Oregon State University

Engineered Wetland for Graywater Reuse

BEE 482 Interim Technical Report
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RANE Solutions
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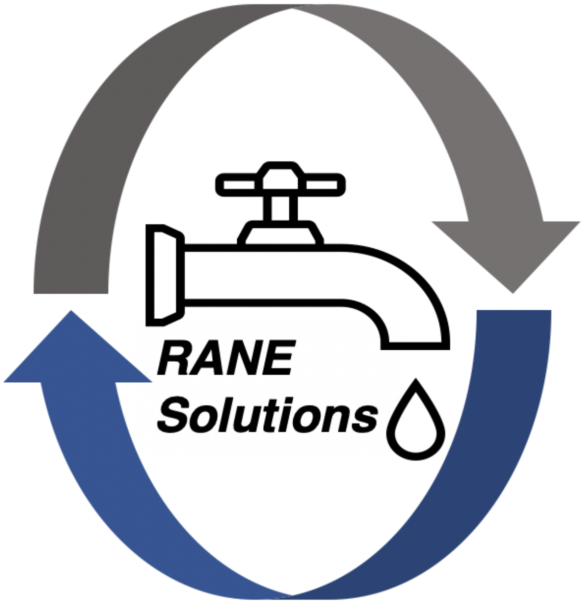

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0.0 Executive Summary:

Pat Heins of the Department of Environmental Quality in Oregon contracted RANE Solutions to create and build a design to achieve Type 2 graywater. Type 2 graywater needs to reduce the biological oxygen demand and the total suspended solids to 10 mg/L or less, as per the Oregon Department of Environmental Quality. The system can only treat a maximum of 300 gallons of water per day. The water can be used for a variety of purposes, namely irrigation or lawn watering.

Final deliverables to the client will include a functioning system that has been tested. The design of the system includes both primary and secondary treatment. Primary treatment will consist of a wood chip filter and secondary treatment will be a horizontal subsurface flow wetland. The system has been designed to take up the least amount of space possible.

This report outlines the design process, the design, results, and considerations. RANE Solutions began the design process by conducting a survey of technologies to find feasible designs to create the system. A decision matrix was completed comparing possible technologies. Based on the decision matrix, a design was selected. As of now, the woodchip filter has been built and the wetland has begun being built. However, in the next 3 months, RANE Solutions will conduct experiments on the horizontal subsurface flow wetland to determine how to reduce short circuiting and experimental water retention times. Experiments on the amount of wood chips needed in the filter will also be conducted. Testing on both for BOD and TSS concentrations will be completed and synthetic graywater will be made in the lab. Considerations of the design include unintended consequences, social, ethical, environmental, and economic impacts of our design. Ethical considerations are based on the engineering canons to hold RANE Solutions accountable for the design. Environmental impacts include a life cycle analysis of the design, while the economic impacts include estimated and potential hidden costs.

1.0 Introduction:

Humanity’s future is inextricably intertwined with freshwater access. Water scarcity and drought pose an issue to the continuation of the American lifestyle, as 35% of the contiguous United States experiences severe to extreme drought, while 45% experienced moderate to severe drought per the Palmer Drought Index (NOAA, 2021). Despite the Pacific Northwest being known for its rainy winters, Oregon is not exempt from this trend and experiences similar impacts. As it stands, 98.6% of Oregon is considered to be under at least moderate drought conditions, with 72.1% of Oregon having severe drought conditions or worse. Water scarcity is being exacerbated by unsustainable usage, environmental pollution, and uneven distribution of potable water. This issue is likely to be compounded by population growth and by climate change's continued effects. The value of water is likely to increase greatly, making diligence about maximizing water resources more important. This raises the question: where will the water needed to sustain human life come from? To answer this question, we need to look at sustainable water technologies which reduce dependence on municipal water.

One promising way to reduce dependence on fresh water sources is to reuse non-sewage water. This concept is known as graywater reuse and can decrease water scarcity, as it accounts for 50-80% of household water consumption (Mohamed et al., 2014). Graywater is formally defined under Oregon law as wastewater from showers and bathtubs, bathroom sinks, kitchen sinks (without garbage disposals), and laundry machines (DEQ, 2019). Reusing a portion of graywater from a household increases the amount of water available to a home while decreasing potable water demand. It is important to note that the uses of graywater are limited, but uses for average households include irrigation and reuse in laundry machines and toilets.

Applicable uses are based on the permits obtained from the Department of Environmental Quality (DEQ). The Oregon DEQ recognizes three levels of treated graywater for reuse. Type 1 graywater is untreated graywater that has passed through a physical process to remove solids, fats, oils, and grease (FOG). The water contains dissolved oxygen and can be used in subsurface irrigation of gardens, lawns, landscape plants, food crops (except crops that have edible portions that contact the graywater), and compost (DEQ, 2019). Type 2 graywater is water that has passed through some type of chemical or biological process to reduce solids and organic matter. Type 2 water can be used for all Type 1 applications, surface drip irrigation, and landscape ponds that are not intended for human contact (DEQ, 2019). Type 3 graywater is Type 2 graywater that has been disinfected. The use of Type 3 graywater is typically considered to be beyond the scope of residential applications but can be used for laundry and toilets (DEQ, 2019). Permits are required to ensure safe usage, as these systems can be used in residential homes. The requirements to use both Type 1 and Type 2 graywater include a connection to a wastewater system and a concentration of 10 mg/L or less of both the five-day biochemical oxygen demand (BOD) and total suspended solids (TSS).

To meet the permit requirements, current technologies and designs were researched. The feasible technologies that remove BOD and TSS to meet the requirements for Type 2 graywater included a wood chip filtration system, a slow sand filter, and a horizontal subsurface flow wetland (HSFW). The wood chip filter is a low cost, easy setup, and minimal maintenance system that uses wood chips and mulch. Slow sand filters utilize an active biolayer (schmutzdecke) and a porous media that contributes to the breakdown of oils, solids, and bacteria. HSFWs use soil, plants, and microbes to reduce contaminants including hydrocarbons and sulfates. This report provides a survey of different design alternatives, design feasibility, a final design layout, and economic, environmental, social, and regulatory considerations.

2.0 Problem Statement:

2.1 Overview and Objectives

The goal of this project is to create a replicable prototype for a graywater reuse system that recycles at least 50 gallons of graywater per day from a single-family residence. The remaining graywater will be diverted to the sewage system as wastewater. This prototype will lift the created graywater in the household to a central location. The system will meet the requirements for a Type 2 permit for graywater reuse from the DEQ, namely treating the graywater to have BOD and TSS concentrations of 10 mg/L or less. Economically, the goal is to create a system under $500.

It should be noted that a permit is required to be able to use a graywater recycling design and must include a complete maintenance strategy, an operating plan that accounts for seasonal variability, and a connection to the wastewater system. However, we will not be obtaining a permit.

Success will be measured by the ability of the design to treat a minimum of 50 gallons of water per day, achieve a BOD and TSS of 10 mg/L or less, and be created under $500.

2.2 Assumptions

We assume that the system will treat at least 50 gallons of water per day and will not exceed 300 gallons of water per day. Untreated water will be pumped to a centralized location for purification at the reuse system. The water not recycled will be diverted to an approved sewage system, meaning that up to 250 gallons of water may be diverted and considered waste. The system will be designed for a temperature range of 34 to 90 degrees Fahrenheit. This system will not be designed for grease and the design will ignore this consideration.

