UBC Social Ecological Economic Development Studies (SEEDS) Student Report

Grey Matters: Turning Rainwater into Greywater

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Abstract

Preserving what resources we have is a goal that we should all achieve no matter how abundant the resources may seem. In this case, it is water. The new Student Union Building (SUB) at the University of British Columbia (UBC) strives to achieve such a goal by including a rainwater harvesting and filtration unit. This report's purpose is to analyse different filtration and disinfection options for the rainwater systems so that water can be used for greywater purposes. A Triple Bottom Line assessment that takes into account environmental, economic and social impacts will be used to determine the best option.

The water filtration methods considered include sand filtration, reverse osmosis, ultrafiltration, and microfiltration. The water disinfection methods considered include distillation, chlorination, ozone, and ultraviolet (UV) light. Based on our results, we recommend an implementation of microfiltration and UV radiation as the ideal method to treat rainwater to form greywater.

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Glossary

Cistern: A waterproof receptacle for storing rainwater. It ranges in capacity from a few litres to thousands of cubic metres, effectively forming covered reservoirs.

Dimer: A chemical unit formed by two separate subunits bonding together. This bonding causes the unit to behave differently than the parent structures.

Disinfection: A process that destroys microorganisms on non-living objects. Disinfection does not necessarily kill all microorganisms, especially non-resistant bacterial spores; it is less effective than sterilisation, which is an extreme physical and/or chemical process that kills all types of life.

Greywater: Greywater is wastewater generated from domestic activities such as laundry, dishwashing, and bathing, which can be recycled on-site for uses such as irrigation.

LEED: Leadership in Energy & Environmental Design (LEED) is an internationally recognized green building certification system, providing third-party verification that a building or community was designed and built using strategies intended to improve performance in metrics such as energy savings, water efficiency, CO_2 emissions reduction, improved indoor environmental quality, and stewardship of resources and sensitivity to their impacts.

Pathogen: An infectious biological agent, such as a virus, bacteria, prion, or fungus that causes disease to its host.

Potable: Safe to drink.

Transmembrane Pressure: The difference in pressure between the filtrate side of the membrane and the permeate side of the membrane. The transmembrane pressure is the driving force for the membrane separation. In general, an increase in the transmembrane pressure increases the flux across the membrane.

SUB: Student Union Building.

1.0 Introduction

The eastern coast of Canada was once teemed with the golden fins of the Atlantic cod. They were so plentiful that it was said that you could scoop them up into a ship with buckets. It was so much so that the pioneers of the age deemed the land “la Bra D'or”; the arm of gold. Now, the Atlantic cod is listed as 'vulnerable' on the IUCN Red List of Threatened Species[1]. Resources on this planet are finite. There is only so much that the Earth can bounce back from, particularly in the face of human activity. No matter how abundant a resource might seem today, in a few years from now it could become a precious commodity.

Fresh water is one of the most essential needs of the human species. 97.5% of all the water available on the Earth is salt water and unsuitable for use. Of the 2.5% that is fresh water, 70% of it is locked up as ice in the polar ice caps. This leaves less than a percentage of the Earth's water supply available[2].

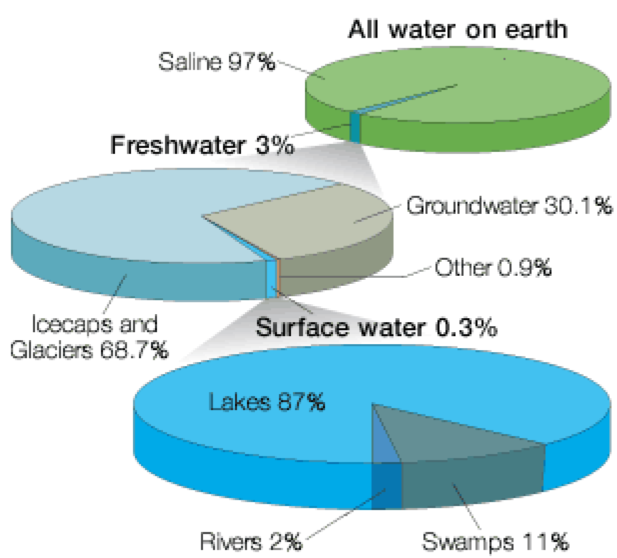

Figure 1. Distribution of Water on Earth[3]

All of humanity is dependant on this tiny fraction of fresh water for its survival. However, as the world's population increases, the demand of water also increases, but the available supply is decreasing due to pollution. This is why the development of sustainable practises is crucial. It is critical to the health of the planet and to future generations that we learn to preserve and use wisely what resources we have.

This report will address the budding technology of rainwater harvesting and filtration. It will provide an explanation of the topic as well as various methods on how to achieve the objective of obtaining rainwater suitable for human usage. A case study of the CK Choi building which already has a rainwater filtration system in place will be discussed. In addition, a rainwater filtration system for the new Student Union Building (SUB) will be proposed in detail using the specifications detailed by the project stakeholders. A triple-bottom line analysis will be conducted to determine the costs and benefits of the project.

Recommendations backed by quantitative values in order to propose a particular kind of rainwater filtration and disinfection system for the new SUB will be provided in the body of this report. Other aspects of the harvesting system such as catchment and storage are outside the scope of this report and will be covered by other groups of the APSC 262 course. From multiple meetings with UBC SUB stakeholder Andreanne Doyon, the specifications of the system were obtained. It is noted that the new SUB aims to be certified LEED Platinum; the highest standing of sustainable design. In order to achieve this, the maximum number of LEED points must be obtained. This is important as more points can be obtained if no chemicals such as chlorine are used in the system. Additionally, the water obtained through this proposed system is not required to be potable. The main use of this grey water is for the irrigation of the rooftop garden and for flushing toilets.

