Sustainable water storage and recirculation system for the Newterra facility

BREE 495

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FAT Factory Acceptance Testing

GAC Granular Activated Carbon

DOC Dissolved Organic Carbon

SDS Safety Data Sheet

UV Ultra-violet

FMEA Failure Mode and Effects Analysis

RPN Risk Priority Number

Executive Summary

With increasing concerns about freshwater availability and long-term environmental sustainability, it is essential to retrofit industrial operations to meet future water use challenges. Newterra, a leading manufacturer of modular wastewater treatment systems, currently discharges approximately 30,000 gallons of water per test at its Brockville, Ontario facility due to the absence of a recirculation system. This project proposes the design of an integrated water recirculation and storage system aimed at significantly reducing annual water waste and enhancing water access across the facility for testing purposes. The design process considers a comprehensive set of technical, environmental, social, and economic factors relevant to the project's pre-construction phase. A prototype of the granular activated carbon filters were tested to determine a suitable mesh size required for our filtration requirements. Cost constraints limited the scope of our testing to carbon media, however, overall, the design requirements were met and recommendations were given to facilitate the implementation of the design in the facility.

Acknowledgements

We would like to thank Deanna Maclean, Joshua Eaton, and Jeff Kempson, from the engineering department at Newterra for the opportunity to work with them, and for their enthusiastic help and expertise throughout the entire design process. Additionally, we would like to thank Yvan Gariepy for his guidance and advice throughout the prototyping process. We would like to extend a thank you to Dr. Clark and the many members of the Department of Bioresource Engineering who we consulted with during our project.

1. Introduction

1.1 Background and Problem Statement

Newterra is a company that has over 150 years of industry experience, specializing in the design and manufacturing of environmental water and wastewater treatment solutions. Their portfolio includes systems such as membrane bioreactors, modular potable systems, membrane bioreactors, reverse osmosis systems and activated sludge treatments. With offices across North America. Newterra operates a manufacturing and assembly facility in Brockville, Ontario, serving a diverse clientele including municipalities and private industries.

As part of its manufacturing process, Newterra conducts factory acceptance testing (FAT) to verify the performance and reliability of its assembled systems. These tests involve running municipal tap water through the systems to ensure proper functionality. Factory acceptance tests run between three to six times per month, lasting 2-10 days, with each test requiring approximately 30,000 gallons of municipal water.

Newterra's current solution to the disposing of the water after the factory acceptance test is simply discharging it into the municipal drainage system, resulting in a monthly water bill of over $700. Also, as the water circulates the system, it accumulates various oil, greases, industrial lubricants, dust, and heavy metals from the steel welds. Under Brockville regulations, wastewater containing fuel or sediments cannot be discharged directly into the sewer system, making Newterra's current disposal practice both environmentally unsustainable and potentially non-compliant with local discharge requirements.

1.2 Goal, Objective, and Approach

Our goal is to ensure Newterra remains compliant with wastewater discharge regulations while simultaneously reducing water consumption.

To achieve this, our objective is to develop a water storage and recirculation system that enhances the FAT process by improving water quality, minimizing wastewater discharge, and enabling water reuse.

This objective consists of two key components: improving the tested water's quality and reducing water consumption. To enhance water quality, a series of filters are carefully selected and put into sequence based on their specific filtration characteristics. To minimize the water consumption, a tank will be integrated to facilitate the reuse of the test water.

By combining these elements, we are designing a comprehensive water management system that includes a full water conveyance system (piping and pumps), a water filtration system to remove the contaminants and a storage tank to retain water between the FAT cycles.

The following report is structured into sections detailing the rationale behind filtration material selection, tank selection, pipe and tubing layout, prototyping procedures, and the environmental, social, and economic considerations associated with our project.

2. Literature Review

Under the scope of BREE 490, multiple filtration alternatives were considered and evaluated in the Pugh matrix, shown in Table B.1. The filtration system required a large filtration capacity, therefore flow capacity was a key criterion. Additionally, the filtration system had to be capable of filtering various contaminants, such as debris, heavy metals and oils and greases.

GAC and nanofilters were selected as the two filtration methods to be integrated within our system.

2.1 Nanofiltration

First created and developed in the 1970's, nanofiltration is a type of water filter that was derived from microfiltration, ultrafiltration, and reverse osmosis (DU et al., 2022). What makes nanofiltration unique is its pressure-driven membrane that features microscopic pores, which act as the filter, allowing the water to pass through the pores while the unwanted contaminants are blocked by the filter (Hoek et al., 2013). Additionally, nanofilters generally have low operating pressure and high permeation flux, which aids in reducing their operating costs (DU et al., 2022). A major problem with some methods of filtration, such as reverse osmosis and ultrafiltration, is that they negatively affect the hydration effects of the filtered water. But due to the average size of nanofilter pores being around a nanometer, this is not an issue (Hoek et al., 2013). The membrane of the filter is the most critical part of the system, allowing it to work as effectively as it does. Nowadays, by far the most prevalent composition for a nanofilter membrane is one that is made up of three layers to form a thin film composite, with those layers being an ultra-thin polyamide layer, a microporous layer, and a non-woven polyester layer, from top to bottom, respectively (DU et al., 2022). To support the structure, there is typically a thick polymer barrier layer also present. Furthermore, depending on the material and how the membrane was synthesized, nanofilter membranes can be classified as either "tight" or "loose" (Hoek et al., 2013). Which classification to use specifically relates to how the top layer of the filter was made. A tight membrane will have its polyamide layer made through the process of interfacial polymerization, which involves immersing the sublayer in an aqueous amine solution and an organic acyl chloride solution to have a very high separation capacity, making it more permeable, thus, more effective (Hoek et al., 2013). A loose membrane is closer to an ultrafiltration membrane, unlike tight ones which are more closely akin to reverse osmosis, in that they are made through the process of phase inversion, which changes the liquid polymeric solution into one of a solid state through either immersion precipitation, controlled evaporation, thermal precipitation, or precipitation from the vapor phase (Hoek et al., 2013). To influence the actual performance quantity of the membrane, it is key to properly choose which monomers to use, the concentration of them, and their reaction time, all of which depends on the intended use of the nanofilter. Nanofiltration is very effective for removing or neutralizing small organic solutes, charged ions, arsenic, pesticides, endocrine disruptors, chemicals, and works partially for desalination and inorganic ions. (Hoek et al., 2013, & Van der Bruggen et al., 2008). Because of this, nanofiltration processes have become a staple part of the industry and market, being an essential in water production, wastewater treatment, and water purification, especially since the growing population and need for clean drinking water has exploded in recent decades (Van der Bruggen et al., 2008). However, like any system and process, there are drawbacks and flaws to it. In a 2008 study by Van der Bruggen et al., six key potential issues with nanofiltration were distinguished for their importance and need to be further addressed, those being membrane fouling, separating solutes, treating concentrates, limited lifespan of membranes, lack of rejection of pollutants in water treatment, and the lack of available modelling and simulation tools. While all six of these issues are significant, they are not all equally significant. The most dominant problem was found to be membrane fouling, which is the buildup of contaminates over time causes the pores to be clogged, reducing efficiency, effectiveness, and its lifespan. Membrane fouling can be broken down into four different types, those being organic fouling, scaling, biofouling, or particulate fouling, all of which are problematic in their own ways (Van der Bruggen et al., 2008). What makes fouling particularly bad with nanofiltration, is that since it is at such a small scale, it can be difficult and complicated to understand and treat. The primary type of fouling seen with nanofiltration is organic fouling caused by the organic solutes, colloids and surfactants (Van der Bruggen et al., 2008). As mentioned before, cleaning nanofiltration membranes is difficult but can be accomplished through pretreatment, such as by using ultrafiltration, microfiltration, ozonation, ultraviolet oxidation, adsorption, and flocculation. More practically, regular scrubbing, flushing, enzymatic cleaning, and vibrational cleaning will all help the membranes productive and will extend their lifespan, with recommended cleaning chemicals reactions including hydrolysis, saponification, solubilization, dispersion, chelation, and peptization (Van der Bruggen et al., 2008). One of the most promising and sustainable solutions was found to be membrane modification, where hydrophilic groups are inserted into the polymeric structure, increasing its resistance to organic fouling. Because of the worthwhile effects and results of nanofiltration, it is a highly desirable processes to include in wastewater treatment systems that has been found to be reliable and impactful since its introduction nearly fifty years ago.