3.0 Survey of Technologies:

3.1 Wood Chip Filtration

Wood chip filtration is an easily constructible graywater filtration technique. These systems are typically small and enclosed in a wooden box or plastic bin. In practice, contaminated water is pumped into the system, flows vertically through the wood chip and mulch mixture, and exits the system via an outlet pipe. Generally, the three components in a wood chip filter include wood chips, mulch, and microbes. The wood chips utilize the large surface area and sharp edges of the wood to mechanically adsorb and remove organic matter and suspended solids (Heggie, 2020). The mulch is used to remove BOD, suspended solids, total phosphorus, and carbon oxygen demand (COD) (Dalahmeh et al., 2011). Materials used for mulch filters include bark, peat, wheat straw, corncob, and calcite (Dalahmeh et al., 2011). The contaminants in the graywater allow the microbes in the system to form on their own, which then consume the contaminants. As a result of these components, wood chip filtration is a great primary treatment option.

Wood chip filtration is commonly used as a primary treatment because of its ability to remove organic matter, suspended solids, and FOG from graywater (Dalahmeh et al., 2011). This process alone qualifies the wood chip filter to produce type 1 graywater based on the contaminants removed (DEQ, 2019). However, it is not probable that the system will achieve type 2 graywater due to the wide range of removal efficiencies for BOD and TSS, reducing 55-99.9% and 51-91% respectively (Dalahmeh et al., 2011). To increase the removal efficiencies, studies have shown that a combination of peat and calcite are the most effective mulch components (Dalahmeh et al., 2011). However, a secondary treatment system would be beneficial to meet DEQ requirements due to the variation in removal efficiencies of the system. Additionally, experimenting with the thickness of the wood chip layer would allow for the highest removal efficiencies of BOD, COD, and TSS to be achieved. It should be noted that the filter does not remove bacteria such as *E Coli*, *Staphylococcus aureus*, and *Pseudomonas* (Oteng-Peprah et al., 2018).

We encourage considering system life and maintenance, soil saturation, and economic and environmental impacts before design construction. After setting up the system, the microbes need at least one week to develop in saturated conditions before use. Microbial growth can be promoted by adding bark, peat, wheat straw, and corncob (Dalahmeh et al., 2011). The developed microbes can prevent clogging of the filter because they reduce the buildup of organic matter and solids. Additional clogging can occur in the outlet pipe due to wood chips' tendency to degrade. To avoid this, a drain should be added at the bottom of the system to ensure only water is leaving the filter. If the system is maintained well, the expected life of the wood chips and mulch mixture is two years.

Both the fixed and variable costs include time and money. The main time constraint is the microbes, which need at least one week to develop. The fixed cost for this system is $55, while variable costs range from $10-20 based on the life span of the system. The process that occurs when treating the graywater is a natural and mechanical process that does not create toxic byproducts (Heggie, 2020). This process is low cost and environmentally friendly, making it an ideal technology for primary treatment.

This technology meets the requirements for type 1 graywater, but fails to meet the requirements for type 2 graywater. The wood chip filter is able to effectively reduce some contaminants and reduce clogging before being filtered into a secondary treatment system.

3.2 Slow Sand Filter

A slow sand filter (SSF) is a simple, ubiquitous technology used for water filtration. The two basic components to a compact SSF unit are the active biolayer (schmutzdecke) and a variety of porous media (soil, sand, and gravel) as seen in figure 1 (CDC, 2012). A typical system is enclosed in a plastic or concrete container with dimensions of approximately 3 feet in height and 1.8 feet in length and width (CDC, 2012). The smaller size allows for an increase in aesthetics.

In practice, contaminated water flows through the top of the sand filter, through the schmutzdecke, then finally through the porous media. Once filtered, the water exits the system through an outlet pipe into a separate container. Typically, to move the treated water to another location, a pump or pressure from the force of gravity of the influent water are used.

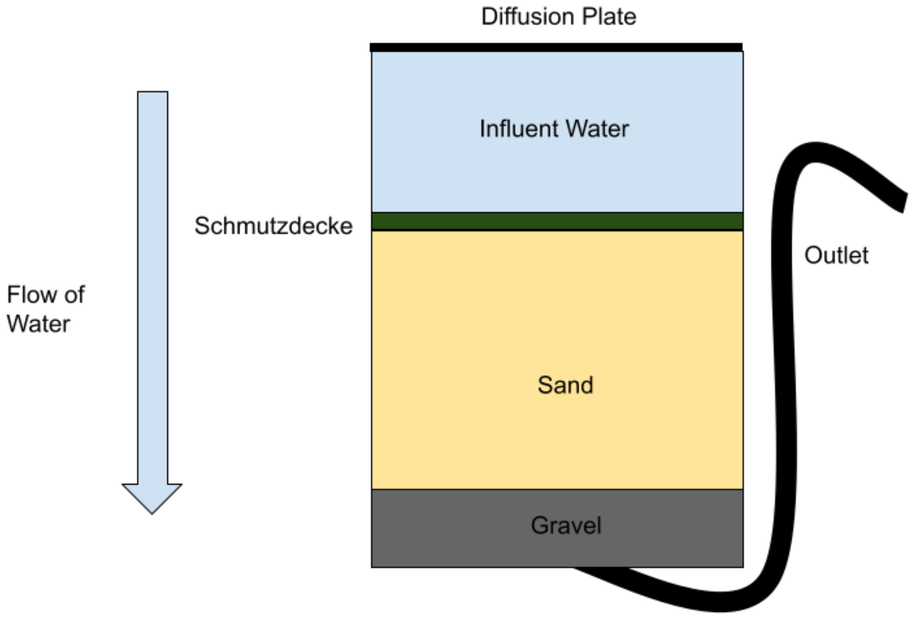


Figure 1: A compact slow sand filter

The purpose of the schmutzdecke is to break down oils, solids, and bacteria (Sacramento State, 2019). Once the water passes through the schmutzdecke layer, solids are filtered out by the porous media (CDC, 2012). SSF devices with a mature schmutzdecke can remove 99.98% protozoa, 80-98% of E. coli, and 90-99% of other bacteria (CDC, 2012). After going through a primary treatment, the SSFs can filter out approximately 90% of TSS and 65% of the remaining BOD (Ellis, 1987). To ensure the SSF system meets DEQ requirements, regular testing for TSS, BOD, and COD concentrations should be conducted. Besides removal efficiencies, a variety of other considerations should be taken into account when deciding whether to implement a SSF.

For the SSF, we encourage considering system life and maintenance, waiting time, and economic and environmental impacts before design construction. After building the system, the schmutzdecke takes two weeks to mature. As the schmutzdecke matures, the removal efficiency of contaminants increases. The system has a relatively high filtration rate, at 0.16 gallons per minute, allowing the system to treat at least 50 gallons of water per day (CDC, 2012). However, the quality and speed of filtration decreases as contaminant levels increase. The schmutzdecke layer is biologically active, meaning that an increase in contaminants results in the promotion of bacteria growth by the nutrients (Livingston, 2013 and Ranjan and Prem, 2018). Additionally, the porous media will clog with contaminants. Overall, the lifespan of a compact SSF can be greater than 10 years if maintained properly (CDC, 2012).

