from source to tap, many remote Arctic communities rely on cisterns to store water for domestic use (Daley, et al., 2017). Threats to water quality and quantity can have a profound impact on health, the environment and the economy (Health Canada, 2002).

In communities such as Neskantaga and Shoal Lake 40 First Nations, where water advisories have been reported for approximately 20 years for each community, generations of children have grown up without access to safe drinking water from their taps (Klasing, 2016). In fact, this has been going on for so long that a growing frustration has risen where some First Nations people will drink the water from the tap anyway and risk being exposed. Many households report that they are experiencing health issues including skin infections, eczema, hair loss and even diarrhea which may be associated with the contaminated water (Lucier, et al., 2020). The impact of long-term water advisories is a clear violation of human rights. This means that it is critical for water quality safety to be monitored in multiple areas including buildings, treatment plants and trucks.

A study by (Wright, et al., 2018) reported that high incidences of self-reported acute gastrointestinal illness occur in Inuit communities in the Canadian Arctic due to the consumption of potentially contaminated water. Similarly, (Daley, et al., 2018) investigated the microbiological quality of sampled drinking water in northern Indigenous communities and found elevated levels of *Escherichia coli* and total coliforms in one truck used to supply drinking water and a building tap. A study by Gora et al. determined that Arctic communities relying on these systems are vulnerable to hazardous microbial parameters in their water such as heavy metals and microorganisms, due to the influence of system-wide and building specific concerns (Gora, et al., 2020).

2.3 – Boil water advisories and trucked water

Communities are often warned about the water being potentially contaminated through a drinking water advisory that includes recommendations for boiling or otherwise treating water. Household water treatment such as boiling, filtering, and chlorinating water at home has been effective in removing microbiological components in small quantities of water but can be limited in addressing large water supplies (Clasen, 2015). Although these point-of-use treatment methods are acceptable in the short term, they only address microbial water hazards, not chemical water hazards.

Boil water advisories make up most of the drinking water advisories in Canada accounting for on average 98% of all advisories (Canada, 2018). A study by Inuit Tapiriit Kanatami (ITK) the national representative organization for the 65,000 Inuit in Canada, found that the combined total duration Inuit communities spent under BWAs was 9,367 days, or 26 years (Inuit Tapirit Kanatami, 2020). These conditions are common for long durations in Inuit communities but are not tolerable within non-Inuit communities (Patrick, 2011).

Often the duration of the BWA is unknown and the public trust in the water quality of the local area can be degraded (Minnes, et al., 2016). This can push some residents to perform extreme actions. In fact, it is reported that some people will even drink the water from the tap anyways (Lucier, et al., 2020) or retrieve water from local untreated streams and springs and risk being exposed (Goldhar, et al., 2014).

2.4 – Monitoring drinking water quality in cisterns

Standard methods for microbiological monitoring include total coliform enumeration, *Escherichia coli* (*E. coli*) enumeration, fecal coliform enumeration and heterotrophic plate count (HPC). These methods are well-established in determining bacterial regrowth in water distribution systems (Verhille, 2013). In enumeration-based methods, a sample is collected and put onto a plate and then it is placed in an incubator until the colonies are observed. Once the colonies are visible, they are counted one-by-one and the concentration of microorganisms is estimated (Whalen, et al.). While important information can be extracted about the microbiological safety of the water based on enumeration methods, a major disadvantage is the long time required to incubate the plates, with an average of 3-5 days (Chen, et al., 2024). Furthermore, each of these methods only targets a specific microorganism group (e.g., total coliforms or *E. coli*) which can provide a limited overview of the actual bacteria present within the sample.

Adenosine triphosphate (ATP) is an alternative to microbial activity monitoring. It works by measuring the total living biomass of a sample through a reaction of an enzyme called luciferase (also found in the tails of fireflies) to produce light. The unit for this measurement is relative light unit (RLU) (LuminUltra, 2024). The test is performed by commercial kits, and it takes > 5 mins to complete. One major disadvantage, however, is that this test can be extremely sensitive to changes in the sample such as via disinfectants (Chen, et al., 2024).

2.5 – Climate change and stored water quality

Canada has reportedly experienced a 0.1°C rise in global temperatures per decade and this is expected to increase (Lemmen, et al., 2007). With this rise in global temperatures, the thawing of the permafrost in Arctic communities will also increase and add various organic matter to the source water. This is due to the sediment delivery from the melting permafrost and thus increases the bacteria growth and microbial activity within the source water (Vonk, et al., 2015). Additionally, while regularly cleaning and maintaining the cisterns continues to be a challenge, especially in remote Inuit communities where water distribution is faced with logistical challenges (i.e. trucked to homes, and limited resilient piped infrastructure), these contaminants will likely make their way into the cisterns and exacerbate health risks (Patrick, 2011).

Furthermore, research has shown that increased temperatures and prolonged thaw periods lead to the release of previously frozen nutrients and dissolved organic carbon, which may contribute to water discoloration, elevated turbidity, and increased chlorine demand during treatment (Cooper, et al., 2009). As these materials enter the drinking water supply, the effectiveness of traditional treatment systems may decline, and stored water systems like cisterns may experience more rapid microbial regrowth. Without timely intervention or adaptation of treatment protocols, these changes pose a growing threat to water safety and public health in northern regions.

2.6 - Limitations of current water quality guidelines in remote communities

In Canada, there are guidelines developed on drinking water standards that are used throughout the nation which are comprehensive and well-established. For example, the GCDWQ (Guidelines for Canadian Drinking Water Quality) was created by Health Canada to establish safe limits in drinking water for bacteria, chemicals and physical characteristics (e.g., turbidity, taste, color) (Canada, 2025). These guidelines are designed for centralized, continuously monitored distribution systems particularly in southern Canada making adoption of the regulations by Arctic communities difficult. Often these communities are remote, rely on decentralized, truck-to-cistern systems with limited treatment capacity and thus the current guidelines may not adequately reflect the unique risks, logistical constraints and challenges faced by these communities (Patrick, 2011).

A study by Chalmers et al. addressed these limitations by developing a Water Safety Plan (WSP) framework specifically for Nunavut's context. This strategy recognizes that traditional risk assessments often overlook community-specific hazards alongside the absence of existing safety barriers and applies a risk matrix with a likelihood score into a system readiness score and an optional past frequency score (Chalmers, et al., 2025). Innovative approaches like these allow for a more nuanced assessment of water safety risks, accommodating the challenges faced by water systems in Arctic regions.

Chapter 3: Methodology

3.1 – Ethical considerations

This study was conducted in accordance with ethical guidelines for research involving human participants. Ethical approval for the research was obtained from the Ethics Committee at Université Laval under approval number 2024-304, dated February 7, 2024. The research included the administration of a questionnaire titled "Questionnaire about water uses and storage tanks in Nunavik," which aimed to gather information on household water use practices and cistern management. Participation in the questionnaire was voluntary, and informed consent was obtained from all participants prior to their involvement. All data collected were anonymized to ensure the privacy and confidentiality of respondents, and the research was conducted with respect for the cultural context of the participating community.

3.2 – Positionality Statement

This project builds on my previous academic and professional experiences, where I have been involved in water quality research and fieldwork in southern Canadian contexts. Conducting this study in Nunavik allowed me to expand my understanding of decentralized water systems and the unique socio-environmental factors influencing water safety in Arctic environments. I acknowledge the limitations of my external perspective and have made efforts to engage respectfully with local knowledge systems and align my research practices with ethical standards that prioritize community well-being.

As a graduate researcher trained in civil engineering and water infrastructure, my positionality in this research is informed by both my academic background and my professional interest in improving water quality outcomes for underserved communities. I do not identify as Indigenous or as a member of a northern community; however, I recognize the importance of cultural context, community experiences, and local knowledge in understanding water-related challenges in Arctic regions.

3.3 – Water sample data collection and equipment used

Water samples were collected (grab sampling) from 40 cisterns located throughout the community. Each cistern was sampled at least twice. Samples were collected from the top of each cistern using a Whirl-Pak. Among these, 4 cisterns were sampled both before and after they were cleaned. Water samples were also collected from the water treatment plant including the raw water outlet, the sand filters outlet, nano-filtration outlet and the outlet of the post chlorination water. Lastly, water was also sampled from the trucks that carried the water from the treatment plant to the houses. See the figure below for a schematic of the sampling points. All samples were collected in sterilized and clean sampling bottles.