2.0 Background

Rainwater harvesting is the accumulation, treatment and storage of rainwater. It can be used to provide drinking water for both humans and animals, crop irrigation and for washing purposes. Rainwater has many useful traits that making its collection desirable. In most places of the world, it is almost neutral in pH, contains no dissolved salt or minerals and is free of contaminants[4]. The collection of rainwater for human use is an ancient technique that is currently making a resurgence in the Western world as a part of a water conservation effort. In recent times, it has been widely regarded as foolish to use potable water from purposes that do not require it such as toilet flushing. Rainwater harvesting is common in many areas of the world such as Brazil, China and Thailand[5].

There are many advantages to rainwater harvesting and can be easily integrated into existing systems. Rainwater can be collected from roofs and therefore would not require additional land usage, simply using what is already available to accomplish its goal. It can also ensure an independent water supply during times of water restrictions. In addition, utilizing available rainwater instead of pulling water from the city reservoirs can reduce the cost of utilities as well as reducing water demand. This latter benefit is especially important in places where water is not abundant.

2.1 Feasibility

In British Columbia, rainwater harvesting can be used as a sustainable practise to provide an alternative source of water to supplement low volume wells that dry up in the summer and places with limited piped water supply or poor quality groundwater[6]. In addition, rainwater harvesting can be a very good emergency precaution in the case of fires and earthquakes where piping infrastructure could suffer damages and otherwise limit the available water supply. With the interest of sustainability in mind, there are many other uses that collected rainwater to go towards. Rainwater does not necessarily have to be made potable, which is a costly process. Rainwater is very useful for things such as flushing toilets, washing clothes and cars as well as watering a garden. In British Columbia, these activities take up half of a household's water usage. Toilet flushing alone accounts for 30% as seen in Figure 2. All of this currently uses potable water which is not necessary. Grey water obtained from rain would be more than sufficient to meet the demand.

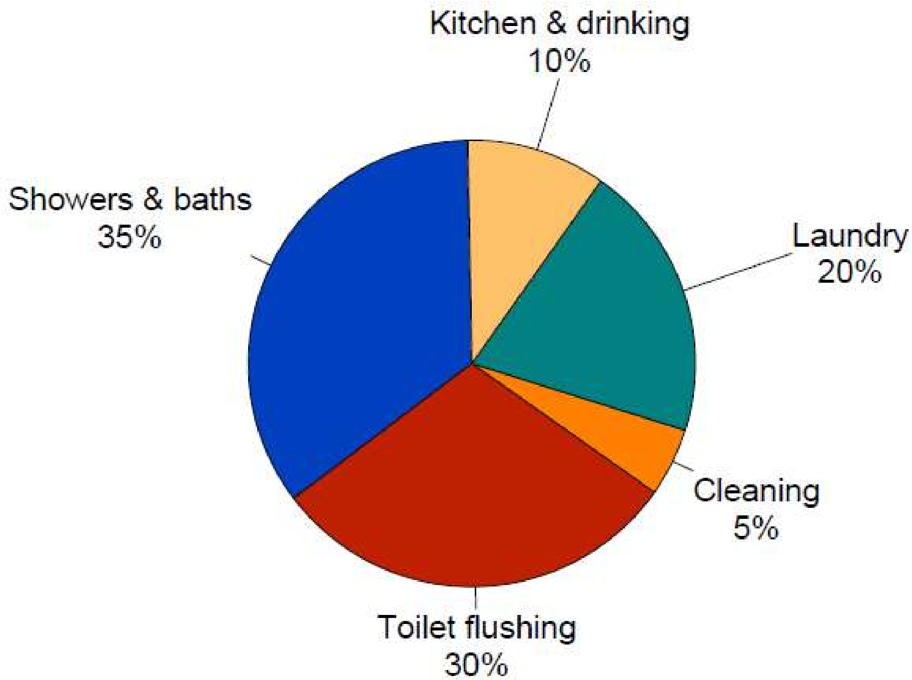

Figure 2. Residential Water Use in BC[7]

For a non-commercial rainwater collection system to be cost-effective, the average annual rainfall in the area of instalment should be greater than 200 mm[8]. Figure 3 outlines the typical rainfall pattern at UBC Vancouver.