Primary maintenance concerns include sustaining the schmutzdecke and unclogging the media. To sustain the schmutzdecke, the water level must always ensure submersion. If the water level dips below the schmutzdecke, the bacteria present die off and the SSF has to reset, which takes two weeks (Gottinger, 2011). However, to avoid a disturbance in the schmutzdecke the water flowing into the system must not be turbulent and the water can be diffused with a plate. Additionally, cold temperatures can kill the schmutzdecke (Huisman and Wood, 1974). To avoid killing the schmutzdecke, either a pause in usage or placement into a warm area that is not exposed to freezing temperatures would need to occur. To unclog the system, intermittent agitation of the top sand layer is required (CDC, 2012). The water should become cloudy at the top of the sand layer, and can then be drained. However, cleaning the system disturbs the schmutzdecke and will put the system out of commission for two weeks until the schmutzdecke matures.

Both fixed and variable costs include time and money. Since the schmutzdecke has to mature, the system cannot be used right after initial construction or after maintenance for 2 weeks. The typical fixed cost to implement the system is $60 dollars, while variable costs can range from $15-20 depending on the frequency of maintenance (CDC, 2012). The main downfall of the SSF is that it does not effectively remove viruses (CDC, 2012). If viruses are present in graywater, these viruses have a high likelihood of appearing in the treated water and can contaminate food grown if water is used in gardens.

This technology meets the requirements to create type 2 graywater. The tiny spaces between the particles of sand act as a physical screen and filter out solids, while the schmutzdecke satisfies the biological component for water treatment.

3.3 Horizontal Subsurface Flow Wetland (HSFW)

Engineered Wetlands (EW) are a popular form of water treatment because of their low maintenance needs in combination with their modularity, allowing them to provide high efficacy treatment for any number of contaminants.

There are several forms of EWs that are used today, which are separated by flow type (EPA, n.d.). Surface flow wetlands (SFW) mimic natural wetlands. They feature plants rooted in a soil layer with the water above ground level, allowing for aerobic conditions near the surface and anaerobic conditions below. The benefits of SFWs are low initial and maintenance costs, uncomplicated construction and maintenance, and habitat creation. However, SFWs need a large amount of space to provide effective treatment, which limits applicability.

Figure 2: Surface Flow Wetland (Leachate Management Specialists)

The alternative, subsurface flow wetlands, have a sealed porous substrate layer below ground with vegetation rooted into the substrate layer and a horizontal or vertical water flow through the substrate. Water that flows through the system horizontally are called horizontal subsurface flow wetlands (HSFW). HSFWs are able to provide more treatment per unit area due to porous substrate, meaning they can be made smaller and provide faster treatment than SFWs.

Figure 3: Subsurface flow wetland

HSFW are also more resilient to cold weather than SFWs, but can be more expensive to build and maintain since they can be overwhelmed by large flows.

Treatment for EWs primarily comes from microbes and the biofilm that accompanies the plants, water, and substrate of the system. Treatment occurs via deposition of sediment from slowed flow, filtration through a porous substrate, chemical transformation, adsorption on the surface of sediment and plants, use of nutrients by plants, and predation of pathogens by microorganisms (EPA, 2000). The treatment needs are determined by the chemical process. For example, if the goal is to reduce sulfates a reducing environment would be needed, or if the goal is to precipitate iron, then an oxidizing environment would be needed. For the removal of BOD and TSS, EW's are highly effective at providing treatment for these two parameters. EWs are documented to have a 98% removal rate for BOD, COD, nitrogen, phosphorus and suspended solids (ESAA, 2009). When compared to other treatment methods, EWs are unique in their ability to provide habitat as a secondary impact. Furthermore, wetlands are living systems and are more resilient than artificial treatment systems, have a lower operating cost, and can operate without power. One important note is that SFWs and HSFWs can never have complete removal of BOD because the decomposition of wetland components contributes to BOD. BOD removal occurs by physical entrapment in porous media and consumption by the microbes lining the substrate and plants. TSS is removed similarly, being filtered by the substrate then consumed by microbes. The microbial community will change overtime to deal with the influent, so there is potential for the treatment to become more efficient with proper maintenance.

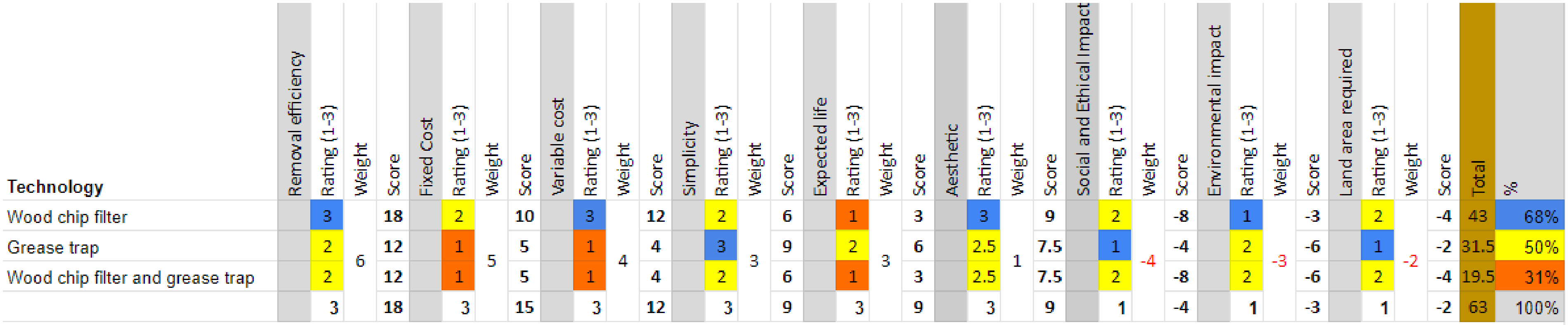
EW designs are variable and site dependent. Before design implementation, there should be an understanding of the regional climate paired with a site evaluation to assess existing conditions. Additionally, the size of the system depends on the treatment and flow needs, where a system requiring higher removal percentage or more treated water will be greater in size. EWs are typically modeled as ideal plug flow reactors as mixing occurs from water moving through the system, not by active mixing (EPA, 2000). Therefore, sizing calculations are done using a modified version of an ideal plug flow reactor equation. Cost is size dependent. A system used for a homeowner would have a lower fixed cost and a lower variable cost than a commercial EW (UN, 2008). An estimation of cost per acre of EW's places fixed costs at $10,000 per acre, and variable costs at $240 per acre (Tyndall et al., 2016). Lastly, it is important to ensure that the size of the wetland is large enough to prevent influent from leaving the system without treatment (EPA, n.d.). Monitoring activities during the installation and testing phases are crucial.