2.2 Coconut Shell Based GAC Filtration

The GAC filters we will be testing and implementing in our design are ones derived from coconut shell. The use of coconut shells within activated charcoal filters results in an overall increase in its ability to remove heavy metals (Kurniawan et al., 2011). Because of their dense structure, high strength, and low levels of ash content, coconut shells have become a reliable add-on to activated carbon and charcoal filters (Deng et al., 2021). What really makes coconut shells a particularly effective ingredient, is the present oxygen that mixes with various surface functional groups, creating carboxylic, carbonyl, hydroxyl and lactone compounds that increases the hydrophilicity, surface charge density, and the adsorption ability of the polar molecules (Kurniawan et al., 2011). Besides their practical benefits, coconut shells also present a few economic benefits. Because the shells are usually viewed as a waste product in the coconut production industry, it has become an underutilized market, making them a very affordable option (Kurniawan et al., 2011). Additionally, agents including but not limited to acid, alkali, potassium, and iron, can be mixed with the coconut shells to increase its effectiveness against specific metals that are more prevalent in certain conditions (Deng et al., 2021).

2.3 Why Activated Charcoal Filters Were Prototyped

To treat and store Newterra's wastewater from their factory acceptance tests, a number of different filters will be used to ensure all different types of contaminants are removed. Included in these filter choices are activated charcoal filters picked for several reasons. Standard granular activated charcoal filters (GAC), which are those without specialty add-ons like coconut shells and specific meshes, are most used to filter out dissolved organic carbon (DOC), which include biodegradable organic matter, micropollutants and halogenated hydrocarbons (Velten et al., 2011). They work similarly to activated carbon filters and after being oxidized, they treat the water through adsorption, which is when chemical attraction brings the unwanted compounds to the pores on the surface of the material, which then traps those compounds, filtering them out (Mozammel et al., 2002). Similarly to adsorption, GAC's can filter out pathogens and pollutants through bioadsorption, which utilizes biomaterial to biodegrade certain contaminants in addition to the non-biodegradable matter that is filtered out through standard adsorption (Xing et al., 2008). Because of their dual use, they are considered a superior version and typically used in fixed bed or fluidized bed bioreactors (Xing et al., 2008). In a study conducted by Xing et al., several types of wastewaters were treated with adsorption and bioadsorption to test their effectiveness. Among all their tests, the most important result was with the treatment of real primary treated sewage effluent, where adsorption and bioadsorption removed 54% and 96% of DOC, respectively. (Benstoem et al., 2017) executed a wide scale literature review across 44 different studies that investigated the effectiveness of GAC in disposing of organic micropollutants. While their inquiry focused on a multitude of factors regarding the use of GAC, such as bed volume, adsorber operating time, empty bed contact time and manufacturing method, the consensus regarding the overall performance of GAC was that it is a very efficient and reliable method of filtration.

For the reasons and benefits discussed, using activated charcoal filters as part of our wastewater treatment design becomes an obvious and necessary choice. Another reason we have chosen to utilize GAC filters as part of our design is because Newterra already has their own supply of these filters, so they would not have to order more. This makes the project more financially desirable for them as it works with what they already own and have used before, so they are familiar with its properties.

3. Standards

3.1 Occupational Health and Safety

When working in an industrial setting, it is critical to adhere to health and safety protocols, as outlined by the Government of Canada and the Government of Ontario. For this recirculation project, these codes are important during both the installation and continued use of the system.

Given the handling of chemical agents such as Sodium Hypochlorite, contaminated water, and the installation of an industrial plumbing system, the Occupational Health and Safety Act governs the adequate use of safety gear when handling these substances, proper comprehensive safety training before handling, and the presentation of SDS and clear signage around the area of work.

Safety gear includes protective footwear, hand protection, eye protection and respiratory protection if handling chemical agents.

Table B.2, provides a summary of the regulations found in the Canadian Occupational Health and Safety Codes as well as additional regulations that may apply to the implementation of this project.

3.2 Water Standards

To ensure the safety of all workers handling the water system and working close to the systems, our design will treat the water to meet the Ontario Regulation 169/03 of the Safe Drinking Water Act, 2002.

The Ontario Safe Drinking Water Act regulates various contaminants and chemical levels in the water, deemed safe for human consumption. For Newterra, this water is not intended for human consumption, but through meeting drinking water standards, the water will be fit to be handled, and if water is splashed onto skin, eyes or clothes, there is no risk. Table B.3. presents a summary of water contaminants that the recirculation filters are strategically targeting. These contaminants were determined through discussions with Newterra on October 30th, 2025 regarding the path of water flow within the tested systems, and the various products and processes used during assembly. Other drinking water limits will be met.

3.3 Brockville ByLaws

Given Newterra’s location in Brockville, the design will ensure that Bylaw 046-2014, which regulates the use of sewers within the city of Brockville, will be met during any periods of discharge.

Notably, the water discharge must:

- Not exceed 40°C
- pH must remain between 6-9
- May not contain any fuel
- E. coli cannot exceed 200 CFU/100mL

- Be clear of all sediments

This bylaw governs the response action required in the event of a spill to the sewer system, as part of article 15. Notably, this includes alerting the city of Brockville that a spill has occurred, attempt to contain the spill, and documenting information regarding the volume, duration, and characteristics of the water.

3.4 Plumbing Codes

Well established plumbing and building codes in Ontario serve to regulate fire codes, drainage standards, recirculation systems, and loads on the plumbing elements. These codes are presented in Table B.4.

3.5 Mechanical Codes

Table B.5. presents a non-exhaustive list of mechanical standards that apply to the design and implementation of our project.

4. Experimental Procedure

4.1 Purpose/scope

The goal of the experiment is to evaluate a suitable carbon media, capable of pretreating the water before arriving at the nanofilters. Due to financial limitations, the selection of filters for prototyping is restricted to those provided by our clients. As a result, only the carbon filters are tested. Given the constraints on available materials, the prototype may only demonstrate partial effectiveness of the carbon media. The aspect of the theoretical design that cannot be prototyped and tested is validated through literature review and consultations with professionals in the field.

The purpose of the GAC filters in the design is to pretreat the water before it reaches the nanofilters. To achieve this, any chlorine must be removed as it is detrimental to the nanofilters ("FilmTec Product Data Sheet", 2015). In addition to this, the more oils, greases, and metals that are removed from the water, the better the life of the nanofilters will be.

Based on the literature review, GAC filters are excellent in filtering greases and heavy metals. However, depending on different raw materials and treatment methods used, different GAC filters can have varied characteristics(Vignuzzi I et al., 2024).

4.2 Justification

While our final water treatment design utilizes many filters, including but not limited to GAC filters, these are the only ones we are running physical tests on. The primary reason for this is due to the constraints of this project, we lack the necessary time, budget, and resources to conduct a full scaled-down version of our design that would include all the filters in their proper series and parallel layouts. The GAC filters were prioritized due to their availability to us and their importance in our design. Newterra already has a supply of various GAC filters of different grit sizes and different biomass sources, so they were able to supply them to us at no cost. Additionally, they are familiar with this type of filter and have used it before, so it is very realistic for them to utilize it with our design when building the full-scale version. As discussed in the literature review, GAC filters have good properties for water filtration that make them very versatile and reliable, meaning they are one of the most important components to our design. Furthermore, our other filters, such as the ceramic ones, are more basic and have less variability to them, reducing their need to be tested by us. Because of their availability and importance, GAC filters were determined by us to be a high priority item to test.

4.3 Materials

The main components, such as filters, are provided by our clients. These include two types of GAC filters (coconut-based 8x30 and coconut-based 12x40), a Xylem (Washington, DC) Flojet diaphragm pump to push water through the filters, and 12.7 millimeter diameter clear PVC pipes to hold the filters, and bag filter material which holds the media together.

4.4 Methodology

The experimental procedure was formed based on guidance from Yvan Gariepy, as well as our advisors at Newterra.

A 2 ft. long portion of 2 in. diameter PVC pipe is fitted with flange fittings on both sides. The pump is attached to the bottom with a pressure-regulating valve in series. On the top of the PVC pipe, a tubing is attached for water disposal or collection. Using the bag filter material provided, 4 tubes were cut (5.1 cm diameter, 27.8cm long), sealed with hot glue along 3 sides, and filled with 200 g of each media. The filled tubes were weighed before and after the media was added. Each filter was loaded into the PVC pipe at a time and filled with water using the pump. This time was used to measure the contact time and adjust the water pressure as needed so that it exceeds 15 minutes. The media was soaked for 24 hours before discarding the water and running the trials. Unfortunately, the pump was not able to provide water at a low enough pressure. As a result, the contact time was about 1 minute for all of the trials.Each filter was subjected to three consecutive trials of oil and water. The filtered water was tested for oil residuals for each trial and each filter, totaling 12 data points. To simulate the contaminated water, the bottom of the filter was injected with 1.454g of canola oil which is equivalent to 4 weeks of use (see assumption 1). Then, the filter is loaded in the housing and one liter of water is passed through the system.

To test and validate our selection of filter media, the EPA Method 1664 Revision B was used. This method is for the determination of n-hexane extractable material (HEM, oils, and greases) in surface and saline waters and industrial and domestic aqueous wastes. This method can measure in the range of 5 mg/L to 1000 mg/L (5ppm to 1000ppm). The results of this method will yield total oil and grease concentrations of samples taken from before and after media filtration. The results of this method will also determine the capabilities of each medium of filtering oils and greases to an acceptable level required to begin nanofiltration.