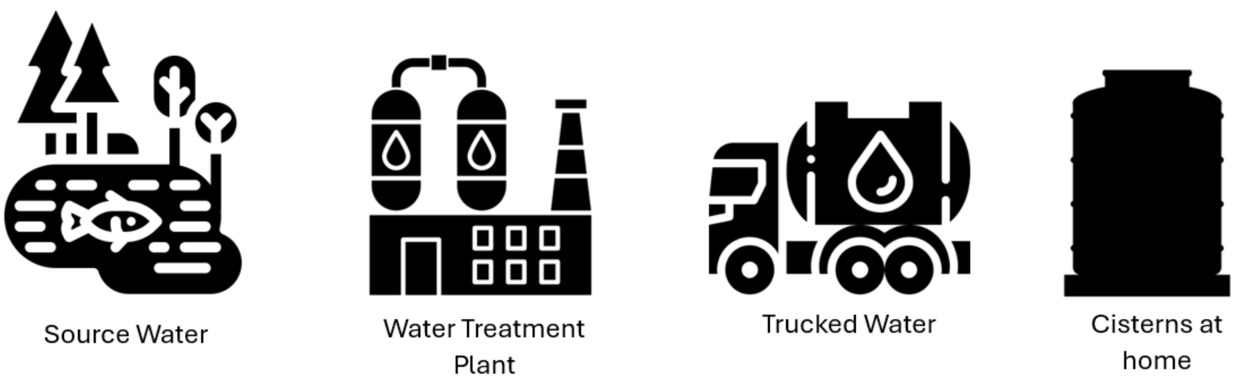

Figure 3-3: Sampling Points

Adenosine triphosphate (ATP) is the main carrier of energy for all living organisms (Gollasch, et al., 2012) was measured to indicate the amount of microbial activity present within a drinking water sample. This method yields rapid results—available in less than five minutes—and requires simple equipment and procedures. We used a commercial ATP measurement kit (LuminUltra QGA) to measure ATP with simple equipment and procedures. An important note is that microbiological activity cannot identify specific water-borne pathogens, but it does provide information about whether a water sample is conducive to microbiological growth or not.

A range of field equipment to measure key water quality parameters during the sampling campaign. The Hach DR 300 was used for chlorine concentration levels. For turbidity, the Hach 2100Q was used, which provides reliable and accurate readings even in low-light conditions (Hach Canada, 2025). pH measurements were taken using the PHC20101 probe. Lastly, the Real Tech UV254 sensor was used to assess organic matter through

UV absorbance, giving insight into dissolved organic carbon levels. Together, this equipment provided a solid foundation for high-quality, real-time water data collection. See the figure below for the images of the devices used.

Figure 3-4: Equipment/Devices used for sampling water quality parameters (adapted from hach.com and realtechwater.com)

3.3.1 - Preliminary cistern survey

A field survey was conducted at each cistern to collect data regarding the physical characteristics of the cisterns. These characteristics included general shape, orientation of the cistern (vertical or horizontal), maximum capacity, materials used, design/manufacturing and location of piping. The ATP levels were gauged against the total volume of the cisterns to determine if the size had an impact on water quality. This was done to investigate whether any physical characteristics of the cisterns may directly influence water quality. The results were entered into an online form (SurveyMonkey) and analyzed to identify important similarities and differences between different cisterns.

3.3.2 – Cleaning procedure

Potable water cisterns require regular maintenance and cleaning to ensure that the water is safe for use and consumption; it is recommended to be cleaned annually (CSA Group, 2023). Upon conducting the sampling at the cisterns, it was found that several of the cisterns were not cleaned for long durations and often the last time they were cleaned was unknown. Fortunately, the cisterns were scheduled to be cleaned upon conducting the sampling. The procedure for the cleaning is shown in the schematic below.

Figure 3-5: Cleaning process of cisterns

Figure 3-5 presents the procedure for the cisterns' cleaning. The approximate time for cleaning ranged from 45 minutes to 1.5 hours, depending on the number of cisterns within the mechanical rooms and the level of contamination present. Once the cisterns were fully cleaned, the trucks that supplied the potable water were called to refill them. This procedure was repeated for all the cisterns that were scheduled for cleaning. 4 cisterns were sampled before and after they were cleaned. Appendix A presents two photos of one of the cisterns that was sampled before it was cleaned and after it was cleaned.

3.4 - Data analysis

Understanding the relationship between microbial activity and the cistern characteristics requires advanced statistical analysis. Statistical tools such as Shapiro-Wilk tests and Brown-Forsythe tests were employed for data analysis. This is to determine whether any observed trends are significant or part of natural variability. Hypothesis testing and regression analysis can be essential in this context. Hypothesis testing allows researchers to assess whether there is critical evidence to support the existence of a trend. Regression analysis can be used to study the relationships between a dependent variable and one or more independent variables. Both hypothesis testing and regression analysis will be utilized to investigate any significant trends related to water quality and the cisterns. All statistical tests were conducted with a significance level of 5%.

3.4.1 – Testing for normality

Normality was tested for each dataset through Quantile-Quantile (Q-Q) plots. If the relationship between theoretical values and actual observations were identical, then the dataset could be considered normally distributed. See Figure 3-6 for an example of this.

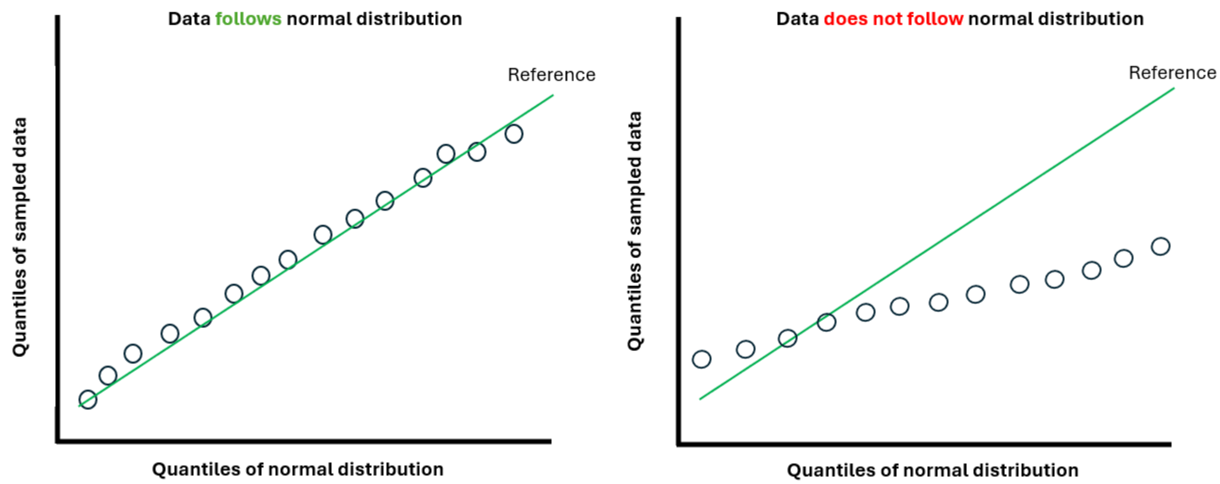

Figure 3-6: QQ plot normal vs non normal distribution (Mahgoub, 2025)

Shapiro-Wilk tests were also chosen to verify normality since they are more appropriate for datasets with less than 50 observations (Mishra, et al., 2019). In this case, the zones that were investigated had fewer than 50 observations. The null hypothesis was set to the data comes from a normal distribution and the alternative hypothesis was the data does not come from a normal distribution. The key assumption is that distribution is normal, and the limitation is that it is sensitive to large sample sizes (Shapiro, et al., 1965).

3.4.2 – Non-parametric hypothesis tests for data with non-normal distributions

Data that was found to violate the assumption of normality for a one-way independent ANOVA was analyzed using the Kruskal-Wallis (KW) test (Field, 2009). This non-parametric method test was used to test the central tendencies across multiple sets of data. The null hypothesis for the KW test is that the mean ranks of the groups are equal, and that the alternative hypothesis is the mean ranks of the groups are not equal. This test assumes that all observations in each dataset are independent and come from the same population (Kruskal, et al., 1952). Furthermore, it utilizes variation amongst ranked sample means. The population distribution can be arbitrary, and does not try to determine the source of variation (Chan, et al., 1997)

It is important to note the limitations of the KW test in that it does not provide information on differences in sample means, does not determine the source of difference in the event of a significant test and is less effective with normal data (since its parametric counterpart is intended to be used with normal data).