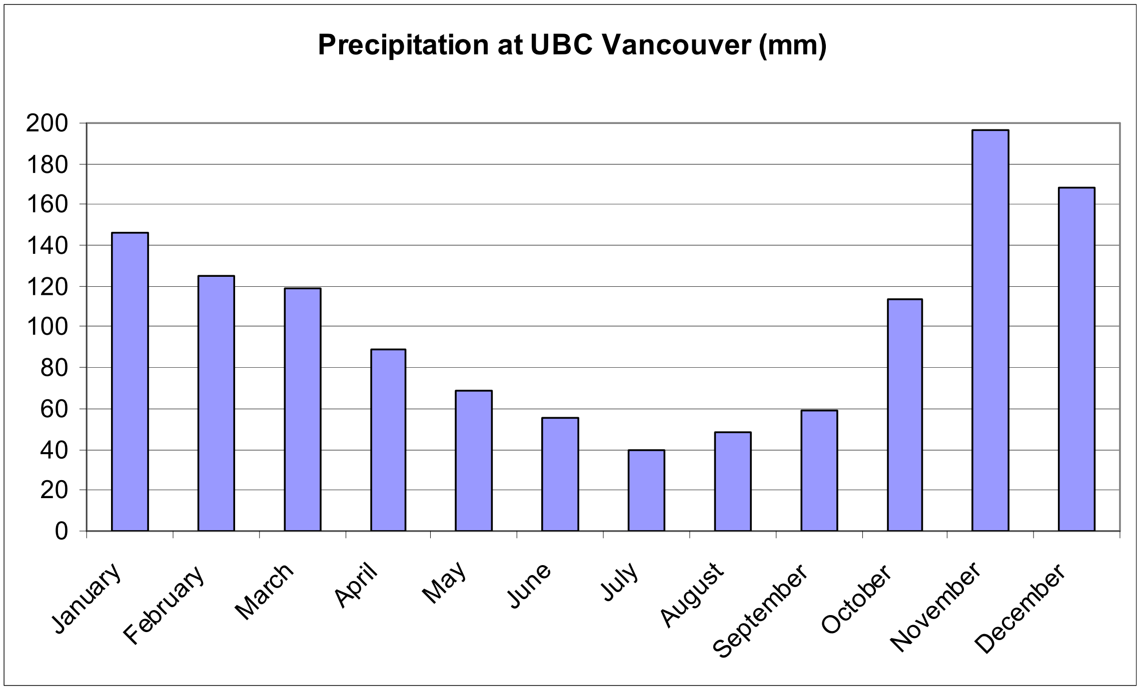

Figure 3. Average Precipitation at UBC Vancouver[9]

Over the span of a year, UBC Vancouver receives 1200 mm of rainfall. This is six times greater than the minimum requirement as dictated by economics. This substantial volume of rainfall implies that large water savings are possible as the utilization of rainwater can replace that of potable water in circumstances which do not require fresh water.

Additionally, is should be noted that rainwater harvesting is legal in all provinces of Canada[10]. In the states of Colorado, Utah and Washington[11], rainwater diversion of any sort is illegal. No permits are required to install and use a rainwater harvesting system in the province of British Columbia.

2.2 LEED Requirements for Water Efficiency

With the average rainfall on UBC campus being 1200 mm a year, the new SUB project will attempt to maximize water efficiency to help achieve their goals of being a LEED Platinum structure. LEED, Leadership in Energy and Environmental Design, is an internationally renowned green building certification system built using strategies to improve performance such as energy savings, water efficiency, CO_2 emissions reduction, among other metrics. LEED offers a point system by which they grant a structure their certification. These certifications are[12]:

- Certified - 40 - 49 points
- Silver - 50 - 59 points
- Gold - 60 - 79 points
- Platinum - 80 points and above

LEED provides 5 credits for reducing indoor water use which are outlines in Table 1. WEc1 – Water Efficient Landscaping rewards projects for reducing or eliminating potable water use for irrigation. WEc2 – Innovative Wastewater Technologies rewards projects that reduce generation of wastewater from fixtures such as toilets and urinals. WEc3 – Water Use Reduction rewards projects that reduce demand for all indoor water fixtures including showers, lavatories, kitchen faucets, toilets, and urinals[13].

	% Savings	LEED Points
WEc1 - Irrigation	50%	1
	100%	2
WEc2 (flush fixture water savings)	50%	1
	100%	2
WEc3 (total fixture water savings)	20%	2
	30%	3
IDc1 (exemplary performance WEc3)	40%	4
IDc1 (process water savings)	10% of WEc3 baseline	1

Table 1. LEED Points Available For Water Efficiency

2.3 Case Study: The C.K. Choi Building

The C.K. Choi building is a highly sustainable building located in the University of British Columbia. It showcases many innovative design features that enable it to conserve energy, water, and materials. This includes a multiple water-saving features that enable it to be completely independent from the campus' sewer connection[14]. One prominent feature is the collection of rainwater on its roof. The water is then stored in an 8,000 gallon (30 m^3) subsurface cistern[15]. The results of these sustainable features led the building to win many awards, including the 1996 Earth Award from the Building Operators and Managers' Association of B.C. and the Progressive Architecture Award for Green Architecture in 1995[16]. The entire project cost $6 million[17].

Given the huge successes of the C.K. Choi Building, it would be ideal to bring some of its features to the new SUB and improve on them, too. Any excess rainwater from the heavy Vancouver rains can be diverted in the campus' stormwater system[18]. The rainwater collected in the C.K. Choi Building is solely used for irrigation. The water collected by the new SUB will also be non-potable. However, we can introduce more advanced ways of treating the water such that the water can be used for more applications (such as in the flushing of toilets). Through this, we can further reduce the usage of potable water - only the building's drinking and cooking water supply will require it.

The new SUB will have approximately six times as much total assignable space as the C.K. Choi Building[13, 17]. It is hence ideal that the cistern in the new SUB be larger by a factor of six. This will ensure that the cistern will store enough water the increased usage.

3.0 Rainwater Filtration and Disinfection

Before rainwater can be used for domestic purposes, it must first be treated to remove particulates and other undesirable matter. The degree of treatment is dependant on what the end use of the water will be. As seen in Figure 4, rainwater filtration system consists of four main parts; collection, filtration, disinfection and storage.