Assumption 1:

We received advice from Mr. Yvan Gariepy on February 21 2025 to scale down the oil content linearly by weight, but to increase the amount of oil by the period of time that we wanted to test for, meaning that to simulate 4 weeks of usage, we could multiple the oil load for one week by 4.

flow rate of 0.001262 m^3/s and contact time of 15 minutes requires 1.183 m^3 [41.77 ft^3] of carbon media. This is the total amount of carbon that is in the full design.

From the manufacturer's specification sheet, the density of the media is 29-33lb per cubic foot. To reach 41.77 cubic feet, conservatively, we will need:

$$33\ lb/ft3 \cdot\ 41.77\ ft3\ =\ 1378\ lb\ of\ carbon\ media$$

Since we used 200g of media per test, this is equivalent to 200 g/625 kg = 1/3125. In the full design, assuming 10ppm concentration of oil in the water (this is a high point assumed from the water tests conducted), the load for one week would be 1,135,623.5 mg. Dividing this by 3125, the 200 g of media will be filtering 363.40 mg of oil per week. For 4 weeks, it will be filtering 1453.598 mg, or 1.4536 g. The scale used in the experiment only measures down to 1×10^{-3} g, so the oil was measured at 1.454 g.

5. Prototyping & Results

5.1 Results

The results of the prototyping procedure, detailed in Fig. 1 and Fig. 2 which are located in Appendix A, indicate that the 8 x 30 mesh size GAC has a higher capacity of filtering oils and greases than the 12 x 30 counterparts. Both trials of 8 x 30 filters left residual oil contents of

0.195 grams 0.4525 grams of oil. Comparatively, the 12 x 30 mesh left oil residuals of 0.81 grams and 0.565 grams. These results are presented in Table B.7. Therefore, given these results, the 8 x 30 mesh will be selected as the preferred GAC for the carbon filter.

6. Design & Justification

6.1 The Design

The layout of the proposed design, including pipes, filters, and tank, is pictured in Figure A.3. As pictured, from any of the 8 access points, the used water is pumped into the preliminary tank. It is not pumped through the filters until the first valve is opened, ensuring that technicians can do any maintenance needed.

6.2 Factory layout

The design of the water recirculation system must include pumping and piping capabilities to convey the cleaned water from the tank to any machine in the factory, and vice versa. Fig. 4 in Appendix A shows the piping layout on the blueprint of Newterra's building. The design involves a pipe that conducts wastewater from the access points to the tanks and filters, and another pipe that conducts clean water back to the access points. The pipes run parallel to each other and are represented by one line in Fig. 2. Both pipes travel upwards from the filtration system to the ceiling at 7.62 m high. At each access point, the pipes travel down to 1.22 m above the ground. The total length of piping required for this layout is 432.4 m. The longest path that will be traveled by water is 185.6 m [609 ft].

6.3 Piping and Tubing

For piping, the National Plumbing Code of Canada (2020) Section 2.6.3.5 states: "The maximum permitted water velocities shall be those recommended by the pipe and fitting manufacturer". Fabricated Plastics Limited, a Canadian plastic parts manufacturer based in Maple, Ontario, provides detailed engineering data on the use of schedule 40 thermoplastic pipes ("Section 12: Engineering Information", 2024) The table on page 353 will be used to size the pipes. According to the table, in a 3.175 cm [1.25 in.] diameter pipe, water moving at 0.001262 m^3/s [20.833 gpm] will travel at 1.35 m/s and experience a pressure loss of 0.0169 MPa per 30.48 m ("Section 12: Engineering Information", 2024). This means that to reach the farthest point in the factory, the water will need 0.1029 MPa [14.9 psi] of pressure to overcome the friction in addition to the head of 7.62 m for the water to reach the ceiling from the floor.

6.4 Carbon filters

Fig. 5 in Appendix A illustrates the flow of the water through the charcoal filters. The charcoal filters in this design use a bottom-up water flow, and the filtered water is collected at the top of the tank. This choice was made based on a personal communication with Dr. Prasher on November 6th of 2024, where he advised that a bottom loaded filter experiences less preferential flow. The water is added into the filters through a distributor. This is a device composed of any number of short PVC pipes that are slotted at a determined width. On one end, they have an end plug, and on the other, they are connected by a hub, through which the water enters ("Machined Slotted Laterals", 2025).

For the backwash cycle, the valves are switched in order to reverse the flow of the water. Backwash water is sourced from the main tank, and the effluent water from a valve at the bottom of the filter vessels is directed to treatment. Figure A.6. illustrates this backwash process.

The total amount of media to be used is determined from the flow rate and required contact time. Considering a flow rate of 0.001262 m^3/s which represents the company's need to process 113.56 m^3 in the span of 24 hours. The EBCT is determined by GAC manufacturers. For oils and greases, the EBCT provided by Newterra is 15 minutes. Mar Cor Purification, Pittsburgh Pennsylvania, recommends an EBCT time of 6 minutes for free chlorine and 10 minutes for chloramine. The required volume of media is given by the flow rate divided by the empty bed contact time (Michaud, 2013).

From the carbon media's specification sheet, the density of the media is 465- 529 kg/m^3 [29-33lb per cubic foot]. To reach 1.183 m^3[41.77 ft^3], conservatively, we will need:

Typical density at 465- 529 kg/m^3, an average value of 497 is used.

$$1.183m^3 \cdot \frac{497kg}{m^3} = 587.9kg$$

In addition to the amount of media required, the tank's surface area is a key aspect of the design, as it is affected by the loading rate of the media, a specification provided by the media's manufacturer. The required surface area is equal to the volumetric flow rate divided by the loading rate (Wirth, 2012). The loading rate of the media used in this design is 5ft/gpm (General Carbon Co, n.d.).

$$\frac{20.8gpm}{5ft/gpm} \approx 4ft^2$$

According to Table B.6., for 4 ft^2 of loading area, the required tank diameter is 30 inches. However, to reduce the height of the column between 4-5 ft, as suggested by Newterra on March 17th, 2025, we will increase the diameter to 1.0668 metres, for a bed depth of 1.326 metres. For system redundancy, two GAC filters will be placed in series. This ensures that during periods of maintenance on the primary GAC filter, the system can continue operating on the secondary GAC filter. Due to this, the GAC media will be separated into the two filters, so each one will contain 0.5904 m

$$V = \pi \cdot h \cdot r^2$$

Equation 1

$$h = 1.32588\,m$$

$$r = 0.5334\,m$$

To account for backwash bed expansion, we account for a 30% bed expansion to prevent the media from escaping the filter cartridge (Wirth, 2012). Therefore, the total height of the filter bed must be 1.72 metres tall, at minimum.

6.5 Pumps

The required pressure of each pump will be calculated in this section.

Pump 1: Placed after the preliminary tank and before the GAC filters. It is responsible for conveying the water through the GAC filters to pump 2 which is placed after the GAC filters. Each GAC filter enacts a pressure drop from the media and another from the water distributor unit. The General Carbon Corp.'s data sheet for the GAC media provides a table, from which a pressure of 2.385 kPa. Mattson/Witt, a water treatment parts manufacturer based in Barrington Illinois, explains the various water distributor units and their expected pressure drop. For a distributor with 0.254mm wide slots, the pressure drop will be below 20.68 kPa for a fluid velocity below 1.524 m/s ("Slotted Laterals", n.d.). Another manufacturer which produces the same water distributor product, Safe Water Technologies Inc. based in Elgin Illinois, offers the exact same numbers for pressure drop ("Machined Slotted Laterals", 2025). A Grundfos CRE 5-2 pump can perform this. Grundfos was confirmed to us as a reliable pump supplier by Newterra in a personal communication on November 15th of 2024.

Pump 2: This pump is placed after the carbon filters and before the nanofilters. A personal communication with Josh Eaton from Newterra on January 13th of 2025 clarified that filters in a series do not require any additional pressure except for the pressure drop of each successive filter, but that filters in parallel require addition flowrate. The nanofilters have a capacity of 10,000 gal/day, meaning that 3 of them in parallel will give us the correct flowrate. Adding another 3 filters in series ensures that the system is robust. The nanofilters have a specified operating pressure of 517.11 kPa and a pressure drop of 89.63 kPa ("FilmTec Product Data Sheet", 2015). The water also needs to be pumped to the valve at the top of the tank, adding

3.279 m of head, or 32.15 kPa, making the absolute minimum pressure requirement 549.26 kPa. A Grundfos CRE 5-7 pump is suitable for this.