Another test that was used was the Brown-Forsythe as a non-parametric method to compare variances across multiple sets of data (Ledolter, et al., 2020). The null hypothesis for this test is that the variances of the groups are equal, and the alternative hypothesis is that the variances of the groups are not equal. The assumptions are that it uses group median when analyzing variance (Ledolter, et al., 2020) robust to non-normality and outliers (Staley, et al., 2022). The limitation being that it is less effective with normal data since its parametric counterpart is intended to be used with normal data.

Appendix B presents a table that shows the normality test confirming that they mainly represent non-normal distribution. This explains the reason for using these tests instead of parametric tests. Furthermore, this analysis was used to investigate the first two research questions; [1] is microbial activity of water in cisterns different in varying locations in the community? [2] Does the cistern's age impact microbial activity?

Chapter 4: Results and discussion

This study aimed to assess the drinking water safety within cisterns for residential use as it relates to microbial activity and the impact of cistern cleaning in a decentralized truck and cistern water system in a Canadian subarctic community. ATP measurements and statistical analysis were used to evaluate geographical location, cistern construction age effects, treatment plant influence, correlations with other water quality parameters and cistern configuration. The research focused on understanding the factors influencing microbial activity in cistern water systems. Firstly, the study investigated the impacts of geographical location within the community, a proxy for cistern age, on microbial activity in cisterns prior to cleaning. It also examined whether different stages of the water treatment process affect microbial activity. Additionally, the research explored how cistern cleaning influences microbial activity within the stored water. Furthermore, the project sought to determine whether other water quality parameters are correlated with microbial activity. Lastly, it assessed whether cistern characteristics—such as dimensions, construction materials, and installation—can be linked to variations in microbial activity.

4.1 - Geographical region and cistern age impact on microbial activity

Water quality and security may be impacted by source location, as previous studies have suggested that geographical location could increase the risk of chemical or microbial contamination, based on natural or anthropogenic activities occurring in those locations (Bock, 1997) (Gora, et al., 2020). Cistern age has also been found to potentially play a role in the microbial content of water by researchers (Alharbi, et al., 2017). This section will look to evaluate whether these characteristics have an impact on water safety. The buildings in the community were subdivided into five individual zones based on the general area where the building was located. Each zone consisted of 4 -15 cisterns that were sampled within that area. Also, the date of construction of the cisterns (which ranged over six decades) was also considered. Since the community was divided into 5 zones, there were five different data sets to compare. Figure 4-7 shows a boxplot of each zone and provides an overview of the data being tested.

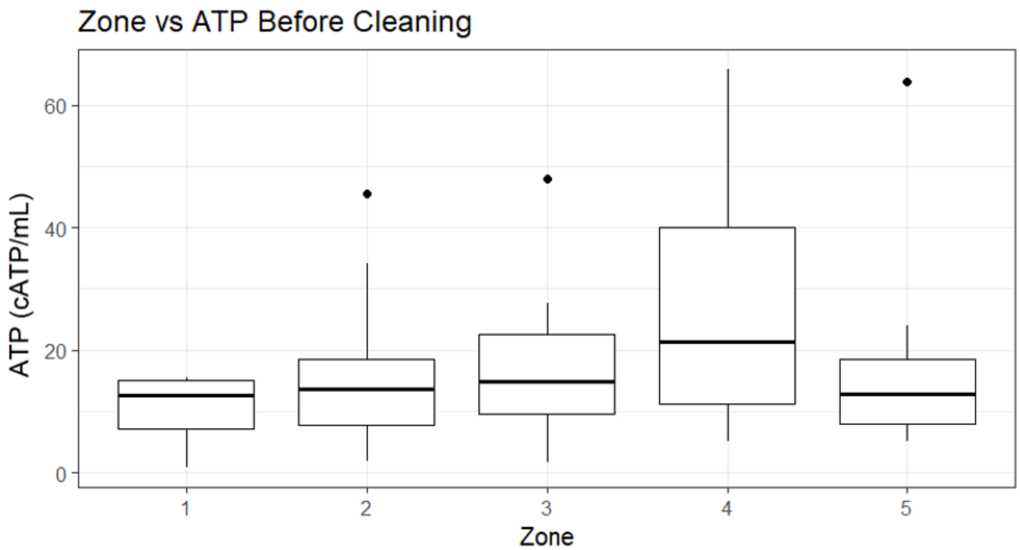

Figure 4-7 ATP measured in cisterns in different zones of the community

While some outliers were observed in the datasets, it could be seen that the median values of ATP levels did not seem to deviate substantially from each other. Similarly, the interquartile ranges for each dataset did not deviate strongly from one another. This suggests that it is likely that the levels of microbial activity present in these cisterns based on specific geographical location apart may not significantly relate to potential contamination of the cisterns over time.

ATP levels of drinking water were compared with the predictor as the date of construction of the cisterns. Since the cistern ages stretched over 6 decades (1970-2020), 6 datasets were compared. The boxplot below (Figure 4-8) demonstrates data for ATP levels relative to the decade of cistern construction.

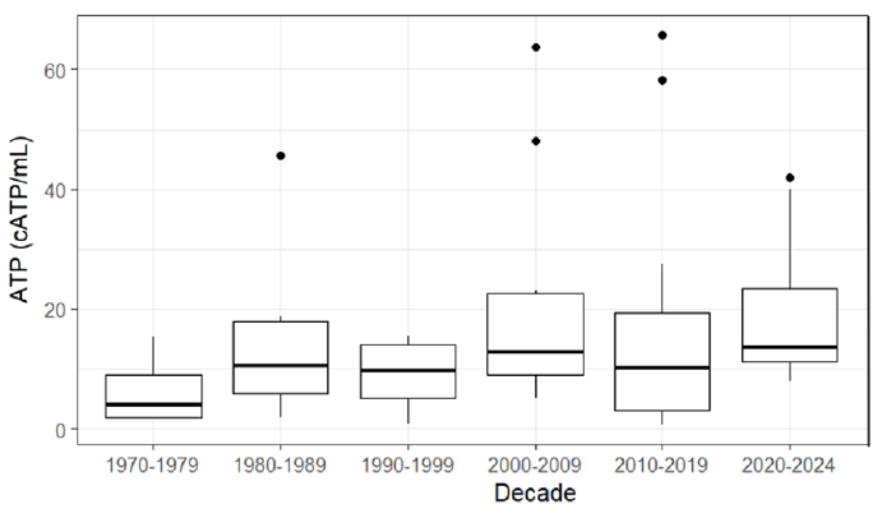

Figure 4-8: Comparison of ATP measured in cisterns constructed in different decades (before cleaning)

Several outliers can be observed in the data. The median values of ATP did not differ strongly across different decades of construction. More specifically, the cisterns constructed between 1980-2020 demonstrated similar central tendencies. Hence, it is safe to infer that the levels of microbial activity present in these cisterns constructed several decades apart may not significantly relate to potential contamination of the cisterns over time. Therefore, revamping/replacing old cisterns may not necessarily improve water quality from a microbiological perspective.

Furthermore, the Shapiro-Wilk test was conducted for each decade to determine normality and the results also demonstrated mixed normality. Therefore, non-parametric methods would be appropriate to test location and dispersion. The Kruskal-Walli's test revealed the following regarding the central tendencies of the datasets:

$H(5) = 9.54, p > 0.05$

The test did not demonstrate statically significant difference, and the null hypothesis was not rejected. A Brown-Forsythe test could then be carried out to further verify whether there was significance within the 6 datasets. The test yielded the following:

$F^*(5) = 1.74, p > 0.05$

The Brown-Forsythe test confirmed that there was no statistically significant difference among the variances of the datasets, and the null hypothesis was not rejected. After completing all the tests, it could be said that there were no statistically significant differences in the ATP levels of drinking water based on the storage cistern's decade of construction. Statistical tests of the central tendencies and variances on the datasets based on geographical location and cistern age of construction in the study location demonstrated no statistically significant differences. Therefore, microbial activity in drinking water was not found to be different in cisterns located in different parts of the community based on the selected parameters of this study.