4.0 Engineering Strategy

4.1 Decision Matrix

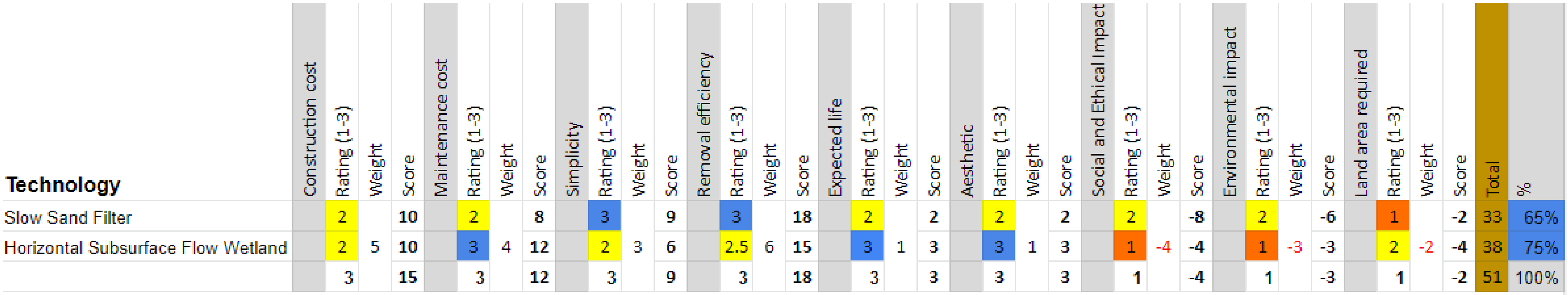
We created a decision matrix to determine the best design to treat type 2 graywater. Two separate matrices were created, one for primary treatment and the other for biological treatment. The primary treatment matrix compared a wood chip filter, grease trap, and a wood chip filter and grease trap combined (Figure 4). The biological treatment matrix compared a SSF to a HSFW (Figure 5). The criteria considered in the matrices were removal efficiency, fixed and variable costs, simplicity, expected life, aesthetic, social and ethical impacts, environmental impacts, and land area required.

Removal efficiency is based on the percentage of BOD and TSS removed. The fixed cost criteria is based on the time and materials needed to build and implement the design. Variable costs are based on the amount of time, effort, and money each system would need to be continuously maintained. The simplicity of the design is the difficulty of erecting the system, while the expected life is the life span before replacement. The aesthetic is based on the look of the design. The social and ethical impacts include the cost and acceptance of the system. The environmental impact includes the cradle to grave impact. Lastly, the land area required for the system is based on the dimensions of each design.



Technology	Removal efficiency	Rating (1-3)	Weight	Score	Fixed Cost	Rating (1-3)	Weight	Score	Variable cost	Rating (1-3)	Weight	Score	Simplicity	Rating (1-3)	Weight	Score	Expected life	Rating (1-3)	Weight	Score	Aesthetic	Rating (1-3)	Weight	Score	Social and Ethical Impact	Rating (1-3)	Weight	Score	Environmental impact	Rating (1-3)	Weight	Score	Land area required	Rating (1-3)	Weight	Score	Total	%
Wood chip filter		3	6	18		2	5	10		3	4	12		2	3	6		1	3	3		3	1	9		2	-4	-8		1	-3	-3		2	-2	-4	43	68%
Grease trap		2		12		1		5		1		4		3		9		2		6		2.5		7.5		1		-4		2		-6		1		-2	31.5	50%
Wood chip filter and grease trap		2		12		1		5		1		4		2		6		1		3		2.5		7.5		2		-8		2		-6		2		-4	19.5	31%
		3		18		3		15		3		12		3		9		3		9		3		9		1		-4		1		-3		1		-2	63	100%

Figure 4: Decision matrix for physical filtration comparing a wood chip filter, a grease trap, and a combination of the two



Technology	Construction cost	Rating (1-3)	Weight	Score	Maintenance cost	Rating (1-3)	Weight	Score	Simplicity	Rating (1-3)	Weight	Score	Removal efficiency	Rating (1-3)	Weight	Score	Expected life	Rating (1-3)	Weight	Score	Aesthetic	Rating (1-3)	Weight	Score	Social and Ethical Impact	Rating (1-3)	Weight	Score	Environmental impact	Rating (1-3)	Weight	Score	Land area required	Rating (1-3)	Weight	Score	Total	%
Slow Sand Filter		2	5	10		2	4	8		3	3	9		3	6	18		2	1	2		2	1	2		2	-4	-8		2	-3	-6		1	-2	-2	33	65%
Horizontal Subsurface Flow Wetland		2		10		3		12		2		6		2.5		15		3		3		3		3		1		-4		1		-3		2		-4	38	75%
		3		15		3		12		3		9		3		18		3		3		3		3		1		-4		1		-3		1		-2	51	100%

Figure 5: Decision matrix for biological filtration comparing a slow sand filter with a horizontal subsurface flow wetland

4.1.1 Primary Treatment

A comparison of the quantitative and qualitative variables for the primary treatment systems can be seen in tables 1 and 2, respectively. The wood chip filter removes BOD and TSS better than a grease trap with cheaper costs (Table 1). However, the expected life span of the wood chip filter is 3-5 years less than the grease trap (Table 1). Both systems have similar sizes, but the wood chip filter can be up to one cubic foot larger than the grease trap (Table 1).

All three options are relatively acceptable in terms of social and ethical impacts (Table 2). The wood chip filter can be large and slightly awkward, making it more difficult to find an adequate location. The grease trap is small and easily installed, but it can have more odors than the wood chip filter. The direct environmental impact for the grease trap is higher than the wood chip filter since the grease has to be disposed of (Table 2). Grease disposal can be done by using enzymes and chemicals, but the chemicals can create toxic byproducts. The wood chip filter has no direct environmental impacts as the wood chips and mulch mixture can be composted (Table 2). The grease trap is simpler than the wood chip filter since it does not have to be built (Table 2). The overall aesthetic of the wood chip filter is good, but has the potential to be bulky. However, the grease trap can smell, decreasing the overall aesthetic of the system (Table 2). Overall, the wood chip filter is better equipped for a graywater reuse system in a homeowners backyard.

Table 1: Comparison of quantitative variables for the primary treatment technologies in regards to removal efficiency, fixed and variable costs, expected life span, and overall size.

	Removal efficiency (%)		Fixed cost ($)	Variable cost ($)	Expected life (years)	Size (ft^3)
	BOD	TSS				
Wood chip filter	55-99.9 [a]	51-91 [a]	55	10-20	2	2-2.5
Grease trap	5-25 [b]	15-30 [b]	100-500	175-200	5-7	1-1.5
Wood chip filter and grease trap	5-99.9 [a,b]	15-91 [a,b]	100-500	175-200	2	2-2.5

[a] Dalahmeh, 2011

[b] Oyler, 2001

Table 2: Comparison of qualitative variables for the primary treatment technologies in regards to impacts, simplicity of building, and aesthetic.

	Impact		Simplicity	Aesthetic
	Social and Ethical	Environmental		
Wood chip filter	Relatively acceptable	Materials can be composted	Have to build	Somewhat bulky
Grease trap	Relatively acceptable	Needs to be cleaned, but can't be composted	Have to place	Can smell
Wood chip filter and grease trap	Relatively acceptable	Has to be cleaned and some materials can be composted	Have to build and place	Can smell and be somewhat bulky

4.1.2 Secondary treatment

A comparison of the quantitative and qualitative variables for the biological treatment systems can be seen in tables 3 and 4, respectively. The HSFW has a higher average removal efficiency for both BOD and TSS compared to the SSF (Table 3). The fixed and variable costs are less for the HSFW, even though the costs vary based on the amount of space it takes up. For example, if the size of the HSFW were to range from 15 to 100 in area, the fixed cost would range from \$3.45 to \$23 and the variable cost would range from \$0.10 to \$1.00 (Table 3). It should be noted that these costs are typically utilized for industrial sized wetlands that are much larger in size, making it more difficult to estimate the cost of small scale HSFWs. The expected life span of the HSFW is twice that of the SSF (Table 3). The SSF is smaller in size despite the variability in size of the HSFWs.