Pump 3: This pump must convey the water to all parts of the building. The pressure requirement has been calculated in section to be 0.1029 MPa. A Grundfos CRE 5-2 can do this. When the pump is not in use for water conveyance, it will circulate the water around the tank to ensure consistent concentration of chlorine throughout the tank. In the past, our design included a ceramic filter to prevent microbial buildup. However, a personal communication what Dr. Grant Clark on January 2nd of 2025 brought to light that such a filter may not be necessary as the filtered water will be free of particulates. We did not find evidence in the literature for its necessity. Hence, it was removed from the design.

To calculate the energy cost of the pumps, we are assuming that they will be run at mid-peak hours, which means according to Ontario's energy prices, we will be paying 12.2 c/kWh (Ontario Energy Board, 2025). A FAT takes approximately 24 hours to run and from the data sheets of the pumps it was found that the CR 5-2 pump and CR 5-7 pump will use 0.37 kWh and 53.4 kWh, respectively. Therefore, the price to run a FAC test for the CR 5-2 pump and CR 5-7 pump will cost $1.08 and $156.36, respectively.

$$CR\,5-2\;Energy\;Price\;=\;0.37\;kWh\;x\;24\;hours\;x\;0.122\;\$/kWh$$
$$=\;1.08\;\$/kW\;per\;FAC\;test$$

Since there are two CR 5-2 pumps, the total cost for all pumps for one FAC test is $158.52

$$Total\;Pump\;Cost\;=\;(2\;x\;\$1.08)\;+\;\$156.36\;=\;\$158.52$$

6.6 Main storage tank

The storage tanks are sourced from Granby composites, a fiberglass tank manufacturer located in Ham-Nord, Quebec.

The primary holding tank is sized for 11,644 liters and is their NN06090115 product. The secondary holding tank is sized for 115,743 litres and is the NN10331171EU product. The secondary tank will be situated outside. Therefore, to ensure the tank does not freeze, a layer of 152.4 mm polyurethane insulation will cover the entire tank. The secondary tank has a 3.048 metre diameter, and is 16.901 metres in length, occupying a total footprint of 78.302 m^2

Due to the tank size, it is important to select the appropriate outdoor location. Important considerations for the site selection include the property boundary line, topography of the terrain, and the drainage route. According to Granby Composites, the tank must be installed on a bed or foundation of natural 'B' gravel or crushed gravel ("Installation Manual", 2018). Additionally, proximity to the factory is critical, to reduce piping requirements between the indoor and outdoor facilities. Given the size of the tank and the plumbing requirements, the water tank may require additional permitting with the city of Brockville. Figure A.7. shows the proposed location of the outdoor holding tank.

6.7 Heater & Insulation

Insulated tanks for cold weather can be requested and installed through Granby Composites. This insulation includes a 101.6 mm thick layer of urethane insulation across the entire surface area of the tank. While Granby has not provided an exact R value for this material, we assume R-6.25 per inch, for a total R-Value of the 101.6 mm thick layer of insulation at R-26.08, based on a personal communication with Newterra on January 20^{th}, 2025.

To ensure that the water does not freeze during winter, immersible heaters will be installed along the large storage tank.

According to The Weather Network's historical weather database, the coldest temperatures occur between the months of January and February, at an average of -18 °C. Given the uncertainty of weather patterns in winter, a safety factor of 1.5 will be integrated to account for cold spells.

Equation 3, found in Annex C, governs the heat loss of the tank system to the surroundings. Given the layers of insulation surrounding the tank, as well as the small temperature difference between inlet water and water already sitting in the tank, we consider the losses to radiation and convection to be negligeable.

$$Q = \frac{A \cdot \Delta T}{RSI}$$

Equation 2

Q = Heat loss of the system (Watts)

A = Surface area of the tank provided by Granby Composites (m^2)

T = Temperature difference between water at 4°C (target temperature) and air at -18°C

RSI = RSI-value of polyurethane (0.043 m^2 * °C /mm)

$$N = \frac{1.5Q}{5kW}$$

Equation 3

N = Number of heaters required

According to Equation 3, The total Q_{loss} of the system at a given point in time is 936.13 W (see annex for full calculations). The number of heaters required to heat the tank, according to Equation 4 (see Appendix C) is 1, 5kW flanged heater. For the tank heaters, we have selected a model from Wattco, a manufacturer based in Montreal Quebec, specifically for their 635 mm flanged heater. To prevent the water from reaching cold temperatures, a temperature sensor will be included within the tank for continuous monitoring. In addition to temperature sensors, a tank level sensor will be integrated for overflow detection. To track both parameters, an electronic level and temperature sensor LT8022 sourced from ifm (Essen, Germany), will be installed in the tank.

6.7.1 Power Consumption of the heaters

We assume that during the winter months, the heater will run for 12 hours, for approximately 90 days.

$$kWh = 5\ kW\ x\ 12\ hours\ x\ 90\ days = 5400\ kWh$$

During mid-peak times, the price of electricity in Ontario is 12.2 c/kWh (Ontario Energy Board, 2025). The total price for electricity over the course of a year:

$$Price = 5400\ kWh\ x\ 0.122\ \$/kWh = 658.80\ \$$$

6.8 Chlorine and UV disinfection

Given that water microbiota is complex, with many variations in the identity and composition of microbial communities, both chlorine and UV treatment were selected to ensure that the water distributed in the system is safe for use (Oliveira et al., 2024)

The combined effects of UV irradiation for primary disinfection followed by the addition of chlorine residuals for secondary disinfection can treat against the formation of biofilms, pathogens and heterotrophic bacteria, which are all common sources of microbial water contamination (Oliveira et al., 2024). A minimum dose of 40 mJ/cm^2 has been found to reduce the likelihood of reactivation, especially when paired with a residual chlorine level of 0.5 mg/L (González et al., 2023). UV radiation inactivates microbes by damaging their DNA and ability to replicate whereas chlorine acts by destroying the nucleic acids and cell membranes of organisms (González et al., 2023). While UV is beneficial due to its short contact time, it does not maintain any residual disinfection within the tank. Therefore, the choice to integrate chlorine is to reduce the likelihood of biofilm formation and reactivation over long periods of time.

As the water exits the nanofilters, it will pass through UV irradiation at the inflow of the primary water holding tank. To accommodate a flow rate of 0.000063 m^3/s and a dose of 40 $mJ/cm2$, Viqua 650653 UVMax PRO20 was selected as the UV disinfector. VIQUA, a division of Trojan Technologies, is based out of London, Ontario.

The water in the storage tank will be held for a variable period, such that the circulation of the water throughout the entire facility will depend on the frequency of testing. As such, there is a risk of developing biofilms within the tank and the piping network (Oliveira et al.,2024). The maintenance of effective residual concentration in the water guarantees long term prevention of biofilm formation. The presence of biofilms in water distribution systems are often responsible for water quality deterioration and a possible source of public health risk (Oliveira et al., 2024). As previously mentioned, the water in the system will not be distributed for drinking water purposes but will maintain chlorine levels at a level safe for operators.

Sodium hypochlorite is the selected chlorine disinfectant due to its large accessibility, and ease of operation. Sodium hypochlorite targets E. coli, cyanotoxins and contaminants due to fecal matter (Oliveira et al., 2024).

The chlorine disinfection system will include a liquid chlorine injection system manufactured by Hydro Instruments, Telford, Pennsylvania, and a chlorine sensor by Endress & Hauser, Burlington Ontario. The automation of this system will ensure that variable flow rates and long water holding periods do not negatively impact the safety of the water.

A 12.5% concentration of liquid sodium hypochlorite will be stored in an outdoor storage tank, shielded from sunlight and temperature variations. The sodium hypochlorite will then be injected into the tank and monitored to maintain a residual chlorine content of 0.5 mg/L. In general, the recommended contact time for water and chlorine is 30 minutes (Health Canada, n.d.). Chlorine contact time is dependent on the temperature and pH of the inflow (see Appendix for contact time calculations).

If a 0.2 $mgL^{-1}d^{-1}$ chlorine decay rate is assumed (García-Ávila, 2020) then a standard container of 20 litres would last approximately 110 days (see Appendix C for calculations). Given the short shelf-life of sodium hypochlorite and the sensitivity to temperature changes (Hydro Instruments, n.d), it is preferable to maintain small storage quantities in favour of large drums. This additionally reduces the fire hazards associated with chemical storage.