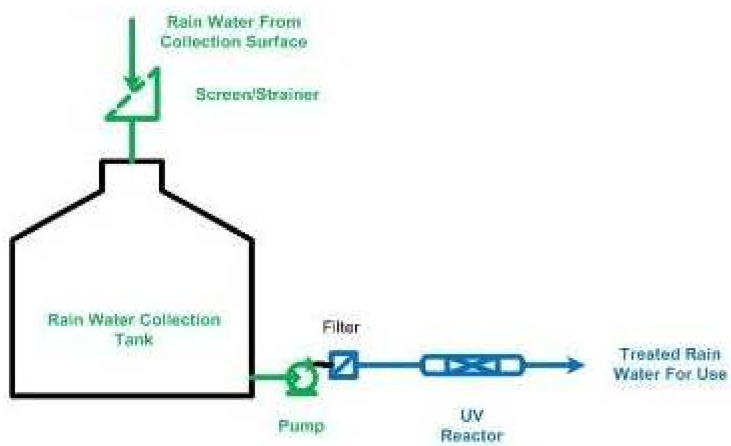

Figure 4. Rainwater Treatment Schematic[19]

Rainwater is collected from a surface, typically a rooftop. The roof must be designed such that rainwater does not pool on the surface, but is instead shunted to the gutters to enter the treatment and storage system. Filtration can be completed via a variety of methods. Its purpose is to remove particulates and eliminate turbidity in the treated water. Additionally, it can also serve the function of initial pathogen removal. However, the next step usually serves this purpose. Disinfection destroys any remaining pathogens from the water. Since the supply of rainwater is often not in conjunction with demand, excess rainwater must be stored in a cistern.

3.1 Statistics of the New SUB

The SUB is the most heavily trafficked area in the entire UBC campus, servicing the student population which has since exceeded 45,000 individuals. Due to the increasing expanding growth of the student populace over time, it is becoming rapidly evident that the aging facilities are insufficient in meeting student needs. Additionally, the current SUB is over 40 years old and is beginning to show signs of wear. In 2007, a committee was formed to solve this problem and the decision was made to build a new SUB[20].

This vision of this new SUB is to not only meet the needs of the students, but also to stand as a model of sustainability. In order to achieve this objective, it has been decided that the installation of a rainwater collection system be integrated into the design of the building. This system will help reduce the demand of municipal water by providing a source of greywater. The new SUB is projected to last 100 years[21] and so the system chosen for this purpose must have either an equal lifetime or be easily upgradeable. The budget for the new building is $103 million[20].

The total roof area of the new SUB is 5439 m^2, but only half of it will be available for rainwater capture[14]. This catchment process is calculated to be 75% efficient in achieving its objective. Since the annual precipitation in the UBC Vancouver area is 1200 mm, according to the equation in Figure 5, the annual volume of greywater obtained by this system will be 2500 m^3. This volume will be sufficient to cover 100% of the flush fixture demands of the SUB. A detailed breakdown of the water consumption calculation is presented in Appendix A.

Captured Rainwater [m^3] = Annual Precipitation [m] x Catchment Area [m^2] x Efficiency

Figure 5. Calculating Captured Rainwater Volume

In order to utilize rainwater for 100% of the flush fixture demand, a cistern size of 1100 m^3 would be required. A large cistern size is necessary because greywater must be stored during the winter months for use in the summer months where less precipitation falls. However, if rainwater is used for only 50% of the flush fixture demand, a cistern size of 22 m^3 would be adequate. This is a more reasonable alternative as the savings obtained by 100% use would be dwarfed by the capital cost involved with installed a large cistern. This cistern will be made of concrete. It is suggested that the concrete base be lined with fibreglass as water stored in a concrete basin has a tendency to have an unpleasant taste. Additionally, the fibreglass lining can be replaced as necessary and unlike polypropylene; it does not react with UV light[22]. This is important as UV irradiation systems are commonly used to disinfect greywater. The cost of installing this cistern is approximately $7000[23].

3.2 Filtration Methods

The methods of filtration we have considered include: sand filtration, reverse osmosis, ultrafiltration and microfiltration. These four methods provide the amount and credibility necessary to achieve maximum LEED points.

Sand Filtration

Sand filtration is a non-pressurized system that uses biological processes to filter the water. Its benefits include using no electricity, little to any mechanical power or chemicals and they require minimal operator training and periodic maintenance[24]. It can be used to create potable water, a solution that is not necessary, but certainly a benefit. However, sand filtration is very slow. The amount of water being filtered accumulates from 0.1-0.2 $m^3/m^2/hr$.[24] The flow rate required by the new Student Union Building is greater than 0.85 m^3/hr.[13]

Reverse Osmosis

Reverse osmosis is accomplished by pressurizing water forcing it to move from higher concentration to lower concentration. Water then passes through a membrane while moving to lower concentration creating filtered water. Water flow can be regulated by the pressurized system and the recovery of purified water depends upon various factors including: membrane sizes, membrane pore size, temperature, operating pressure and membrane surface area. This process is used to provide drinking water for many countries around the world[25]. The capital costs of reverse osmosis include the cost of electricity and the cost of membrane replacement and labour[26].

Ultrafiltration

Ultrafiltration uses semi-permeable membranes to which hydrostatic pressure is applied forcing suspended solids and solutes to be retained and allowing water and molecules smaller than the membrane to pass. There are also systems in which pressure is not applied and the system is immersed where pressure is applied by the pressure from the feed column. Practical uses for ultrafiltration include dialysis of blood treatment and fractionation of protein[27].