Both options are socially and ethically acceptable. The SSF is less acceptable because it does not have plants (Table 4). The environmental impacts of the SSF exceed those of the HSFW because the schmutzdecke can be toxic (Hwang et al., 2014). The media from both systems will need to be discarded as it may contain contaminants (Table 4). The SSF is easier to implement, as the HSFW needs more maintenance for plant growth (Table 4). Lastly, the HSFW provides natural foliage giving it a better appearance than the SSF. Overall, the HSFW is better equipped for a graywater reuse system in a homeowners backyard.

Table 3: Comparison of quantitative variables for the biological treatment technologies in regards to removal efficiency, fixed and variable costs, expected life span, and overall size.

	Removal	Fixed cost (\$)	Variable cost (\$)	Expected life	Size (ft^3)

	efficiency (%)				(years)	
	BOD	TSS				
Slow Sand Filter	65 [a]	90 [a]	60	15-20	10 [b]	10
Horizontal Subsurface Flow Wetland	98 [c]	98 [c]	0.23 per ft^2 [e]	0.01 per ft^2 [e]	20 [d]	Variable

[a] Ellis, 1987

[b] CDC, 2012

[c] ESAA, 2009

[d] EPA, n.d.

[e] Tyndall et al., 2016

Table 4: Comparison of qualitative variables for the biological treatment technologies in regards to impacts, simplicity of building, and aesthetic.

	Impact		Simplicity	Aesthetic
	Social and Ethical	Environmental		
Slow Sand Filter	Acceptable (less than HSFW)	Waste from media, schmutzdecke can be toxic [a]	Have to layer sand and wait for biofilm	Tall tube
Horizontal Subsurface Flow Wetland	Acceptable	Waste from media	Have to layer sand and plants, while keeping plants alive	Natural foliage

[a] Hwang et al., 2014

Our overall design will consist of a wood chip filter as the primary treatment and a HSFW as the biological treatment, based on the decision matrices. The wood chips will act as a physical filter, screening out FOG and solids. This filtration process will include wood chips and mulch. This mechanical adsorption and filtration process does not remove all contaminants, but it removes a significant amount to lessen the contaminant load for the HSFW. The wetland will act as the biologically active layer that will break down particles unseen by the human eye. Figure 6 shows a simplified figure of the overall design.

4.2 Calculations

The wood chip filtration system will be gravity fed, contained in a 10 gallon bucket, and treat at least 50 gallons of water per day. The dimensions of the wood chip filter are 1.43 feet (17.13 inches) in height, 1.3 feet (15.63 inches) in diameter, with a volume of 1.9 cubic feet and a cross sectional area of 1.33 square feet (Appendix A). The bucket will be filled with a layer of 0.83 feet of mulch and wood chips. The predicted removal efficiency of BOD for the wood chip filter is 72% and the average concentration of BOD in graywater in America is 86 mg/L (Kaetzel, 2018 and Oteng-Peprah et al., 2018). Our calculations indicate that 62 mg/L of BOD will be removed from the contaminated water (Appendix A). However, tests will need to be performed to determine an optimal wood chip layer depth based on the layer's contaminant removal effectiveness. Figure 7 shows the dimensions and design of the wood chip filter.

After flowing through the wood chip filter, the water will flow into the HSFW. The initial BOD concentration entering the HSFW was assumed to be 24 mg/L (Appendix A). A factor of safety of 1.5 was adopted to account for potential flooding and it was assumed that there was a kinetic rate constant of 1.61 feet per day (0.49 m/day) (Mitsch and Gosselink, 2007). The sizing of the HSFW is based on a plug flow model that accounts for flow rate, concentration of BOD, background concentration of BOD, and the kinetic rate constant (Appendix B). The area of the wetland was found to be a minimum of 4.1 ft^2. The medium being used in the HSFW is coarse sand with a porosity of 0.67 (USCS, n.d.). The depth of the coarse sand will be 1.5 feet, the minimum depth recommended for subsurface flow by the EPA (EPA, n.d.). Based on the area of the HSFW and the depth of the medium, it will take 0.82 days for 50 gallons of water to be treated (Appendix B). The system will need to be sloped at 1% to aid in the flow of water. Figure 8 shows the dimensions and design of the HSFW.

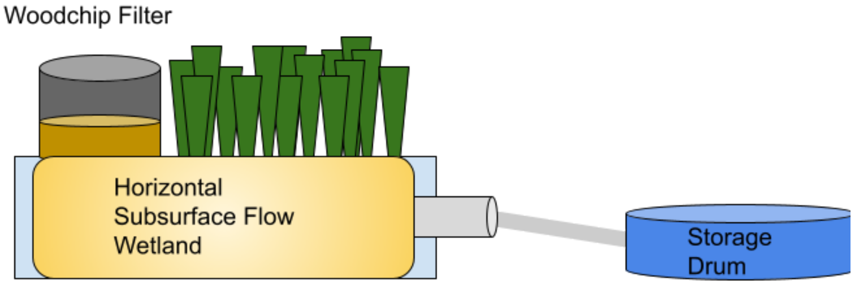


Figure 6: Basic Visualization of System

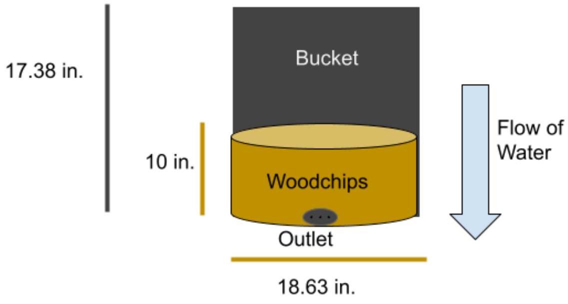


Figure 7: Dimensions and design of wood chip filter

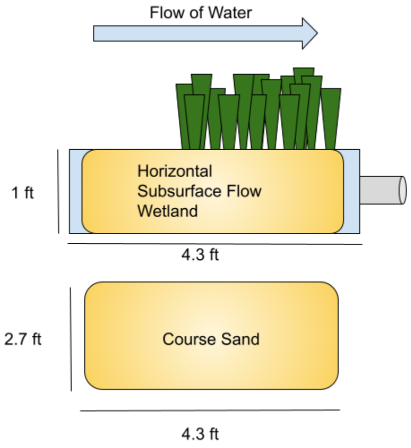


Figure 8: Dimensions and design of HSFW

5.0 Experimental Process

5.1 Building

Our system was officially done being built on Thursday, April 7th, 2022. The system we created is very similar to the original design. Some things we have changed in our system while building include a gravel, sand, and woodchip mixture under the woodchip filter bucket, a grate secured over our outlet pipe, and a gravel mixture in front of the outlet pipe to prevent sand leaving our system.