4.2 - Impact of water treatment process on microbial activity

Datasets were developed by collecting samples at 4 points in the water treatment process. These points include the raw water outlet, sand filter outlet, nano-filter outlet, and the fully treated water (final stage of the treatment process) and are compared against each other and the ATP of the cisterns before cleaning (Figure 4-8). By comparing (ATP) concentrations across these four treatment stages, this study aimed to evaluate the effectiveness of each filtration barrier in reducing microbial activity. In addition, ATP concentrations from these stages were compared to ATP levels measured in household cisterns prior to cleaning. This comparison provides insight into how treatment performance may relate to the microbial quality of water once it is delivered and stored within residential cistern systems.

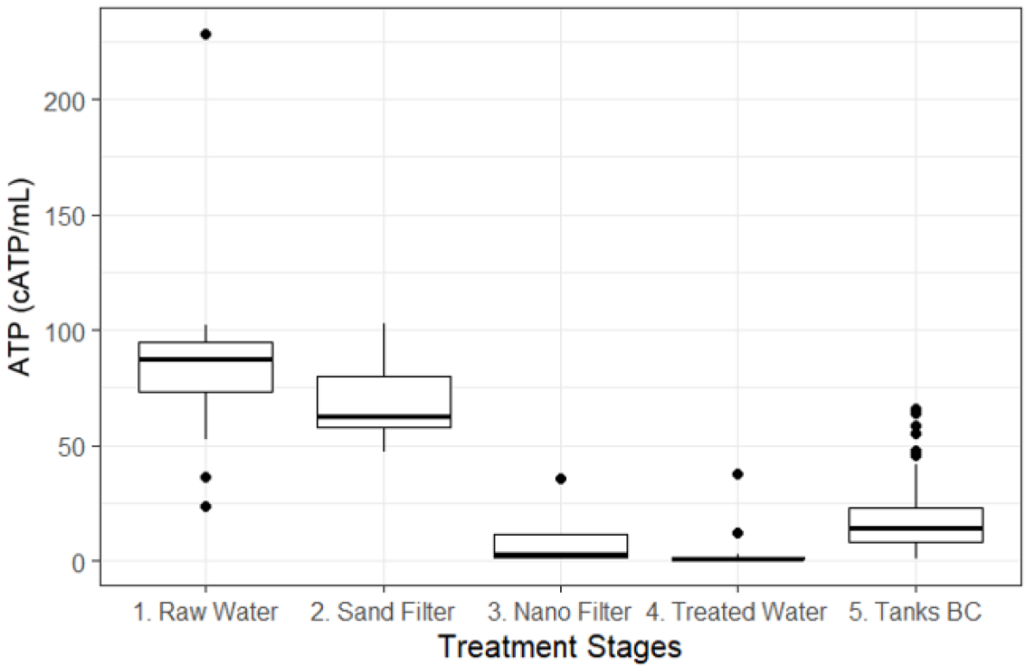

Figure 4-9: ATP measured at different locations in the water treatment plant

A clear discrepancy can be seen in the data among each of the stages. Visual analysis suggests that microbial activity drops substantially after nano-filtration, which is in line with what would be expected as nano-filtration membrane should remove all particulate matter, including microbial contaminants, from the water. There appears to be greater variability in the ATP measurements from the cisterns before the cleaning compared to different stages of the WTP. This is also expected since the cisterns are separate for each of the households with varying construction dates and cleaning procedure timelines. Upon conducting a Kruskal-Wallis test, the p-value was lower than the significance level, the null hypothesis was rejected, and the test was significant. Thus, there was a significant difference in microbial activity at different stages of the water treatment and distribution system. Therefore, it may be concluded that advanced water treatment processes such as nano-filtration membrane could play a key role in reducing microbial contamination in drinking water cisterns.

4.3 - Impact of cistern cleaning on ATP measured within the cisterns

The ATP data from all 40 cisterns, including some cisterns that were sampled only before cleaning, some that were sampled only after cleaning, and some that were sampled both before and after sampling, was pooled and tested for normality using the Shapiro-Wilk test ($p < 0.05$ indicating a non-normal distribution). Then the Kruskal-Wallace test was conducted to determine whether cistern cleaning impacted microbial activity in the cistern. The results shown in Figure 4-10 suggest that cistern cleaning significantly reduced the microbial activity in the cistern.

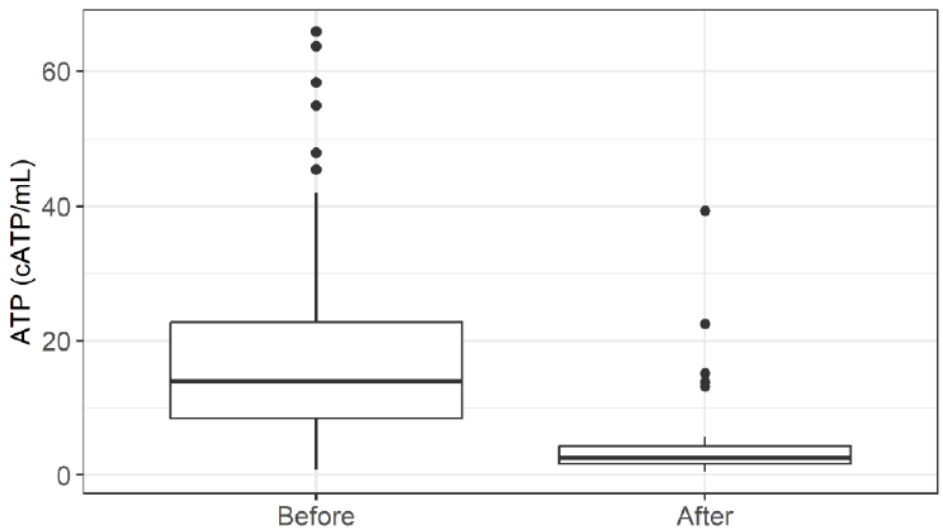

Figure 4-10: Impact of cleaning on ATP measured in cisterns

Next, the dataset was filtered so that it only included data from the cisterns that were sampled before and after being cleaned (Figure 4-10). The same statistical tests were applied to this sub-dataset and the results were like when the full dataset was pooled and analyzed in aggregate. Microbial activity was significantly higher in the cisterns before cleaning compared to after cleaning. Visual analysis indicated that the reduction in microbial activity was greater in cisterns that had higher microbial activity before cleaning than in cisterns that had lower microbial activity before cleaning.

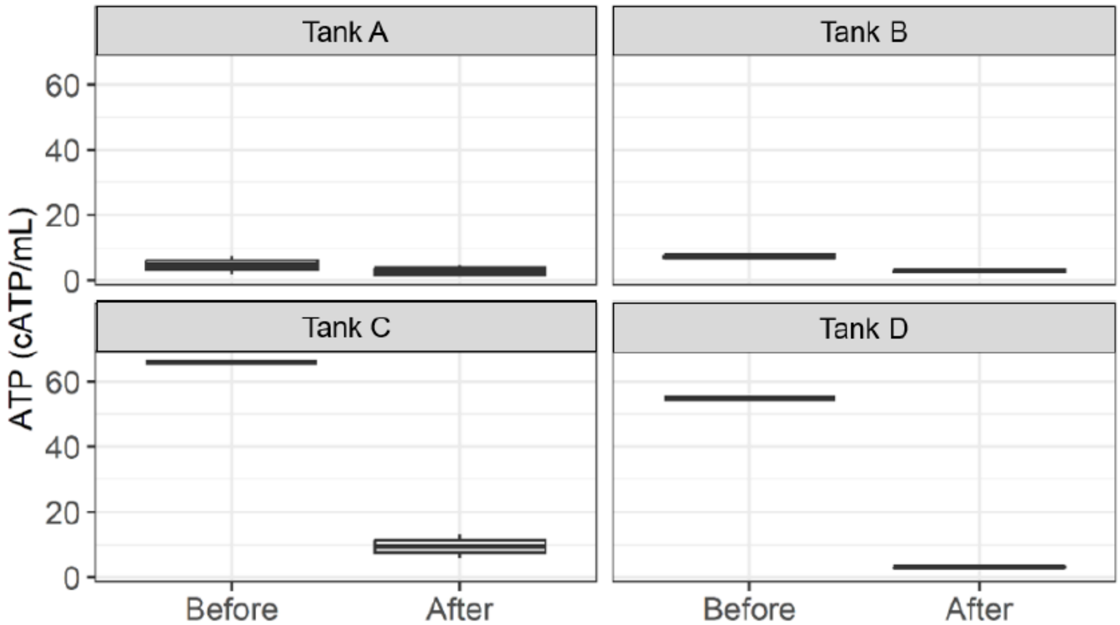

Figure 4-11: ATP levels in four cisterns before and after cleaning

4.4 - Correlations between ATP and other common water quality parameters

Correlation testing is useful for determining the strength and statistical significance of the relation between two water quality variables. For this study, three sets of non-parametric correlation analyses were conducted using, Spearman and Kendall tests and the results are shown in this section. In the first analysis ATP was taken as the dependent variable and its correlation was examined against five physical parameters; turbidity, dissolved oxygen (DO), pH, free chlorine and total chlorine were taken as the independent variables. The second analysis used turbidity as the dependent variable, tested against the same set of independent variables. Similarly the last analysis consisted of ultraviolet absorbance at 254 nm (UV254) as the dependant variable against the same set of independent variables. Correlation strength was determined based on the following assumptions:

Strong correlation: ρ/τ = (0.7 to 1), (-1 to -0.7)

Moderate correlation: ρ/τ = (0.4 to 0.7), (-0.7 to -0.4)

Weak correlation: ρ/τ = (0.1 to 0.4), (-0.4 to -0.1)

4.4.1 – ATP as dependent variable

The table below presents the distribution of the entire dataset to assess its normality and determine the appropriate use of parametric or non-parametric statistical tests. The Shapiro test was used to determine the normality with the p-value set to 5%.

Table 4-2: Normality for the full dataset and sub-datasets

Dataset	Parameter	Shapiro test p	Normally distributed?	Appropriate statistical tests
Full dataset	ATP	< 0.05	No	Non-parametric
	Turbidity	< 0.05	No	Non-parametric
	DO	< 0.05	No	Non-parametric
	pH	< 0.05	No	Non-parametric
	Total Chlorine	< 0.05	No	Non-parametric
	Free Chlorine	< 0.05	No	Non-parametric
Cisterns before cleaning	ATP	< 0.05	No	Non-parametric
	Turbidity	< 0.05	No	Non-parametric
	DO	> 0.05	Yes	Parametric and non-parametric
	Total Chlorine	< 0.05	No	Non-parametric
	Free Chlorine	< 0.05	No	Non-parametric
Cisterns after cleaning	ATP	< 0.05	No	Non-parametric
	Turbidity	< 0.05	No	Non-parametric
	DO	> 0.05	Yes	Parametric and non-parametric
	Total Chlorine	< 0.05	No	Non-parametric
	Free Chlorine	< 0.05	No	Non-parametric
WTP	ATP	< 0.05	No	Non-parametric
	Turbidity	< 0.05	No	Non-parametric
	DO	< 0.05	No	Non-parametric
Zones (ATP only)	Zone 1	> 0.05	Yes	Parametric and non-parametric
	Zone 2	< 0.05	No	Non-parametric
	Zone 3	> 0.05	Yes	Parametric and non-parametric
	Zone 4	< 0.05	No	Non-parametric
	Zone 5	<0.05	No	Non-parametric

Once the normality was determined, the appropriate statistical test was chosen, and since the majority of the dataset was non-normal distribution, the Spearman test and Kendall test were used. The following tables display results for correlations when ATP was set to be the dependent variable against turbidity, dissolved oxygen (DO), pH, free chlorine and total chlorine. Table 3-4 shows the Spearman test and Table 4-4 shows the Kendall test.

Table 4-3: Spearman correlation test results with ATP as the dependent variable

Dataset	Parameters	P	Significant?	ρ	Strength of Correlation
Full dataset	ATP ~ Turbidity	> 0.05	No	0.11	Weak
	ATP ~ DO	**< 0.05**	**Yes**	**0.35**	**Weak**
	ATP ~ pH	**< 0.05**	**Yes**	**-0.5**	**Moderate**
	ATP ~ Total Chlorine	> 0.05	No	0	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.15	Weak
Cisterns before cleaning	**ATP ~ Turbidity**	**< 0.05**	**Yes**	**0.59**	**Moderate**
	ATP ~ DO	> 0.05	No	0.46	Moderate
	ATP ~ pH	> 0.05	No	0	Weak
	ATP ~ Total Chlorine	> 0.05	No	0.3	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.04	Weak
Cistern after cleaning	ATP ~ Turbidity	> 0.05	No	0.27	Weak
	ATP ~ DO	> 0.05	No	0.45	Moderate
	ATP ~ pH	> 0.05	No	0	Weak
	ATP ~ Total Chlorine	> 0.05	No	0.26	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.38	Weak
WTP	**ATP ~ Turbidity**	**< 0.05**	**Yes**	**0.75**	**Strong**
	ATP ~ DO	> 0.05	No	0	Weak
	ATP ~ pH	> 0.05	No	0	Weak
	ATP ~ Total Chlorine	> 0.05	No	0	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.3	Weak

While most of the correlation analyses revealed weak to moderate strength of correlation when ATP was taken as the dependent variable, there were still a few significant findings observed. The Spearman test indicated that there are moderate to strong correlations between ATP and turbidity before cistern cleaning and across the WTP. The Kendall test was performed to assess the strength of correlations for the dataset again.

Table 4-4: Kendall test results with ATP as the dependent variable

Dataset	Parameters	P	Significant ?	τ	Strength of Correlation
Full dataset	**ATP ~ Turbidity**	**> 0.05**	**Yes**	**0.07**	**Weak**
	ATP ~ DO	**>0.05**	**Yes**	**0.26**	**Weak**
	ATP ~ pH	**> 0.05**	**Yes**	**0.32**	**Weak**
	ATP ~ Total Chlorine	< 0.05	No	0	Weak
	ATP ~ Free Chlorine	< 0.05	No	0.1	Weak
Cisterns before cleaning	**ATP ~ Turbidity**	**< 0.05**	**Yes**	**0.27**	**Weak**
	ATP ~ DO	> 0.05	No	0.16	Weak
	ATP ~ pH	> 0.05	No	-0.19	Weak
	ATP ~ Total Chlorine	> 0.05	No	0	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.02	Weak
Cisterns after cleaning	ATP ~ Turbidity	> 0.05	No	0.16	Weak
	ATP ~ DO	> 0.05	No	0.39	Moderate
	ATP ~ pH	> 0.05	No	-0.02	Weak
	ATP ~ Total Chlorine	> 0.05	No	0.19	Weak
	ATP ~ Free Chlorine	> 0.05	No	0.3	Weak
WTP	**ATP ~ Turbidity**	**< 0.05**	**Yes**	**0.57**	**Moderate**
	ATP ~ DO	> 0.05	No	-0.08	Weak
	ATP ~ pH	> 0.05	No	-0.02	Weak
	ATP ~ Total Chlorine	> 0.05	No	0.02	Weak
	ATP ~ Free Chlorine	> 0.05	No	-0.04	Weak

The Kendall test, which is more conservative, suggested that most correlations are weak to moderate as well. Also, between ATP and turbidity before cleaning and across the WTP, which was found to be strong, the Kendall test suggests it to be more moderate as well. Both the Spearman and Kendall tests indicated that there are no significant correlations between ATP and DO in this dataset. Figure 4-12 depicts the correlations between ATP and turbidity in samples collected at the WTP.