Microfiltration

While the fundamentals are virtually equivalent to ultrafiltration, microfiltration does not require pressure to function. It uses a microporous membrane size of 0.1-10 μm to filter typical solids, solutes and pathogens like oocysts, cysts and large bacteria[28]. These particulates are retained by the membrane which requires periodic cleaning by maintenance staff.

3.3 Disinfection Methods

After the filtration of rainwater, a disinfection method must be in place to ensure that no pathogens grow in the stagnant water held in the cistern. The methods considered for disinfection include: distillation, chlorination, ozone and ultraviolet light.

Distillation

Distillation is the process whereby mixtures are separated based on differences in their volatility in a boiling liquid mixture. Industrial distillation focuses on a continuous distillation process as mixture is put into the tank. The process is commonly used for removing nitrate, bacteria, sodium, hardness, dissolved solids, most organic compounds and heavy metals from water. The distillation equipment also requires space to accompany the cistern. It also requires constant supervision and maintenance. Economically, it is not appropriate for uses like flushing toilets, bathing, washing clothes and cleaning[29]. While a household distiller costs $200-$1500, to maintain the cistern will ensue great cost and using a continuous process will add more to the electricity bill.

Chlorination

Chlorination is a fairly common practice in disinfection of pools and sewage plants. The process requires the addition of chlorine to water to disinfect stagnant water. However, LEED points are given for not using a chemical disinfection method as it is harmful for the environment[13]. Chlorine can be used as a residual disinfectant for other methods, as well.

Ozone

Ozone is very effective in inactivating pathogens that form cysts and especially *E. coli*. Ozone is made by passing oxygen ultraviolet light or other electrical discharges. It must be added by bubble contact and made on-site[30]. Its main disadvantage is that it leaves behind no residual disinfecting properties. This will force a second residual disinfectant so that the water does not form pathogens as time progresses.

Ultraviolet Light

Similar to ozone, ultraviolet light is very effective at inactivating cysts and is best used in low turbidity water[31]. It can be applied using tubular lights and does not have to make contact with the water. However, like ozone, there is no residual disinfection which can be added should the water not be used for days.

3.4 Proposed Method

In the case of the new SUB, it is proposed to first filter the rainwater via microfiltration then disinfect the water with UV irradiation. Leaf gutters installed on the roof will be the preliminary screening device to remove out any large materials. After the water flows down from the roof into the gutter system, it will pass through a series of filters of decreasing pore size. Filters are designed to physically block objects that are larger than the pores from passing through the layer. Substances with dimensions smaller than the pore size can pass freely through the filter.

A cross-flow microfiltration system is suggested to perform this separation of particulates from the rainwater. A cross-flow configuration means that the flow of the water into the system is tangential to the membrane layer as seen in Figure 6, rather than flowing perpendicularly.

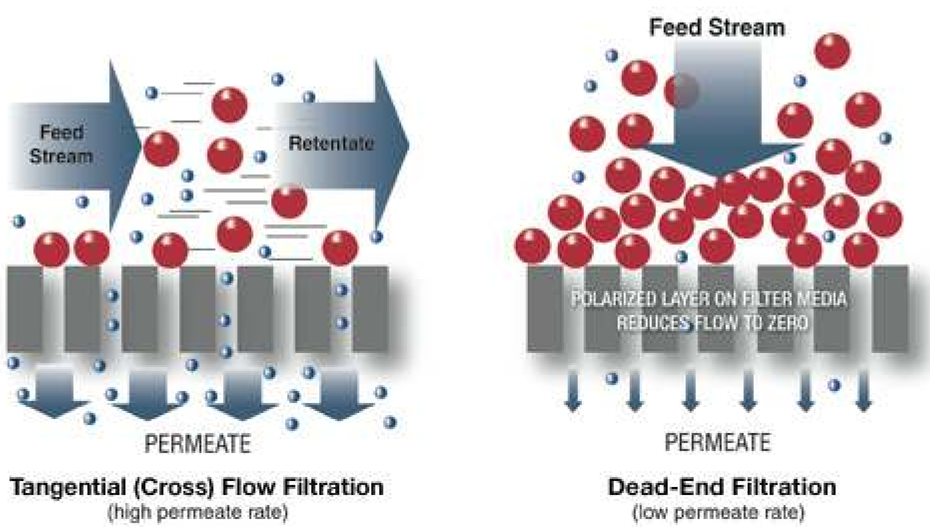

Figure 6. Cross-Flow vs. Dead-End Filtration[32]

This configuration results in a higher rate of permeation as flow through the membrane is not slowed down by the accumulation of particles on the membrane surface. Additionally, the sweeping action of the flowing water across the membrane surface helps keep particles from becoming stuck in the pores, meaning that the system does not require maintenance as frequently as it self-cleans. A transmembrane pressure is applied perpendicularly to the membrane surface to act as a driving force for the filtration separation. Microfiltration membranes are reusable as the pore size is reasonably large; on the magnitude of 10^{-3} to 10^{-6} meters in diameter. Particles that become stuck in the pores can be forced out by backwashing the system. Clean water is applied in a dead-end filtration orientation to the membrane for a short period of time to accomplish this[33].