When we first built our system exactly like our design, we quickly learned that an entire engineered wetland of sand would not infiltrate fast enough. When we poured water through the wood chip filter, after a while the area around the woodchip filter would overflow with water. Our infiltration time was slower than anticipated, so we knew we needed to change parts of our system. We dug out sand underneath the wood chip filter, created a mixture of gravel, woodchips, and sand, and placed this under the woodchip filter.

Next, as we were building, we realized that if we stuck a pipe into the sand in our wetland, the sand would continuously wash out into the effluent.

5.2 Experiments

To test the effectiveness of our system we will conduct tests on the effluent TSS and BOD from our system using synthetic graywater. The TSS tests will be done using vacuum filtration and a drying oven, measuring the weight difference before and after drying the sample. We planned on doing BOD testing, but the wrong materials were sent to us, making us unable to perform the test. After completing the necessary training to become lab certified, we are qualified to conduct the TSS testing at the Gilmore Hall lab.

The results of the tests were compared to the 10 mg/L TSS requirements for type 2 graywater to see if our system is effective at fulfilling the permit requirements. We also compared the initial TSS concentrations in the influent synthetic graywater to the TSS concentrations in our effluent. This allows us to determine the expected removal efficiency of the system.

After performing these tests, we found that our entire system reduced the influent graywater TSS from 309 mg/L to 28.5 mg/L. We also measured the wood chip filter removal individually and found that it reduced the TSS from 309 mg/L to 109 mg/L. This data can be found in figure 9 below. This proves the effectiveness of both systems. While we did find that TSS was reduced by over 90%, we did not lower the TSS enough to achieve the standards for type 2 graywater.

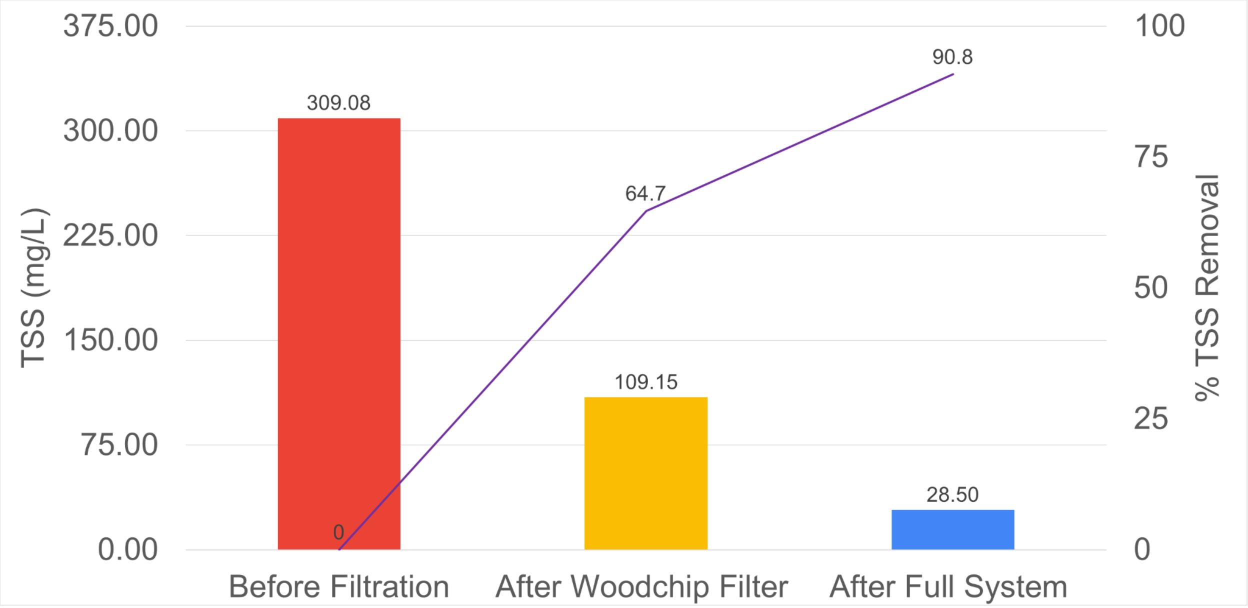


Figure 9: TSS testing results

6.0 Impacts:

6.1 Economic Impacts

The materials needed for our design will cost $303. The overall design includes pumping, a wood chip filter, a HSFW, and a storage drum. The pumping and storage system will cost $120, the wood chip filter will cost $33, and the HSFW will cost $160. The materials needed to create the pumping and storage system, the woodchip filter, and the HSFW can be seen in tables 5, 6, and 7 respectively.

Table 5: Materials needed to create the pumping and storage system

Material	Price ($)
20 feet of PVC pipe	25
PVC Elbow	2
Check Valve	13
Sump Pump	60
Storage Drum	20
Total price	120

Table 6: Materials needed for the wood chip filter

Material	Quantity	Price ($)
Wood chips	½ yard	4
Mulch	1 (bag)	3
10 gallon Bucket	1	26

	Total price	33

Table 7: Materials needed for the HSFW

Material	Quantity	Price ($)
Coarse sand	6 bags	60
Slough Sedge seeds	1 packet	10
Stock tank	1	90
	Total price	160

Replacement and maintenance costs are also important economic considerations. Replacement costs vary based on the life cycle of each system (Table 8). The relative cost of replacement for the pump, wood chip filter, and HSFW is $10, $3, and $3.5 per year respectively. However, all of these costs are dependent on how well the system is maintained by the homeowner. Maintenance time for the wood chip filter includes scooping out the wood chips and replacing them as the flow slows. After the mulch and wood chip mixture is exchanged, the filter will need at least one week to develop microbes. The majority of maintenance costs for the HSFW is tied to replacing medium and tending to the sedge plants. However, maintenance of each system requires the homeowner's time, which is not free. Volunteer time costs $28.54 per hour (Independent Sector, 2021). It is assumed that the homeowner will spend a total of 10 hours building the system and 10 hours to maintain the system, totaling $570 worth of volunteer time. This makes the total maintenance cost $302 yearly.

Table 8: Replacement Costs of each system

System	Life Span	Total Replacement Cost ($)
Pumping	10	100
Wood Chip Filter	2	3-6
HSFW	20[a]	70

[a]EPA, 1993

The economic impact of plumbing must also be considered, as many residential houses do not separate graywater and blackwater. Plumbing costs vary based on if the house is currently being built or if the house is already built. If the house is currently being built, plumbing costs are dependent on the square footage of piping needed, costing a homeowner $4.50 per square foot (HomeGuide, n.d.). However, repiping an existing home ranges from $0.40 to $2.00 per linear foot of PEX tubing (HomeGuide, n.d.). Additional plumbing includes transportation of treated graywater to an irrigation system, which can use PVC piping.

Non labor costs include permitting and utilities. Permitting costs for residential graywater reuse systems are permitted by the DEQ. A tier 2 permit costs $550 for the application fee and $52 annually (DEQ, n.d.). Utilities for the system include electricity and water. Electricity in Corvallis, Oregon costs 10.38 cents per kWh while water costs 0.3 cents per gallon (Electricity

Local, n.d. and COPW, 2021). However, rather than paying for water from treatment plants, treated graywater from the reuse system can be used instead. To offset the fixed and estimated variable costs, savings would begin after 68.5 months (5.7 years). This assumes the family without the graywater system buys the same amount of water the system filters from the water treatment plant and uses 75 gallons of water per day. In Corvallis, Oregon every 748 gallons of water used, for an average water meter size of ¾ inch, costs $1.76 (COPW, n.d.).