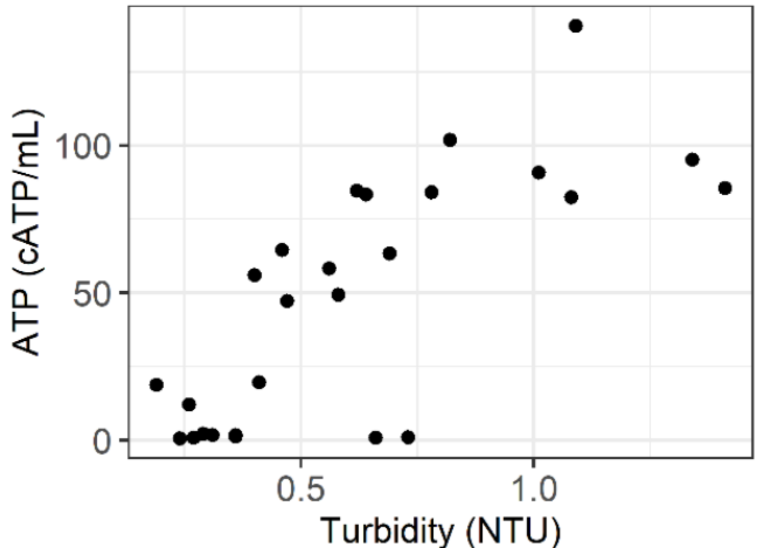

Figure 4-12: Correlation between ATP and turbidity in samples collected from the WTP

4.4.2 – Turbidity as the dependent variable

This section of the study examines turbidity as the dependent variable to assess its relationship with other water quality parameters using non-parametric statistical methods. Both Spearman's rank correlation and Kendall tests were applied to identify potential associations between turbidity and independent variables, including ATP, dissolved oxygen, chlorine concentrations, and pH. These tests were chosen for their suitability with non-normally distributed data and their ability to detect trends without assuming linearity. A significance threshold of 5% ($p < 0.05$) was used to determine whether observed correlations were statistically meaningful.

Table 4-5: Spearman correlation test results with turbidity as the dependent variable

Dataset	Parameters	P	Significant ?	ρ	Strength of Correlation
Full dataset	Turbidity ~ ATP	> 0.05	No	0.11	Weak
	Turbidity ~ DO	> 0.05	No	-0.01	Weak
	Turbidity ~ pH	> 0.05	No	0.02	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	0.02	Weak
	Turbidity ~ Free Chlorine	**< 0.05**	**Yes**	**0.33**	**Weak**
Cisterns before cleaning	**Turbidity ~ ATP**	**< 0.05**	**Yes**	**0.35**	**Weak**
	Turbidity ~ DO	> 0.05	No	-0.01	Weak
	Turbidity ~ pH	> 0.05	No	-0.15	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	-0.09	Weak
	Turbidity ~ Free Chlorine	**< 0.05**	**Yes**	**0.33**	**Weak**

Cistern after cleaning	Turbidity ~ ATP	> 0.05	No	0.27	Weak
	Turbidity ~ DO	> 0.05	No	-0.01	Weak
	Turbidity ~ pH	> 0.05	No	0.25	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	0.01	Weak
	Turbidity ~ Free Chlorine	**< 0.05**	**Yes**	**0.33**	**Weak**
WTP	**Turbidity ~ ATP**	**< 0.05**	**Yes**	**0.75**	**Strong**
	Turbidity ~ DO	> 0.05	No	0.20	Weak
	Turbidity ~ pH	> 0.05	No	0.19	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	-0.02	Weak
	Turbidity ~ Free Chlorine	> 0.05	No	0.08	Weak

Table 4-6: Kendall test results with turbidity as the dependent variable

Dataset	Parameters	P	Significant ?	τ	Strength of Correlation
Full dataset	Turbidity ~ ATP	> 0.05	No	0.07	Weak
	Turbidity ~ DO	> 0.05	No	0	Weak
	Turbidity ~ pH	> 0.05	No	0	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	0	Weak
	Turbidity ~ Free Chlorine	**< 0.05**	**Yes**	**0.24**	**Weak**
Cisterns before cleaning	**Turbidity ~ ATP**	**< 0.05**	**Yes**	**0.25**	**Weak**
	Turbidity ~ DO	> 0.05	No	-0.11	Weak
	Turbidity ~ pH				
	Turbidity ~ Total Chlorine	> 0.05	No	-0.07	Weak
	Turbidity ~ Free Chlorine	> 0.05	No	0.19	Weak
Cisterns after cleaning	Turbidity ~ ATP	> 0.05	No	0.16	Weak
	Turbidity ~ DO	> 0.05	No	-0.08	Weak
	Turbidity ~ pH	> 0.05	No	-0.07	Weak
	Turbidity ~ Total Chlorine	**< 0.05**	**Yes**	**0.44**	**Moderate**
	Turbidity ~ Free Chlorine	> 0.05	No	0.11	Weak
WTP	**Turbidity ~ ATP**	**< 0.05**	**Yes**	**0.57**	**Moderate**
	Turbidity ~ DO	> 0.05	No	0.12	Weak
	Turbidity ~ pH	> 0.05	No	0.13	Weak
	Turbidity ~ Total Chlorine	> 0.05	No	0.06	Weak
	Turbidity ~ Free Chlorine	> 0.05	No	0	Weak

The analysis provided insight into the factors that may influence turbidity levels in stored water systems, particularly in the context of Arctic water storage infrastructure. However, upon inspection of the results, it became clear that there is low correlation between turbidity and ATP, dissolved oxygen, chlorine concentrations, and pH.

4.4.3 – UV254 as the dependent variable

To further investigate relationships between water quality parameters, correlation analyses were conducted using ultraviolet absorbance at 254 nm (UV254) as the dependent variable. UV254 serves as an indicator of the presence of natural organic matter (NOM) in water, which can influence disinfection by-product formation and microbial regrowth potential. The independent variables selected for this analysis included turbidity, dissolved oxygen (DO), pH, free chlorine, and total chlorine—key parameters that influence or reflect overall water quality conditions.

Similarly, the same non-parametric correlation tests, Spearman's rank correlation coefficient and Kendall's tau correlation coefficient, were used to assess the strength and direction of the relationships between UV254 and the selected independent variables. The results are shown in the tables below.

Table 4-7: Spearman correlation test results with UV254 as the dependent variable

Dataset	Parameters	P	Significant?	ρ	Strength of Correlation
Full dataset	UV254 ~ ATP	> 0.05	No	-0.20	Weak
	UV254~Turbidity	> 0.05	No	-0.21	Weak
	UV254~ DO	> 0.05	No	-0.22	Weak
	UV254~ pH	> 0.05	No	0.35	Weak
	UV254~ Total Chlorine	> 0.05	No	-0.03	Weak
	UV254~ Free Chlorine	> 0.05	No	-0.11	Weak
Cisterns before cleaning	UV254~ ATP	**< 0.05**	**Yes**	**-0.48**	**Moderate**
	UV254~Turbidity	> 0.05	No	-0.26	Weak
	UV254~ DO	**< 0.05**	**Yes**	**-0.39**	**Weak**
	UV254~ pH	**< 0.05**	**Yes**	**-0.69**	**Strong**
	UV254~ Total Chlorine	> 0.05	No	-0.01	Weak
	UV254~ Free Chlorine	> 0.05	No	-0.11	Weak
Cistern after cleaning	UV254~ ATP	> 0.05	No	0.18	Weak
	UV254~Turbidity	> 0.05	No	0.20	Weak

	UV254~ DO	> 0.05	No	0.36	Weak
	UV254~ pH	> 0.05	No	-0.48	Moderate
	UV254~ Total Chlorine	> 0.05	No	0.18	Weak
	UV254~ Free Chlorine	> 0.05	No	-0.11	Weak
WTP	UV254~ ATP	> 0.05	No	0.37	Weak
	UV254~Turbidity	> 0.05	No	0.02	Weak
	UV254~ DO	> 0.05	No	-0.41	Moderate
	UV254~ pH	> 0.05	No	-0.26	Weak

Table 4-8: Kendall test results with UV254 as the dependent variable

Dataset	Parameters	P	Significant ?	τ	Strength of Correlation
Full dataset	UV254 ~ ATP	>0.05	No	-0.13	Weak
	UV254~Turbidity	>0.05	No	-0.16	Weak
	UV254~ DO	>0.05	No	-0.14	Weak
	UV254~ pH	<0.05	Yes	0.25	Weak
	UV254~ Total Chlorine	>0.05	No	-0.01	Weak
	UV254~ Free Chlorine	>0.05	No	-0.07	Weak
Cisterns before cleaning	UV254~ ATP	<0.05	Yes	-0.32	Weak
	UV254~Turbidity	>0.05	No	-0.20	Weak
	UV254~ DO	<0.05	Yes	-0.27	Weak
	UV254~ pH	**<0.05**	**Yes**	**0.46**	**Moderate**
	UV254~ Total Chlorine	>0.05	No	-0.01	Weak
	UV254~ Free Chlorine	>0.05	No	-0.06	Weak
Cistern after cleaning	UV254~ ATP	>0.05	No	0.18	Weak
	UV254~Turbidity	>0.05	No	0.11	Weak
	UV254~ DO	>0.05	No	0.22	Weak
	UV254~ pH	>0.05	No	-0.35	Weak
	UV254~ Total Chlorine	>0.05	No	0.20	Weak
	UV254~ Free Chlorine	>0.05	No	-0.023	Weak
WTP	UV254~ ATP	>0.05	No	0.23	Weak
	UV254~Turbidity	>0.05	No	0.03	Weak
	UV254~ DO	>0.05	No	-0.31	Weak
	UV254~ pH	>0.05	No	-0.14	Weak