A 50 µm filter screen will be used to remove large particulates and sand. This screen should be easily accessible and cleaned on a quarterly basis. Replacement filters cost $25[34]. This filter should be immediately followed up by a 10 µm filter, then a 0.2 µm filter in series. These finer filters eliminate algae, *Giardia lamblia* cysts, *Cryptosporidium* oocysts and large bacteria from the water[35]. They should be changed on an annual basis. Membrane replacements cost on the order of $100-$500. Microfiltration systems that are applicable for the filtration of rainwater costs $10,000-$100,000 with a typical industrial system costing $55,000.[36] A transmembrane pressure of 35-275 kPa is required to drive the separation process. The operational cost of applying this force comes to $0.08/m^3 of filtered rainwater[37].

This microfiltration process removes much of the total suspended solids from the rainwater. However, it is not capable of eliminating all colloids and viruses from the water. These pathogens are smaller than the pore size of the membrane and as a result; do not get removed from the water by the filtration process. Therefore it is suggested that UV disinfection be applied to the system in order to sterilize the water.

UV irradiation has been in use in Europe for over a century[38] and is only recently garnering widespread interest and use in North America. With UV light, it is crucial that this step take place after and not before filtration. Organisms must be completely exposed to the light for this treatment to be effective. If particulates are not screened out first, then they may cast shadows and shield the pathogen from the light[39]. UV light is capable of disinfecting water by penetrating an organism's cell wall and causing adjacent thymine nucleotides to form dimers, thus disrupting the genetic code[40]. Note that this process does not kill the pathogen, but renders it incapable of reproducing. After this process, the pathogen is functionally dead and causes no harm if consumed.

The great benefit to UV light is that they are insensitive to water temperature or pH. Additionally, the bulb does not have to be in direct contact with the water which makes maintenance much easier. It is typically housed in a quartz glass case which required cleaning once a year. Most importantly, UV disinfection does not alter the chemical composition of the water and leaves no by-products. UV bulbs should be changed out annually. The capital and operational costs of utilizing the UV disinfection system are remarkably low. A professionally installed UV disinfection unit costs \$1,200.[41] Replacement bulbs cost \$60-\$100 depending on size and wattage[42] and the operational cost is \$0.03/m^3. Figure 7 shows a schematic of the UV irradiation system.

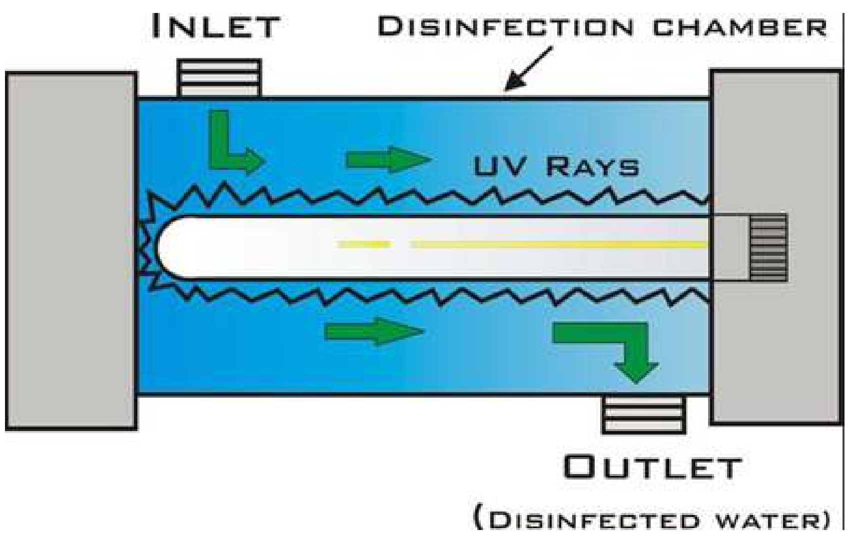

Figure 7. UV System Schematic[43]

An economic analysis on this system using a price of \$55,000 has determined that the price of treated rainwater is \$0.41/m^3 over the projected lifespan of the new SUB. Municipal water costs \$0.80/m^3 [44]; twice the price of the treated rainwater. This results in a yearly utility saving of \$987.94. If a cheaper \$10,000 microfiltration unit is utilized, the cost of treated rainwater would drop to \$0.23/m^3, resulting in an annual savings of \$1,438 and a payback period of 7.79 years. All calculations are presented in Appendix A.

4.0 *Triple Bottom Line* **Impact**

In this section, we will assess the environmental aspect of the proposed technology, estimate the financial cost of device deployment and maintenance, and examine the social impact of rainwater harvesting on the campus community. With further comparisons with other rainwater treatment methods such as sand filter and ozone, we bring out the advantages and disadvantages of employing our microfiltration and UV disinfection system. Finally, through our triple bottom line analysis, we will show that our proposed method is more preferable and indeed an eco-friendly and cost-effective way of treating collected rainwater for the new SUB.

4.1 Environmental Impact

We first examine the ecological impact of our microfiltration and UV disinfection systems. This includes the waste released to the surrounding environment and any potential health-related issues.

The main function of the filtration system is to improve water quality by removing some of the contaminants in the water. Two commonly used rainwater filtration methods are sand filtration and microfiltration. As introduced in Section 3.2, sand filtration could be an ideal pre-treatment process for surface water containing parasites, bacteria and suspended solids[45]; however, it has been rejected primarily due to its low filtration rate. Also, from an environmental perspective, using sand filtration often produces large volumes of sludge thereby increasing the difficulty in waste disposal. In contract to sand filtration, the cross-flow microfiltration model introduced in 3.4 offers several advantages including lowered energy consumption, increased yields and reduced waste disposal[46]. A detailed research on microfiltration by American Water Works Association explains the waste generation between the filtering membranes — "residuals produced from backwashing of low-pressure membrane [the secondary and tertiary membranes] will consist of filtrate together with naturally occurring feedwater solids retained by the membrane[47].” The removal of backwash wastes is therefore relatively easy and the backwash water can be recycled for continuous use with negligible environmental impact.