There can also be hidden costs associated with the design. Hidden costs include transportation of contaminated materials, installing electricity lines or solar panels in rural areas, and inspection. Transportation of contaminated materials would likely vary in cost based on location and amount of material needed to be moved. The material should be transported by a professional waste treatment company to decrease the environmental impacts of the waste. The pump that is used to move the water from the house to the graywater treatment system, electricity is needed. Installing electricity lines or solar panels for those who live in rural areas would increase the cost substantially. Inspection of the design includes testing the treated graywater to ensure that it meets Oregon DEQ requirements. This could be done by the homeowner, and the cost would vary based on the testing kit they obtain.

The only hidden cost associated with the system itself is the transportation of contaminated materials. Therefore, a 25% contingency is added onto the cost of the system. Maintenance and building costs total $872. With the contingency, the estimated cost of building and maintenance of the graywater treatment system is $1,110.

One potential way to offset these costs, is enrolling in rebate programs through the consumer's local or state government. For example, the state of California has many different options. The City of Glendale will rebate residents $500 for installing a Laundry to Landscape system, East Bay residents who use East Bay Municipality Utility District can receive a $50 rebate for purchasing a brass three-way diverter valve, and residents in Santa Clara can receive sa $200-400 rebate for installing a graywater reuse system in their homes (GCWP, n.d., EBMUD, 2021, and Valley Water, n.d.). However, we can not guarantee that every consumer's city will offer a rebate program for installing a graywater reuse system, so they should not rely on rebates to reduce the price.

The overall cost of the system, regardless of whether it falls on the consumer or RANE Solutions will initially be high, but afterwards slowly become a net positive over time as the system cuts water needs.

6.2 Environmental Impacts

Reusing graywater has positive environmental benefits. This is exemplified when comparing the environmental impact of a wood chip filter to the wastewater process that the graywater would otherwise undergo. The wastewater process includes chemical and energy usage and an increased amount of toxic byproducts, such as . In contrast, a wood chip filter has no direct negative impacts, since the treatment process is natural and mechanical (Heggie, 2020).

Another aspect of wastewater treatment is the release of greenhouse gasses such as carbon dioxide, nitrous oxide, and methane. These are released from the biological process that occur during the wastewater treatment. Since graywater produced at the residential house would not go to the wastewater treatment plant, there would be a decrease in the amount of water going into the wastewater treatment plant and therefore reduce the amount of produced. A report from Wageningen University found that 2.86 kilograms of CO_2 emissions are produced per m^3 of wastewater treated at a conventional plant, meaning that over the course of a year our design could save 237 kilograms of CO_2 emissions that would otherwise be produced assuming there are not unintended microbial outputs (Snip, 2010).

HSFWs are considered a low impact treatment option, since they coexist with greenspace. They require little infrastructure and limited interaction while providing plant life and habitat. To avoid the spread of invasive species, the plants we have decided to use are slough sedge (*Carex obnupta*) plants which are native to the northwest United States. However, it is important to account for high flows in design and assess the medium used to decrease drainage or flooding issues (EPA, n.d.).

Graywater subjected to standard treatment systems can not be consumed, but it can be used for agricultural purposes. Graywater reuse can reduce freshwater usage and drought stress on plants, which reduces climate change impacts (McCarthy, 2000).

Other environmental considerations include pharmaceutical and microplastic removal. Both pharmaceuticals and microplastics are unseen by the human eye, making it easier for them to enter waterways. Pharmaceuticals tend to enter waterways through treated wastewater, while microplastics can come from clothing and large plastic debris (NOAA, 2021 and USGS, 2018). From our system, the main source of microplastics will be from clothing, as studies have shown that polyester and acrylic can release microplastics during a cycle of laundry (McDevitt et al., 2017 and Napper and Thompson, 2016). It will be necessary to communicate potential risks of microplastic and pharmaceutical release into the environment, as the system is not designed for these contaminants.

6.3 Ethical Considerations

Before choosing our designs, each technology was researched thoroughly. This research provided knowledge about graywater reuse to truthfully express professional opinions (Canon 1c). We considered the health, safety, and welfare of the public, as well as the social, environmental, ethical, and economic needs of the design (Canon 1a and 1f). The health and safety of the public was considered by designing a system to adhere to local, state, and federal laws during all stages of the project (Canon 3b). To continuously ensure the safety of the public, all risks,non-proprietary safety information, assumptions, and requirements of the system will be shared with clients and the public through memos and documentation (Canon 4c through 4e).

Water scarcity will be reduced by the addition of a graywater reuse system at a residential household, as it alleviates demand for treated water so those resources can be used elsewhere. A reduction of water scarcity enhances quality of life and the system's acceptance (Cannon 1b). Besides water usage, a graywater system can help to reduce the use of chemicals and the production of chemical by-products, as what happens in drinking water and wastewater treatment facilities. Without chemical by-products, there is a reduction in detrimental effects to the environment and human health.

Our designed graywater reuse system has environmental impacts from plastic, metal, and wood chips, as these items increase the amount of fossil fuels burned and promote forest degradation. However, after the graywater reuse system is created, no harmful byproducts are produced. Due to the minimal environmental impact of the design, the design adheres to the principles of sustainable development (Canon 2a). Additionally, improvements to the design will be considered as new data and technology are created (Canon 2b).

To maintain communication and progress, RANE Solutions has been engaging both team members and clients in the progress of the design in a professional and amicable way with standards set by the team contract (Canon 5c through 5h).

6.4 Social Considerations

The main consideration for our design is the cost and required space. As of now, our design is based around a typical residential home that has access to a yard or outdoor space. This excludes consumers who live in apartment complexes, condominiums, townhouses, or homes that do not have outdoor space. However, there is potential to scale the technology using a multi family home scale and get permitted under a 2402 general permit . To increase the availability of our graywater treatment system, a large-scale system should be considered. However, the cost of a large-scale system would be substantially increased when compared to the at home system. This could be easily implemented in wealthier areas, as they have the funds to do so. There is incentive to do so, because the apartment complexes could receive rebates for lower water and carbon usage. While this increases the amount of people that can use this system, those who live in lower income communities will still not have access to this technology, even though they would likely benefit the most from water reuse. By having a money-saving technology accessible mainly to the wealthy or middle class, this will further divide the wealth gap. This also poses green technology as something that only rich people can afford. However, this technology is cheaper in the long run when compared to a typical wastewater treatment plant.

Another important consideration is the accessibility of the design for those with disabilities and the elderly. The system itself weighs a little over 300 pounds, and the assembly as well as maintenance will require heavy lifting. This will make it hard for some people to implement the system in their yard and keep the system running efficiently. A solution to this problem would be to have a service where we come and assemble or perform maintenance on their system. This will allow them to have the system and not worry about the labor that comes along with keeping the system running. However, while this aspect of our design is important to consider, going into detail on it is outside the scope of our project.