In this analysis, ultraviolet absorbance at 254 nm (UV254) was used as the dependent variable to assess its relationship with key physicochemical water quality parameters, including turbidity, dissolved oxygen (DO), pH, free chlorine, and total chlorine across four scenarios; the entire dataset, before cleaning the tanks, after cleaning the tanks and within the water treatment plant. Spearman's rank correlation coefficient and Kendall's tau were applied as non-parametric methods to evaluate the strength and direction of these associations. The majority of the results indicated weak to moderate correlations between UV254 and the selected independent variables, suggesting limited direct relationships under the conditions studied. However, a notable exception was observed between UV254 and pH before cleaning, where a strong, statistically significant negative correlation was identified using Spearman's method ($\rho = -0.69$, $p < 0.05$). See the figure below for the plot of UV254 absorbance and pH.

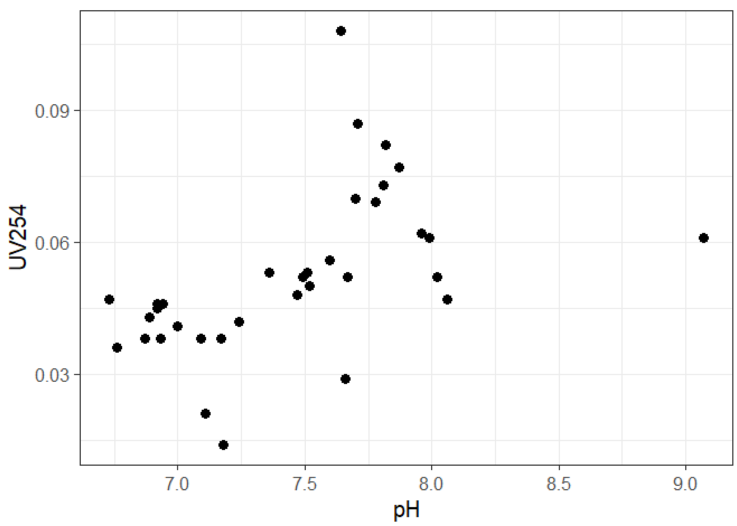

Figure 4-13: UV254 absorbance against pH in samples collected from tanks before cleaning

This indicates that higher pH levels were generally associated with lower levels of UV254 absorbance. Further validation with Kendall's tau confirmed the statistical significance of this relationship, though with a moderate strength correlation ($\tau = -0.49$, $p < 0.05$). These findings highlight a consistent inverse relationship between pH and the presence of natural organic matter, as reflected by UV254 measurements, while other water quality parameters demonstrated less consistent associations.

4.4.4 - Interpretation of Findings in Relation to Previous Studies

The findings of this study align with existing literature that highlights the challenges of maintaining microbiological water quality in household storage systems in Arctic communities. ATP concentrations were consistently higher in household cisterns compared to treated water sampled from the water treatment plant. This observation aligns with the study (Gora, et al., 2020) who reported similar microbial regrowth trends in Pond Inlet, Nunavut, where water quality degraded post-distribution despite initial treatment. This phenomenon reflects the broader issue of deteriorating water quality within storage systems, a concern that has been consistently reported in many Canadian Arctic, subarctic, and remote communities (Wright, et al., 2018; Daley, et al., 2015).

The results from the water treatment plant sampling revealed limited reduction in microbial activity across the sand filtration stage, as indicated by minimal decreases in ATP levels. This was unexpected, given that sand filtration is designed to remove particulate matter and reduce microbial loads through physical straining and biological processes (Crittenden, et al., 2012). The low removal efficiency observed suggests potential underperformance of the filtration system, which may be attributed to operational inefficiencies such as filter clogging, short-circuiting, or insufficient backwashing. Literature suggests that chemically assisted filtration, involving coagulation processes upstream of filtration, is widely adopted to enhance the removal of turbidity and microbial contaminants in small-scale water treatment plants (Crittenden, et al., 2012).

Further analysis of water quality parameters revealed a significant negative correlation between ATP and pH, as well as between UV254 and pH, with the strongest relationship observed between UV254 and pH (Spearman's $\rho = -0.69$). This inverse relationship is consistent with findings in previous research, where higher pH levels have been associated with lower levels of natural organic matter, as measured by UV254 (Banc, et al., 2012). However, it is important to interpret these findings with caution. The sampling conducted in this study was limited in both scope and duration, and a variety of uncontrolled factors may be influencing pH in the system—such as temperature, pipe materials, disinfectant decay, or biological activity.

These observations point to the need for improvements in treatment efficiency, particularly at the filtration stage, and more robust post-treatment water management practices, such as improved cistern cleaning protocols and optimized chlorine dosing, to ensure safer drinking water in northern communities.

4.5 - Physical cistern characteristics and their potential impact on water quality

A total of 40 cisterns were surveyed, all of which were in the residential buildings managed by the housing authority. The cisterns were generally shaped in either a trapezoidal or rectangular shape with a vertical orientation (shown in Figure 4-14). The maximum capacity ranged from approximately 1,000 L to 1,500 L for each individual cistern.

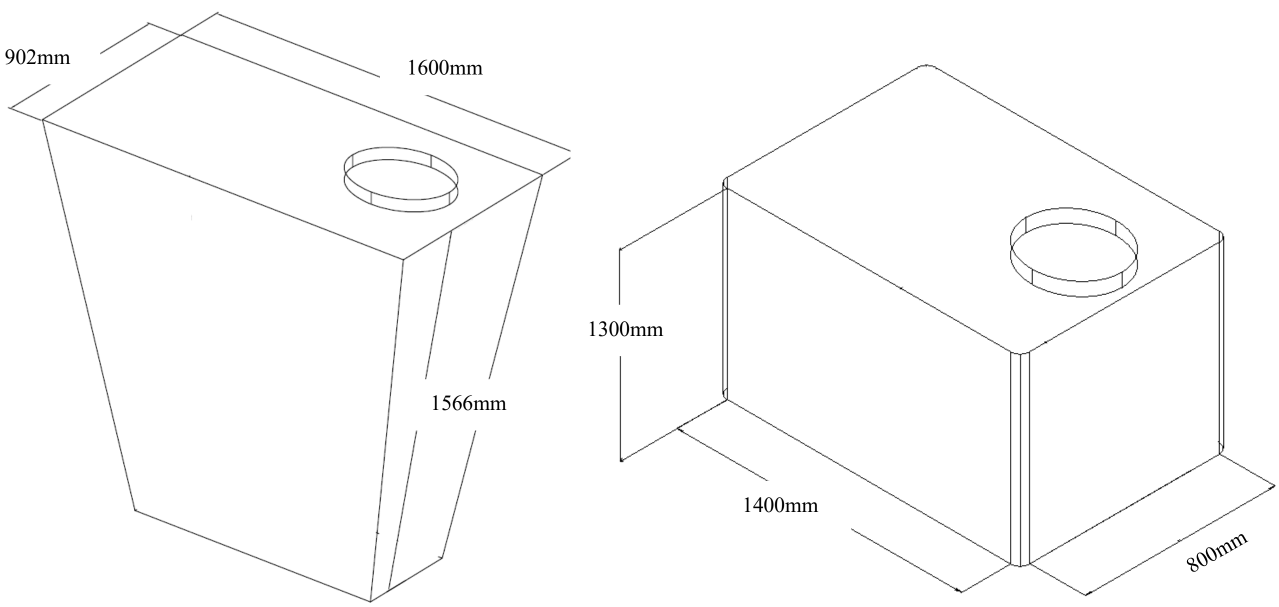

Figure 4-14: Trapezoidal and rectangular cistern shape and orientation

Water enters near the top of the cistern (via the trucks) and exits near the bottom of the cistern through plastic pipes. Each of the cisterns were located within a separate mechanical room that residents did not have access to. Finally, while most cisterns were insulated, there were quite a few of them that were not. Generally, the older ones were not insulated.