Ozone and UV are two well-suited disinfection methods. They are both very effective in eliminating harmful pathogens in water while producing minimal wastes[48]. However, using ozone disinfection poses several health concerns. Given the toxicity of ozone, ozone overdosing is extremely dangerous if the equipment malfunctions. Ozone can also react with other chemicals in water and create harmful contents. Studies show that “if the water contains bromide, ozone oxidizes it to the DBP [disinfection by-product] bromate; bromate is a strong animal carcinogen and regulated pollutant.”[49] Due to the health issues associated with ozone, we strongly recommend using UV as a chemical-free alternative for water disinfection. UV radiation disinfects water without adding chemicals to the water; there are no by-products from the UV disinfection process so nothing is discharged into the water. Additionally, UV radiation does not remove any of the minerals in the water, which creates a health benefit. One disadvantage of applying UV system is that UV has no residual killing effect, which means that microorganisms and pathogens can still form downstream of the system. We can solve this by properly sizing the UV unit to ensure sufficient exposure and maximum sterilisation.

4.2 Economic *Conclusion*

In Section 3.4 Purposed Method, we have looked at the life-cycle finance cost of the microfiltration and UV system. By taking account of the cost of purchase, maintenance and recycling, this section will recapture some of the notable costs for our filtration and disinfection systems and compare them with sand filtration and ozone disinfection, so that this way we can determine the overall feasibility of our purposed method.

An automated sand filtration system costs from $600 for a single filter system to several thousand dollars for larger units[45]. The advantage of using sand filter is its low cost and long life expectancy. The life expectancy of a reputable sand filtration system can be well in excess of 15 years[50]. The major drawback of sand filters is the difficulty in maintenance. Without proper maintenance, surface deposits accumulate at the top of the sand layer eventually reducing the water flow. Depending on the quality of water being treated, surface cleaning is needed once every 3-6 months[45].

The cost for microfiltration systems can range from $10,000 to $100,000 with a typical industrial set up of $55,000.[36] Although the cost for the microfiltration system is expensive, it does offer the ease in maintenance and cleaning. The purposed cross-flow microfiltration system requires its primary filter screen to be cleaned on a quarterly basis and secondary filters to be changed on an annual basis. Filter replacements cost $25[34] while membrane replacements cost on the order of $100-$500. The operational cost is estimated at $0.08/m^3 of filtered rainwater[37].

The cost of a commercial ozone disinfection system is about $1,100.[51] However, it becomes increasingly difficult and expensive to maintain overtime[52]. Further taking account of the health concerns related to ozone, UV lights is considered to be a better alternative. The UV disinfection system has an initial installation of about $1,200,[41] almost the same as an ozone plant. Also, UV has a low operating cost approximately equivalent to the continuous use of a 60 watt light bulb. However, the key disadvantages of UV disinfection are the need for frequent lamp maintenance and replacement. Minerals in the water can coat the UV lamp, reducing the intensity of the output overtime, so regular cleaning is required to ensure that the target microorganisms are not shielded from the UV radiation. Electrode degradation occurs every time the lamp is cycled on and off, and frequent lamp cycling will lead to premature lamp aging[43]. The average service life expectancy for low pressure bulbs is approximately 8,800 hours or one year[43]. Replacement bulbs cost $60-$100 depending on size and wattage[42], while the maintenance of UV lamps can be handled by our service staffs to remove mineral deposits. Overall, the simplicity of installation, low cost of operation, and ease of operation and maintenance make UV an ideal water disinfection option.

Here is a brief summary of the life-cycle financial cost of our filtration and disinfection system. If we purchase a typical industrial microfiltration system ($55,000), the total cost of the filtration and disinfection system will be $56,000, and the average cost of treating rainwater to food safe level will be $0.41/m^3$. Buying water from Metro Vancouver costs $0.80/m^3$. This results in a yearly saving of $987.94. If we could manage to utilize a $10,000 microfiltration unit, then the cost will be significantly lowered to $0.23/m^3$ of treated rainwater, resulting in an annual saving of $1,438 and a payback period of 7.79 years.

4.3 Social *Conclusion*

This section describes the possible impacts on the community and region with our methods for rainwater harvesting. The catchment, storage, filtration, disinfection and usage options will be analysed.

The catchment area on the roof will include a layer of chicken wire for filtering out large objects. This will probably be an unsightly feature if it can be seen. Hence, it will be hidden inside a structure of the building. The janitors of the SUB will be able perform regular cleaning of the chicken wire without much difficulties. No specialised crew will be needed for the maintenance of this filter.

The harvested water will be stored in a huge cistern underground. An apparent issue will be the usage of space in the SUB. A huge lot that could be used for other activities will have to be allocated for housing the cistern. Hazardous substances will gradually build up in the cistern. Even with advanced filtration and disinfecting methods, it is imperative that the cistern has to be cleaned to maintain the quality of the filtered water. A specialised service crew will be called upon on a regular basis to empty the cistern and disinfect it.