6.8.1 Power consumption of the disinfection system

According to the product specifications, the UV system uses 980 kW/year, due to the use of their LightWise technology.

$$Cost = 980\ kW/year\ x\ \$0.122 = \$119.56/year$$

There is no publicly available power consumption for the chlorine systems, however, to get an approximate estimate of the power consumption, we will estimate using a similar model of a Grundfos, Bjerringbro, Denmark, chlorine injection pump at 80W ("Dosing Pumps, Digital", n.d)

$$80\ W\ =\ 0.08kW$$

$$Annual\ energy\ use\ =\ 0.08\ kW\ x\ 8{,}790\ hours/year\ =\ 700.8\ kWh$$

$$Cost\ =\ 700.8\ x\ \$0.122\ =\ \$85.50/year$$

7. Maintenance Plan

An important maintenance consideration is filter backwashing and replacement. Although the manufacturer of the GAC media used in this system does not provide backwashing guidelines, a different manufacturer, Carbotecnia based in Guadalajara, Jalisco offers a guide on backwashing. Although it is stated in this guide that backwashing requirements vary, a reasonable plan involves weekly backwashing. In practice, the true recurrence of backwashing will be based on when the pressure of the water effluent from the filter decreases ("Importance of backwashes and how and when to perform them," 2021). The same information is communicated in the "Backwashing" chapter of "Encyclopedia of Membranes." For the sake of formulating a maintenance plan and budget, a weekly backwash is assumed.

Backwashing is not performed for nanofilters.

The lifetime of the GAC filters must also be considered.

A full summary of the maintenance schedule and work required can be found in Table 8 of Appendix B.

8. Implementation (Safety, Fail safes, FMEA)

An FMEA (failure mode and effects analysis) chart allows us to rate different failure modes based on their probability of severity, occurrence, and detection.

To ensure the reliability and robustness of our system design, a Failure Mode and Effects Analysis (FMEA) was conducted. FMEA is a systematic tool used to identify potential failure modes within a system based on their probability of severity, occurrence, and detection. All ranks are given on a scale from 1 to 10.

Severity (S): Measures the seriousness of failure's consequences, where 1 means failure would not be noticeable to the user and would not affect the user's process or product and 10 represents critical failures that compromise safety or regulatory compliance.

Occurrence (O): Estimates the likelihood of the failure occurring, ranging from 1 (highly unlikely) to 10 (almost inevitable).

Detection (D): Assesses the ability to detect failure before it reaches the end-user or causes significant harm. 1 means easily detectable and 10 indicates the defect caused by failure is not detectable.

These three ratings are multiplied to calculate the Risk Priority Number (RPN):

$$RPN = S \cdot O \cdot D$$

Higher RPN values indicate more critical risks that require attention, either through design mitigation, monitoring, or preventive actions. This analysis allowed us to systematically identify weaknesses in our design and proactively implement measures to reduce risk and enhance system performance. The outcomes of the analysis are depicted in Table B.7.

The recommended actions listed in the FMEA chart, Table B.9., include both measures currently integrated into the design and additional suggestions made to the client to further reduce potential risks.

To prevent overflow of the outdoor storage tank, an overflow alarm is recommended. Overfill Prevention System SOP300 (*Overfill Prevention System SOP300*, n.d.) offers a suitable option, sourced through one of our approved vendors. While the fiberglass material used for the tank is corrosion-resistant, and Granby Sales and Technical Support notes that “if used correctly, the life expectancy is incalculable,” we recommend annual inspections to monitor for any signs of corrosion or structural damage.

To ensure proper operation during extreme winter conditions, the outdoor storage tank is insulated with polyurethane and equipped with three immersion heaters.

To prevent debris from clogging the system, filters with sufficient capacity are installed to remove large particulates. A preliminary tank is also included to buffer water flow if filtration capacity is exceeded. This tank provides temporary storage and helps regulate variations in flow rate and contaminant concentration. Additionally, redundant filters are installed in parallel to handle excess water and ensure uninterrupted operation. Regular maintenance and timely filter replacements, as outlined in the maintenance schedule, are essential to ensure continued effectiveness.

To mitigate the risk of leaks at piping connections, threaded sealant is used, and routine inspection of fittings is recommended.

For pump protection, we suggest the installation of low-level cut-off switches—such as Liquiphant FTL41 (*Liquiphant FTL41*, n.d.) offered by our vendor Endress + Hauser—to prevent dry running when water levels are insufficient.

To prevent bacterial growth in the stored water, chlorine and UV disinfection systems are implemented before water enters the tank. As chlorine dosing requires precise control, we have installed an automatic chlorine injection system coupled with chlorine sensors for accurate regulation.

All system sensors should undergo regular inspection and calibration, recommended weekly to maintain accuracy and reliability.

Finally, human error was also considered in the FMEA to ensure operational safety. A key risk identified was the potential for eye exposure to contaminated water during manual handling. While not a mechanical failure, this poses a significant health hazard. To mitigate the risk, the installation of splash guards at pipe junctions, valves and switches was recommended to improve system safety. Additionally, workers should receive thorough safety training to ensure both prevention and an effective response in the event of an emergency.

9. Budget

9.1 Initial Capital Investment

Newterra's Brockville location spends an average of $713.00 per month on water, 80% of it being attributed to the factory acceptance testing. Based on these figures, the design has the potential to save Newterra $570.40 a month.

Table B.10. shows the initial capital cost for materials needed to construct this project. The sum was calculated to be $165,268.69, based off the quotes and prices found. Price quotes and estimates were provided directly by the vendors and were based on our specific requirements and needs. By far the largest investment for this project is the cost of the water tanks, which cost us over $100,000 for both. The cost of construction was roughly estimated by Newterra to be around $19,800.

It should be noted that these prices are estimates and do not include additional costs from the base value cost, such as taxes or shipping. They are also subject to change due to potential incoming tariffs. Some vendors require a minimum quantity amount to order as well and buying in bulk may be the most cost-effective method of purchasing for the long term.

9.2 Operational Costs

For this system to operate, the pumps, temperature controls, and disinfection systems will need energy. Electrical costs in Ontario, Canada, vary depending on time of day and season, which was accounted for in our calculations. Table B.11. gives a summarized breakdown of our operational costs. The pumps will cost $158.52 per FAC test and the heaters, UV system, chlorine injection system, and sodium hypochlorite, will cost $658.80, $119.56, $85.50, and $401.50, respectively, per year.

10. Considerations

10.1 Environmental considerations

Our proposed water filtration, storage and circulation system is expected to have a positive effect on the environment, particularly by reducing the factory water waste during factory acceptance testing. The benefits are listed in the categories below.

10.1.1 Water use reduction

The proposed system filters the used test water and stores it for reusing; it significantly reduces the water consumption compared to current situation, as they currently dump the water to drain it.

10.1.2 Energy use reduction

Our system does include the usages of pumps, filters and sensors that consume energy. However, this is balanced by the reduction in energy associated with transporting and treating large volumes of new water.

10.2 Safety considerations

Our design system prioritizes worker safety. All components were carefully selected to minimize potential hazards and ensure a safe working environment. The system features automatic chlorine injections to disinfect the water, with continuous monitoring via a chlorine level sensor to prevent overexposure or underdosing.

Splash guards are recommended to be installed at key points such as pipe junctions, valves, and switches, where the risk of water splashes could pose safety risks to operators.

While extensive measures have been taken to reduce safety risks through design, proper operator training remains essential. As outlined in the FMEA, personnel must be thoroughly trained in safe operation procedures and emergency responses to prevent irregular operation and ensure a safe workplace.

10.3 Economic considerations

A detailed initial investment assessment table is prepared for our client as well as the installation and operational cost tables. This breakdown provides them a clear estimate of the financial implications associated with integrating the proposed system into their facility. Although there are more cost-effective parts available on the market, the selected components were chosen for their availability through vendors already approved by our client. Ultimately, these tables ensure that the proposed solution is cost transparent, reducing the risks of delays or unforeseen adjustments during implementation.

10.4 Social considerations

Our design reduces the water usages of Newterra facility by recycling water used during factory acceptance testing. By implementing our system, it not only enhances the operation efficiency, but also strengthens the company's reputation as an environmentally responsible organization. As a lead in sustainable innovation, Newterra can set an example that encourages other facilities to adopt similar water reuse practices. Furthermore, showcasing environmental stewardship can enhance employee morale and attract talent that values sustainability-focused workplace culture. Lastly, this system may also lead to creation of new roles related to system maintenance and monitoring, contributing positively to local employment opportunities and supporting community well-being.

Conclusion & Future Recommendations

To conclude, to prevent the continued wastage of water from Newterra's FAT procedure, a water recycle and recirculation system was designed which utilized GAC filters, nanofilters, UV, chlorine treatment, and featured 8 access points throughout the warehouse that would allow for convenient access to the water. To ensure the success of the design, and more specifically, the effectiveness of the GAC filter, a prototype was built. The prototype was used to compare the proficiency of how well oil could be filtered by the two different mesh sizes of the GAC filters provided by Newterra. Based on the findings from the water tests we conducted from the water samples from the prototype, it was found that the 8 x 30 produced better results. The environmental, social, and economic factors were researched and evaluated. Much of our water quality goals were guided by Ontario's water, safety, health, and technical standards. While the capital investment is high, due mainly to the high cost of water tanks and other expensive materials, the expected water savings are significant. Further consideration was also applied to the long-term operation of this system through a maintenance schedule, FMEA evaluation, and a cost analysis. With our proposed design, we are hoping to make long term, sustainable, and impactful change to Newterra's water usage and water waste to create a greener tomorrow for future generations.