An analysis was done to compare the size of the cistern (in litres) to the average microbial activity (cATP) before they were cleaned to assess whether a trend can be observed. The results are shown in Table 4-7 below.

Table 4-9: Number of cisterns sampled for microbial activity per volume

Cistern volume (L)	Number of cisterns measured	Microbial activity (cATP)	Standard deviation (cATP)
<1,300	16	13.6	10.5
1,300-1,400	21	20.7	14.9
>1,400	3	25.1	23.6

The average microbial activity, measured as cellular ATP (cATP/mL), increased slightly with cistern volume. The cisterns with the volume that was less than 1,300 L demonstrated microbial activity at approximately 13.6 cATP with a standard deviation of 10.5 cATP. The cisterns with volume that were greater than 1,400 L demonstrated the highest microbial activity with approximately 25 cATP and a standard deviation of 23.6 cATP. Despite the increasing trend in average cATP with volume, the standard deviations overlap across all three categories, indicating that differences in microbial activity may not be statistically significant, but this would need to be confirmed with further analysis (e.g., confidence intervals or hypothesis testing). Thus, it can be concluded that the cistern design and manufacturing followed a similar trend within the cisterns in the residential buildings managed by the housing authority, however the water quality did not have a large discrepancy. This means it was likely influenced by other things such as date of construction and previous time cleaned. Further statistical analysis would need to be performed to confirm the significance of this.

Chapter 5: Conclusion

This research provided a study on the microbial activity of drinking water within some of the residential community cisterns located in a Canadian subarctic community. Undertaking such studies is important to shed light on the challenges northern Arctic and subarctic communities face with their drinking water. Microbial activity could be measured through an ATP analysis to quantify its presence.

5.1 – Thesis summary

The research questions were addressed extensively in chapter 3. Firstly, we compared ATP levels in drinking water from household storage cisterns between subdivisions (zones) of the community and cisterns age (decade of construction) to understand if there were differences under the various factors understudied. After confirming the normality and performing Shapiro-Wilk tests on the datasets, it was concluded that there were no statistically significant differences based on zones, while cistern age only slightly impacted the level of microbial activity. Furthermore, we compared the ATP levels at different stages of the WTP to understand the impact of treatment on microbial activity in potable water. After checking the distribution and central tendencies of the datasets, it was found that there was a statistically significant difference in the ATP levels between raw to fully treated water. Furthermore, a correlation study to determine the strength and statistical significance of the relation between ATP levels and five physical parameters was performed. Although the majority of correlations were found to be weak to moderate, there are moderate to strong correlations between ATP and turbidity before cleaning and across the WTP. The general physical characteristics of all the cisterns were collected and they all followed similar designs and manufacturing within the community. The microbial activity did not vary, and no significant correlation was determined. Therefore, it was concluded that there was a meaningful impact by the WTP on microbial activity. The results of this study represent a single three-week sampling campaign conducted in one subarctic community at a specific time of the year. Nonetheless, the overall findings are in line with previous drinking water safety studies conducted in Arctic communities in Canada (Gora et al., 2020). Upon reviewing the results, it is recommended that regular monitoring/cleaning of the cisterns be conducted, as this can lead to reduced microbial contamination and improve overall drinking water quality in communities served by truck-and-cistern water systems.

5.2 – Limitations of this study

A primary limitation of this research is that it is based on a single, three-week sampling campaign conducted in one subarctic community. While the findings provide valuable insight into water quality conditions in this specific setting, they may not fully reflect the diversity of conditions present, over time or between or across all communities in the Canadian Arctic. As such, the results should be interpreted as representative rather than definitive. Furthermore, sampling took place during the summer season and may not capture seasonal variations in water quality, particularly in winter when freezing conditions differ.

Additionally, post-cleaning water samples were collected immediately after cisterns were refilled by truck, which may have resulted in temporarily elevated free chlorine concentrations. This could mask the actual post-cleaning water quality that users experience over time.

5.3 – Opportunities for future research

Future research should seek to analyze the ATP levels in fully treated water at the water treatment plant and the individual trucks that fill the cisterns. In addition, there is a need to carry out more research on the drinking water quality in other remote communities in Canada to improve water quality and water safety. Furthermore, while the microbial activity levels were measured before and directly after the cleaning, it would be interesting to investigate the water quality after a significant time has passed from the cleaning date (ex: 1 month or more), to see if any rebound of microbial activity can be observed.

5.3.1 – Biofilm formation in cisterns

Another potential area of research could be the study of biofilm development within the internal surfaces of domestic cisterns. Biofilms can significantly impact water quality as they can harbor pathogenic microorganisms, including *Escherichia coli* and *Clostridium perfringens* and lead to the deterioration of microbiological water quality (Jagals, et al., 2003). Investigating the formation and composition of biofilms in these settings could provide valuable insights into long-term microbial risks, waterborne pathogen survival, and disinfectant resistance.

5.3.2 – Digital model of cistern at York University

An important area for potential future research involves replicating some of the cistern analysis that was conducted in the Canadian Arctic through a controlled study at York University. Our team has acquired a Polyethylene cistern of similar magnitude to the ones in the Arctic and placed it at York University, Keele campus. The goal in mind is to design a water quality monitoring system using electronic platforms such as an Arduino UNO and incorporating various sensors that could measure drinking water quality parameters. This item was purchased from *Equinox Industrial.* An image is attached that shows what the cistern looks like.

Figure 5-15: Purchased cistern located at York University (Equinox Industries, 2025)

One way to replicate the cistern analysis would be to perform the cleaning procedure that was done in Nunavik on this purchased cistern and attempt to see if it may be improved. This could be by potentially using different cleaning agents or methods of cleaning. The idea would be to enhance this process with the hopes of maximizing the microbial activity reduction.

Furthermore, we are also working toward the creation of a digital twin model of the cistern to simulate and visualize internal conditions. A preliminary 3D model has been developed using SolidWorks, laying the groundwork for potential future integration with live sensor data. As part of the broader research scope, we also aim to investigate the potential for modeling microbial activity growth patterns within the cistern under various storage and environmental conditions. An image of the current 3D model is included below.

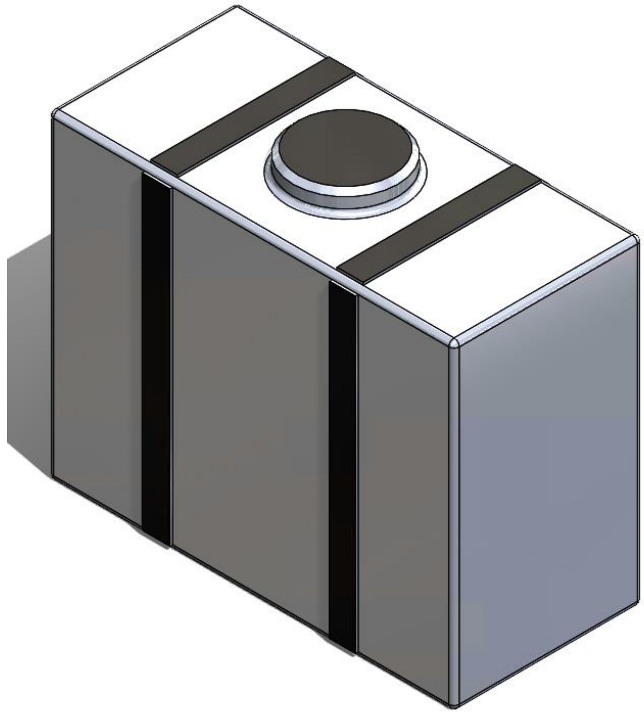

Figure 5-16: Preliminary model of cistern

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Appendices

Appendix A: Supplementary information on cleaning for chapter 3

Figure A-17: Cisterns before vs after cleaning

Appendix B: Supplementary information on normality for chapter 3

Table A-10: Normality tests for correlation analysis

Dataset	Test	ρ	Normality
ATP ~ Turbidity	Shapiro Wilk	8.884e-05	Non-normal
ATP ~ DO	Shapiro Wilk	0.01637	Non-normal
ATP ~ Total Chlorine	Shapiro Wilk	1.227e-07	Non-normal
ATP ~ Free Chlorine	Shapiro Wilk	0.0001898	Non-normal