The microfiltration and UV radiation systems will ensure that the water will be safe enough for janitorial, washroom, and irrigation use. This is the most technically demanding section of the system. A full-time service staff will be hired to watch over the advanced microfiltration and UV radiation systems while they operate daily. Should they require maintenance or replacing, the service staff will be present ensure that mishaps are kept to a minimum. Furthermore, this can create job opportunities for Co-op students. Students in chemical and mechanical engineering can be offered interns for this part. The students can gain real-world experience on filtration and disinfection systems.

A major problem with sand filtration is the space it requires. With the slow rate of filtering, a large amount of land is needed to make up for the amount of water filtered per unit time. This will be a problem for the new SUB; space taken up by the filtration unit will only mean that less space will be available to cater to students' needs. Given that the usable space in the new SUB is a constraint, careful planning must be made. Microfiltration on the other hand, has a compact design that results in a small system footprint[53]. Disinfection with the use of ozone is a much more complex task than UV; more complex systems are required for ozone. As a result, a more technical-intensive (and higher paid) service crew will be needed for the ozone disinfection systems. A major setback with ozone is that it is extremely irritating and toxic[54]. Extra measures must be taken to prevent the harmful gasses from coming into contact with people. This may pose a health hazard to the service crew who work in close proximity to the unit and also the general public too. However, UV lamps and their output used in UV disinfection can be completely isolated by enclosing the unit is an opaque container.

The treated water can be used for janitorial and in the flushing of toilets. As shown in Figure 3, cleaning and toilet flushing accounts for 5% and 30% of clean water use respectively. These activities do not necessitate the usage of tap water - the water produced by this system will suffice. This will enable the SUB to cut down on tap water usage by a significant margin, thus promoting sustainability. Furthermore, this will help promote the awareness of water scarcity and conservation among students.

The treated water will also be used in the irrigation of the SUB's rooftop garden. The produce grown from the rooftop garden will demonstrate to the campus at large that it is possible to obtain tangible benefits from the rainwater harvesting system. Water savings obtained from low-flow fixtures, although substantial, is largely obscured from public knowledge. Physical and edible results from the system will go far in promoting and encouraging the use of these catchment systems to the greater public.

5.0 Conclusion

Through an in-depth triple-bottom line analysis of the filtration and disinfection methods in Section 4, we conclude that the best method for treating rainwater is a combination of microfiltration and UV radiation. A series of filters will first remove the majority of solids from the rainwater, followed by an application of UV radiation that will kill most of the remaining pathogens. This will ensure that the water is safe enough for greywater use. Utilizing water from this system is a cheaper and more sustainable alternative to relying on the municipal water supply. The initial capital setup costs will also be paid back in only 8 years. The environmental impact is minimal as our system produces little or no pollution during its operation. Perhaps a more lasting impact will be the social effect on the public, particularly on the students. By manifesting a strong level of water conservation awareness among next generation leaders of the world, the students will be encouraged to further innovate on better means to sustainable living.

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Appendix A

Occupancy

Description	#	Comment
Full-time equivalents	881	
Full-time occupants (staff)	108	12 months/year, 8 hours/day
Part-time occupants (students), school year	4119	8 months/year, 2 hours/day
Part-time occupants, summer	1030	75% reduction in students, 4 months/year, 2 hours/day
Days occupied per year	260	

Water Demand

Description	Annual water demand
Total fixture demand (toilets, urinals, lavatories, kitchen sinks, showers)	2,807 m3
Flush fixture demand (toilets, urinals)	2,454 m3
Flow fixture demand (lavatories, kitchen sinks, showers)	354 m3
10% of baseline water use (volume required to meet innovation point for process water load reduction)	540 m3

Water Fixtures

Fixture	Flow rate/#
Dual flush toilet	4.2/6.0 LPF
Urinal	0.5 LPF
Lavatory (auto)	1.9 LPM
Kitchen Sink	6.8 LPM
Shower	5.7 LPM
Daily kitchen sink users	108
Daily shower users	6

Rainwater harvesting system

Description	Value
Total Roof Area	5439 m2
Rainwater catchment area (hardscape only – 50% of roof)	2719.5 m2
Cistern collection efficiency	75%
Annual precipitation	1202.4 mm
Annual precipitation volume	3,270 m3
Cistern Collection efficiency	75%
Annual precipitation available for cistern	2,450 m3

Figure 8. Assumptions for Water Calculations

Total Roof Area (m^2)	5439
Rainwater catchment area (hardscape only – 50% of roof) (m^2)	2719.50
Cistern collection efficiency	0.75
Annual precipitation (mm)	1226.50
Annual precipitation volume (m^3)	3335.47
Annual precipitation available for cistern (m^3)	2501.60

Table 2. Rainwater Harvesting System

Microfiltration Unit ($)	$10,000
UV Unit ($)	$1200
Total Capital Cost ($)	$11,200
Filtration Operating Cost ($/$m^3$)	$0.08
UV Operating Cost ($/m3)	$0.03
Membrane Cost ($/yr)	$100
UV Lamp Cost ($/yr)	$60
Operating Cost ($/yr)	$451.34
Lifetime (yr)	100
Present Value ($)	$56,334.26
Annual Cost ($)	$563.34
Municipal Water Cost ($/$m^3$)	$0.80
Water Cost ($/$m^3$)	$0.23
Savings ($/yr)	$1,437.94
Payback Period (yr)	7.79

Table 3. Economic Analysis