There is a great amount of room for future research and improvement for this design. What was most prominent for us was that our original design featured a ceramic filter, but we struggled to find solid evidence for its worthwhile inclusion. So, through either additional research or actual testing, it should be verified if a ceramic filter could add substantial value to the system or not. There is a great amount of room for future research and improvement for this design, particularly to test new configurations of the filters. Additionally, testing different GAC materials, could provide further insight and optimization into the filtration process, potentially reducing the need for as many filters downstream. Further testing could improve the precision of the maintenance schedule, in particular to be adapted to the level of contaminants that Newterra would treat in its water. As for testing other filters, in our design presented in BREE 490, we featured a ceramic filter within the outdoor storage tank. However, a lack of literature on the topic resulted in us removing the filter from the final design. Further testing in this area could provide another outlook for our design.

Appendix A. Figures

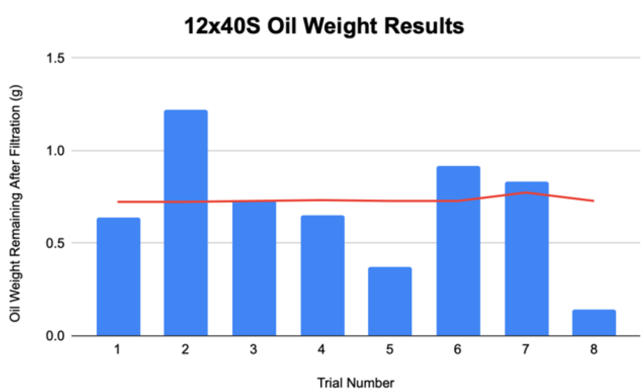

Figure A.1. 12x40 Oil Weight Results

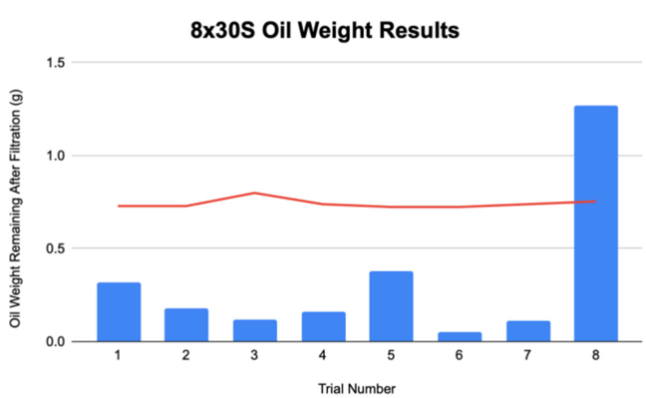

Figure A.2. 12x40 Oil Weight Results

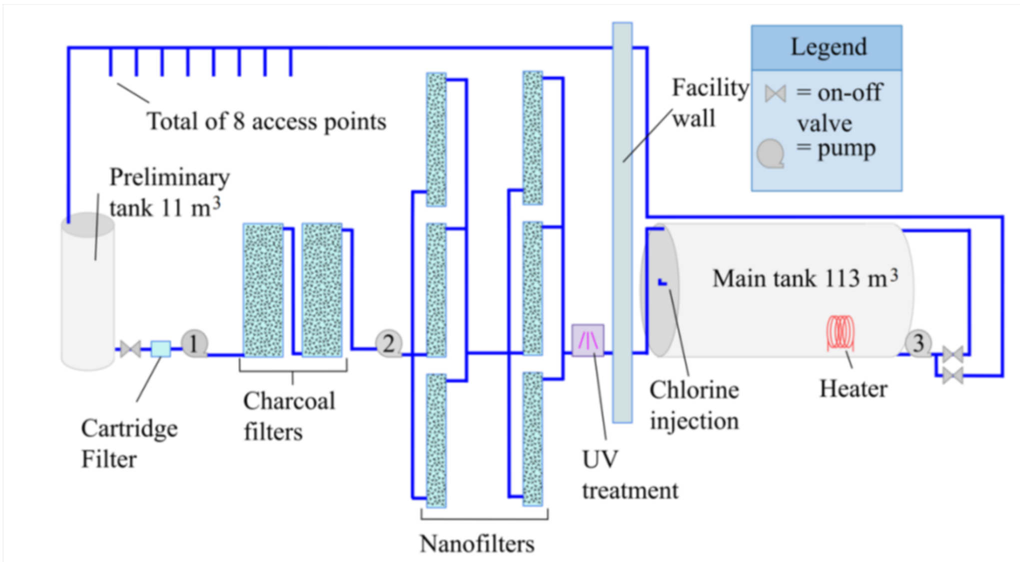

Figure A.32. Layout of proposed water recirculation system

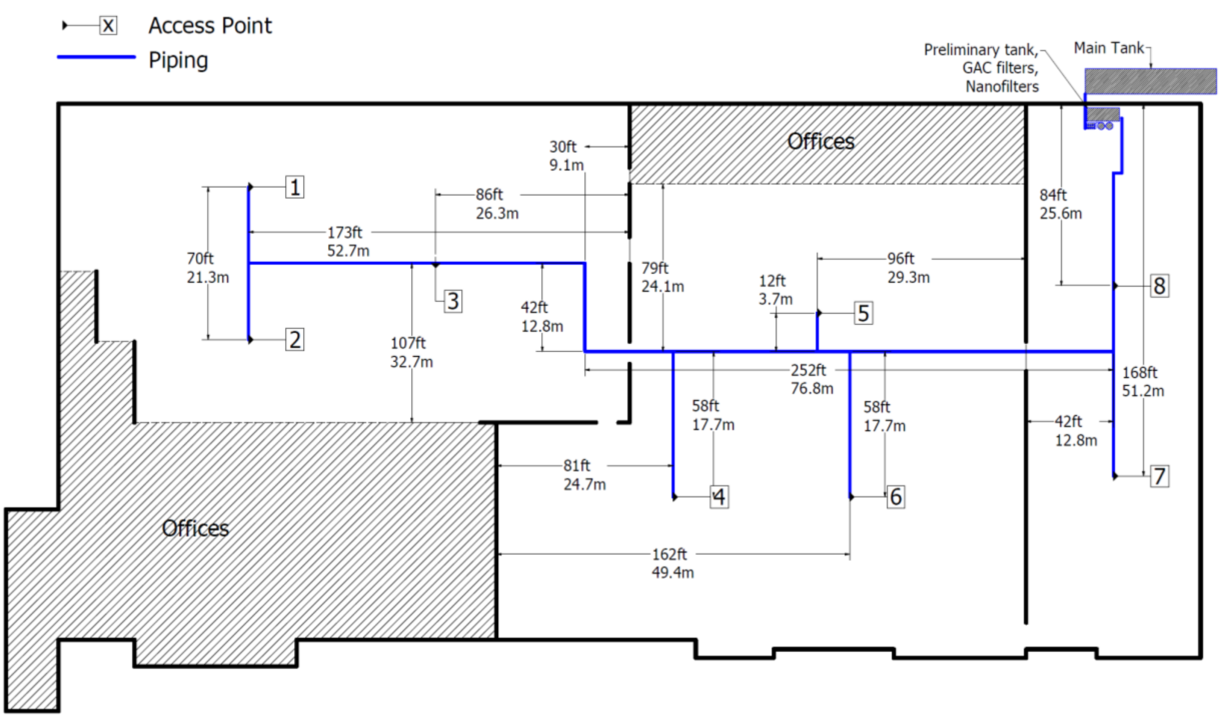

Figure A.3. Piping Layout in Newterra Facility Layout of the proposed recirculation network

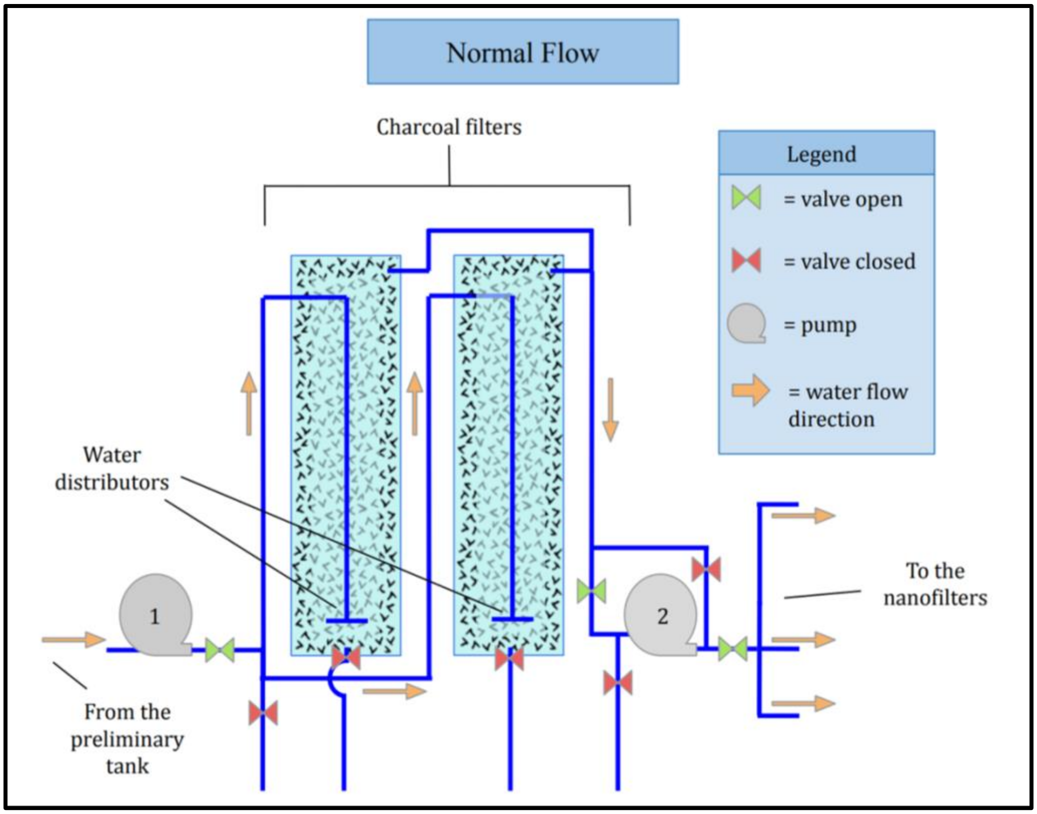

Figure A.54. The normal (non-backwash) flow of water through the piping of the charcoal filters

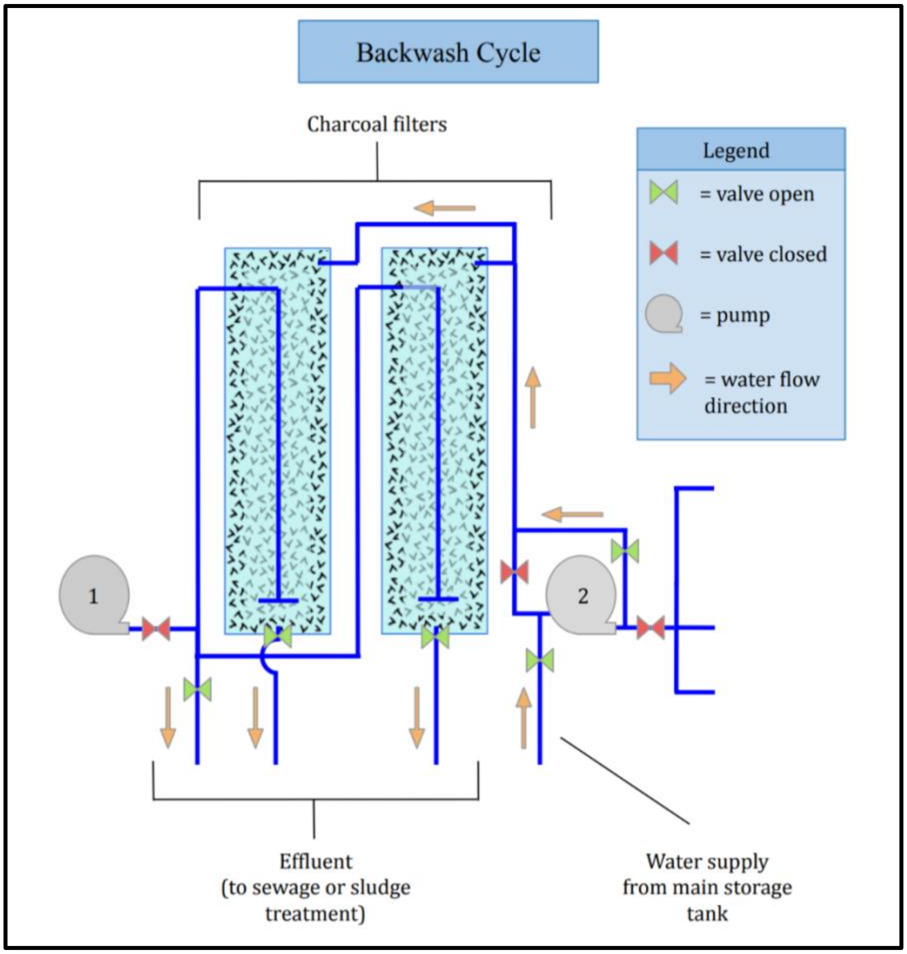

Figure A.5. The backwash flow of the water through the piping of the charcoal filters

Figure A.6. Aeriel view of the Newterra facility including location of outdoor tank. (Google Maps)

Appendix B. Tables

Criteria	Importance	Carbon Block Filter	Biochar Filter	Anion Exchange	Nanofiltration	GAC	Ceramic
Speed	4	3	2	2	1	3	4
Cost	3	2	1	2	2	3	3
Maintenance	2	2	2	1	1	1	2
Metals?	5	4	4	5	5	5	4
Greases?	5	4	3	1	5	5	1
Microbes?	5	2	4	1	5	2	4
Final Score		72	70	51	87	83	74

Table. B. 1. Pugh Matrix

Standard/Code	Requirement
SOR/86-304	Federal Occupational Health and Safety Regulations
OSHA Ontario O. Reg. 297/13 O. Reg 420/21 O. Reg 213/91	Ontario Occupational Health and Safety OHS Awareness and Training Reporting Critical Injuries and Incidents Construction Project Safety

R.R.O 1990, Reg. 860	Workplace Hazardous Materials Information System (WHIMIS)
R.R.O 1990, Reg. 851	Industrial Establishments, Emergency Response, PPE
Ontario Fire Code O.Reg 213/07 20.2	Storage provided for a minimum 30 of days consumption of chemical

Table. B. 2. Occupational Health and Safety Standards

Contaminant	Limit
E.Coli	0 CFU/100 mL
Chromium	0.05 mg/L
Nickel	70 ug/L
Chloramines	3 mg/L
Chlorate	1 mg/L
Chlorite	1 mg/L
HEM (oils and greases)	0

Table. B. 3. Maximum Contaminant Levels Outlined in the Ontario Safe Water Drinking Act

Code/Section	Requirement
NRCC 96193	National Plumbing Code of Canada (NPC)
Ontario Building Code 7.1.5.1 7.6.1.2 7.6.1.3 7.6.1.9 7.7.4.1	All components in contact with chlorine must be certified Outdoor piping must be protected against freezing Shut off valves provided downstream of the tank/intake point. Outdoor pipes must be equipped with a shut-off valve inside the building Must conform with CSA B128.1-06
CSA B128.1-06	Design and Installation of Non-Potable Water Systems
Environmental Protection Act, R.S.O 1990 c.E 19 O. Reg 224/07	Spill Protection and Contingency Plans
City of Brockville's Drainage Bylaw 033-2014, 066 - 2005	Must conform to stormwater management and drainage plans

Table. B. 4. Plumbing codes summarized

Material or component	Standard
PVC Pipes	ASTM D 1784 / CSA B137.3
Plumbing fittings	ASME A112.18.1/CSA B125.1
Pipe flange fittings	ASME B16.5 2017

PVC Pipes and fittings	CSA B137.6-17
Process Piping	ASME B31.3
Chlorinated PVC	ASTM F441

Table. B. 5. Mechanical Codes Summarized

Tank diameter	/183	Surface area in	Volume in per 2.5ft bed depth	Filter rate at 5 gpm/ft	Backwash rate at 12 gpm/ft
30	900/183	4.92	12.30	24.5	59.0
36	1296/183	7.08	17.7	35.4	85
42	1764/183	9.64	24.1	48.2	115.7

Table. B. 6. GAC Tank Diameter Sizing, Adapted from Wirth, 20121.

Trial	Oil Residual After Analysis (g)
1 (12 x 40)	0.81
2 (12 x 40)	0.565
3 (8 x 30)	0.195
4 (8 x 30)	0.4525

Table. B. 7. Results of GAC prototyping

Element	Maintenance Task	Recommended Frequency
Carbon Filters	Replacement of GAC media	Once every 6 months
	Backwashing	Weekly
Sensors (temperature, chlorine, tank level)	Calibration	Weekly
Disinfection	Replenishing sodium hypochlorite stock	Once every 110 days
	Replacing UV lamp	Once every 2 years
Tank	Inspection	Annually
	Cleaning	Once every 3-5 years
	Heater servicing	Annually
Pumps	Pump servicing	Quarterly
	Seal replacement	Annually
Nanofilters	Filter replacement	Every 3 years

Table. B. 8. Maintenance Table

Component	Failure Mode	Failure Causes	Failure Effects	Severity (1-10)	Occurrence (1-10)	Detection (1-10)	RPN	Recommended action
Storage tank	Overflow	Water level too high	Water leak	5	4	2	40	Install overflow alarm
Storage tank	Rupture	Material fatigue, poor sealing, corrosion	Water leak, flooding, test interruption	7	2	2	28	Use corrosion resistant materials, regular check

Storage tank	Water freezes	Insufficient heat to system, winter	Damage to system, inability to use	8	2	4	64	Insulate and install immerse heaters.
Piping system	Piping blockage	Filtration rate insufficient	Reduced flow, system shutdown	8	3	4	96	Regular filter maintenance, filter redundancy and preliminary holding tank
Piping system	Leak at fittings	Wear out, poor joint installation	Water leak	6	2	2	24	Regular check-up and thread sealant
Valves	Stucked	Mechanical wear, filtration rate insufficient	Flow control loss	7	3	3	63	Regular valve testing and maintenance
Pumps	Dry running	Faulty sensor input	Pump damage	7	3	3	63	Regular check-up and install low-level cut-off switch
Pumps	Clogging	Filtration rate insufficient	Reduced flow rate, overheating	6	3	4	72	Regular filter maintenance
Sensors	Sensor malfunction	aging sensors	False readings, unsafe operation	9	2	6	108	Regular calibration
Water reuse	Bacteria growth	Inadequate disinfection, water hold for too long	Odor, health risk	9	3	4	108	Chlorine and UV disinfection
Chlorine injector	Chlorine levels too high/low	Chlorine decomposition rates over-/underestimated	Potential microbial activity and health risk to workers	10	2	4	80	Automatic chlorine injection system coupled with chlorine sensor
Manual handling	Direct contact to contaminated water	Human error, water pressure too high	Health risk to operator	10	3	5	150	Mandatory safety training, labels, slash guards

Table. B. 9. FMEA Analyis

Item	**Vendor**	**Unit name**	**Cost per Unit (CAD)**	**Quantity**	**Sum (CAD)**
Pump 2	Grundfos	CR 5-7 A-B-A-V-HQQV	4500.00	1	4500.00
Pumps 1 & 3	Grundfos	CRE 5-2 A-FGJ-A-E-HQQE	5500.00	2	11,000.00

Charcoal GAC Filters	General Carbon Corporation	GC 8 x 30S	1.79/lb	1375 lbs/unit 2 units	4,922.50
Nanofilter	Canadian Water Warehouse	Filmtec NF90-400/34i Nanofiltration Membrane Element 10,000 GPD (8.0" x 40")	2,120.33	6	12,721.98
Cartridge filter	Shelco Filters	Microvantage 4HP3	5569.08	1	5,569.08
Piping	McMaster-Carr	Standard-Wall Plastic Pipe for Water	16.29	82	1,335.78
Preliminary Tank	Granby Composites	10ft diameter for 30,000 US gallon capacity (NN10331171)	93,266.08	1	93,266.08
Outdoor Tank	Granby Composites	6ft diameter for 3,000 US gallon capacity (NN06090115)	21,415.58	1	21,415.58
Chlorine Injection System	Hydro Instruments	Series LFOV Sodium Hypochlorite Feed System	4,500.00	1	4,500.00
Chlorine Sensor	Endress + Hauser	Flowfit CCA250-M0	1,286.69	1	1,286.69
Sodium Hypochlorite	Lab Alley	Sodium Hypochlorite 12.5% Solution	121.00	1	121.00
UV System	VIQUA	Viqua 650653 UVMax PRO20	3,485.00	1	3,485.00
Immersible heaters	Wattco	2.5” Flanged Immersion Heater, FLC305X2016T 5kW, 16” flange	1,145.00	1	1,145.00
Total Cost					**165,268.69**

Table. B. 10. Cost analysis

Operation	Cost (CAD)
Pumps	158.52 per FAC test
Heaters	658.80 per year
UV	119.56 per year
Chlorine Injection System	85.50 per year
Sodium Hypochlorite	401.50 per year

Table. B. 11. Operational Costs

Tank diameter	D^2/183	Surface area in ft^2	Volume in per 2.5ft bed depth	Filter rate at 5 gpm/ft	Backwash rate at 12 gpm/ft
30	900/183	4.92	12.30	24.5	59.0
36	1296/183	7.08	17.7	35.4	85

42	1764/183	9.64	24.1	48.2	115.7

Table. B. 12. Backwashing rate, Adapted from Wirth, 2012

Highest pH	**Lowest Water Temperature for K Factors**		
	>10°C	**7.2°C**	**<4.4°C**
6.5	4	5	6
7	8	10	12
7.5	12	15	18

Table. B. 13. K Values for Chlorine Contact Time, adapted from https://www.knowyourh2o.com/indoor-4/chlorine-disinfection-contact-time-basic

Appendix C. Equations

C.1. Relevant Theories and Equations

C.1.1. Fluid laws

When analyzing the pressure and velocity of a fluid as it moves through a pipe, a useful relationship is Bernoulli's principle:

$$p_1 + \frac{1}{2}\rho v_1^2 = p_2 + \frac{1}{2}\rho v_2^2$$

Equation 4

p = *pressure*

ρ = *density*

v = *velocity*

This equation shows that as the velocity of a fluid increases, the pressure decreases.

C.1.2. Carbon Filter Loading Rates

Given Granular Activated Carbon's unique pore structure, GAC can remove high amounts of organic content per unit weight. This is attributed to their high surface area and large degree of porosity. The adsorption capacity is related to the contaminant composition, water temperature, and particle mesh size.

C.1.3. Empty Bed Contact Time

The design of a carbon filter is based off the Empty Bed Contact Time (EBCT), a hydraulic flow rate measured in minutes. The EBCT provides a minimum value to which the water must remain in contact with the carbon media before being treated.

$$V = Q \cdot EBCT$$

Equation 5

V = Volume

Q = Flow rate

EBCT = Empty bed contact time

C.1.4. Hydraulic loading rates

Common hydraulic loading rates for filters are 5 gpm/ft^2 and are a function of the filter surface area. To determine filter surface area:

$$Surface\ Area = \frac{Q}{Loading\ Rate}$$

Equation 3

Q = 0.001262 m^3/s

Loading rate = 5 gpm/ft^2 for the GAC media used in the design (General Carbon Co, n.d.)

C.1.5. Backwash flowrate

Backwashing is a method of cleaning clogged filters through reversing the flow of water and increasing the velocity through which it passes in filter media. Backwashing dislodges contaminants from the media and ensures that the filter can run longer and more efficiently. Backwash velocities are given by Table 12. 40 psi pumps are adequate for industrial backwashing. However, the tank dimensions must account for the bed expansion that occurs as we reverse the flow. In general, filters should allow for 30% bed expansion, but the freeboard should be at least 50% to ensure that the media is not lost.

Using Table B.12., the filter tank diameter can be calculated.

C.1.6. Heater calculations

$$Q = \frac{A \cdot \Delta T}{RSI}$$

Equation 2

Q = Heat loss of the system (Watts)

A = Surface area of the tank provided by Granby Composites

T = Temperature difference between water at 4°C (target temperature) and air at -18°C

R = RSI -value of polyurethane

$$N = \frac{1.5Q}{5kW}$$

Equation 3

N = Number of heaters required

In the case of the Granby Composites tank, the calculations are as follows:

Surface area = 185.983 m^2.

Δ Temperature = 22°C

RSI = 4.3688 m^2 * °C/W

$$Qloss = \frac{185.9\ m^2 \cdot 22°C}{4.3688\ \text{m\^{}2} * \text{°C/W}}$$

$$Qloss = 936.13\ W$$

$$N = \frac{1.5Q}{5kW}$$

$$\text{N} = \frac{1.5 \cdot 177.41\ \text{W}}{5\text{kW}}$$

N = 1 heater

C.1.7. Contact Time Calculations

$$Contact\ time\ (minutes)\ =\ K/\ chlorine\ residual\ (mg/L)$$

Refer to table 13 for table of K values for chlorine contact time.

C.1.8. Chlorine demand

We assume a constant rate of chlorination (24 hours per day) to simplify the calculations and to provide an outlook on to the minimum number of days.

$$Chlorine\ demand\ per\ day\ =\ 0.3\ mg/L\ x\ 113{,}562\ L\ =\ 22{,}712\ mg/day$$

$$12\%\ NaOCl\ =\ 125{,}000\ mg/L$$

$$Total\ chlorine\ in\ 20\ L\ =\ 125{,}000\ mg/L\ x\ 20\ L\ =\ 2{,}500{,}000\ mg$$

$$Days\ =\ 2{,}500{,}000/\ 22{,}712.4\ mg/day\ =\ 110.07\ days$$

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