The design should provide a list of things that should be passed along to the client. This includes a maintenance plan, design assumptions, disposal, and water usage. The maintenance plan should include all the maintenance that needs to be conducted in a given year, and a schedule of when to do it plus a way to keep track of it has been completed. A potential maintenance plan for a wetland system of this size would include monitoring basic parameters like flow rate, TSS, BOD once a year, in addition to a visual check of the wetland plants to ensure there are no unwanted plants growing. To ensure that all of the clients are able to understand the maintenance plan, it will be distributed in braille and a variety of languages. The design assumptions are that the system will not filter grease or microplastics. Therefore, the consumer should try to limit the amount of grease and microplastics being used in the household, however this is also true of conventionally treated wastewater as grease can cause build-up in pipes. Once the filter has clogged, the homeowner will need to dispose of both the wood chip and mulch mixture and the sand from the wetland. Depending on the preferences of the consumer the sand can be used in their garden beds or taken to a waste management facility, However, the wood chips will not contain toxic contaminants and can be composted. If the consumer no longer wants to have the system within their backyard, they can send the wetland and wood chip containers to the landfill and compost facility, respectively. The water is not potable and should not be consumed directly. To ensure that people are aware of this, stickers, labels, and warning signs will all be posted on the design itself and verbally communicated to the client.

Benefits of the system include water savings and an opportunity to educate the public. By reusing water, drought, costs, and toxic by-products that are associated with wastewater treatment plants can be decreased. Additionally, this system provides a way to educate the public on what graywater is. With knowledge of what graywater is and the associated environmental and economic benefits of a graywater reuse system, people are more likely to reuse their graywater and be more environmentally conscious.

6.5 Unintended Consequences

The materials associated with this process are environmentally harmful, especially when analyzing the cradle to grave of the system. The creation of plastic, metal, and wood chips increases the rate of degradation of forests and the amount of fossil fuels burned. When created, the plastic uses fossil fuels to mold it, contributing to global warming and fossil fuel depletion. At the end of the wood chip filters life, the wood chips and mulch mixture should be composted instead of ending up in a landfill where it will not decompose as well. If the whole system is created poorly, it has the potential to kill off both animal and plant life.

The pump, piping, wood chip filter, and HSFW should be well installed to decrease system problems. System issues include leaks, pump failures, and poor maintenance which can cause untreated water to damage property and pose health risks. If the wood chip filter is not maintained properly, it could overflow (Graywater Action, 2014). Grease can clog this filter and if the system is clogged excessively, a grease trap will be considered. Additionally, the wood chips degrade rapidly and can clog the filter. The wood chip particles could settle to the bottom of the filter and clog the shower drain, the pipes leading to the wetland, and the wetland itself. To reduce clogging from the wood chips, we could add a strainer before the graywater filters through to the PVC pipes to the wetland. However, the chances of the system clogging are reduced due to microbial life breaking down FOG and suspended solids in the graywater. In the HSFW, the coarse sand medium can become clogged from contaminants, causing surface flow and overflow (EPA, n.d.). A large amount of rain in a short period of time could also cause the wetland to overflow. To account for overflow from clogging, the system should have a factor of safety for the volume and containment.

Within the HSFW sedges are used. These seeds have the potential to disperse around the homeowner's yard, even though they are slow colonizers (Oregon Fauna, n.d.). To address this, the wetland could be placed over a groundcover to prevent any rogue seeds from reaching the soil.

In addition to the environmental and maintenance unintended consequences, social consequences should be considered. This system has the potential to be thought of as more of an 'elitist' technology because not everyone has access to the space required to implement this system. If the price for water increases, the people who have a system that recycles graywater will be in a better position than those who do not. This has the potential to increase the wage gap. For those who do have a yard and the ability to implement this system, they may be working more than one job or working long hours, decreasing the amount of time they have available to maintain the system. If they are unable to maintain the system, it could be a waste of money.

7.0 Compliance with laws

7.1 Local

The City of Corvallis does not have any regulations around the reuse of graywater, and follows Oregon's DEQ regulations.

7.2 State

The state of Oregon abides by the DEQ regulations for graywater reuse. It is mandatory for the effluent to go through a physical and biological process and have a BOD and TSS concentration of 10 mg/L or less (DEQ, 2019). The wood chip filter will act as a physical screen to filter out FOG and solids, while the HSFW acts as a biological process to break down bacteria and reduce BOD. Testing will be done to ensure the system meets requirements.

7.3 Federal

For federal standards of graywater reuse, agencies refer to the National Science Foundation's standards. This system is built for a single-family home, making it a Class R classification, meaning the effluent should have a concentration of 10 mg/L or less for both BOD and TSS (Table 9).

Table 9: Summary of the NSF Standard 350 Effluent Criteria for Individual Classifications

	Class R		Class C	
	Overall Test Average	Single Sample Maximum	Overall Test Average	Single Sample Maximum
$CBOD_5$ (mg/L)	10	25	10	25
TSS (mg/L)	10	30	10	30

8.0 Conclusion

Based on the findings presented in this report our designed graywater reuse system, a combination of a wood chip filter and horizontal subsurface flow wetland, will be able to meet the requirements for Type 2 graywater, as specified by the DEQ.

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Appendix A:

Assumptions:

The system will be contained within a 10 gallon bucket with a length of 1.43 feet (17.13 inches) and a diameter of 1.3 feet (15.63 inches). An expected removal efficiency of BOD from graywater was found to be 72% and an expected TSS removal efficiency was found to be 99% (Choudhury, 2016 and Kaetzel, 2018).

Calculations:

Wood Chip Volume

$$V_{Wood\ Chip} = \pi \bullet r^2 \bullet L = \pi \bullet (7.815\ in)^2 \bullet 17.13\ in = 3286\ in^3 = 1.9\ \text{ft}^3$$

Cross Sectional Area

$$A = \pi \bullet r^2 = \pi \bullet (7.815\ in^{\ 2}) = 191.9\ in^2 = 1.33\ \text{ft}^2$$

BOD Predicted Removal Efficiency

$$R = 1 - \frac{C_o}{C_i}$$

$$C_o = C_i \bullet (1 - R)$$

$$C_o = 86\frac{mg}{L}(1 - 0.72) = 24\frac{mg}{L}(Kaetzel,\ 2018)$$

TSS Predicted Removal Efficiency = 99% (Choudhury, 2016)

Conclusion:

Based on the calculations, the wood chip filter requires 2.8 ft^3 of bark or mulch products and produces a maximum flow rate of 0.087 ft^3/s (7540 ft^3/day). The flow rate of the system is 50 gallons per day, meaning a wood chip filter of this size would be more than capable of dealing with the graywater demand. Through calculations and referenced material, it was proven that wood chip filtration is a viable method to remove a considerable amount of BOD (72%) and nearly all TSS (99%) from graywater. This makes it a great primary filtration system to lessen the load for the HSFW.

Appendix B:

Assumptions:

For a HSFW system, we assume an influent rate of 50 gallons/day, a factor of safety of 1.5, a kinetic rate constant of 180 m/yr or 0.49 m/day, and an initial BOD concentration of 24 mg/L. This BOD concentration comes from the BOD left after woodchip filtration. The system is assumed to be a square with equal width and length. The system will use a coarse sand medium with a porosity of 0.67, which will be located at a depth of 1 foot (EPA, n.d. and USCS, n.d.). The system will be a plug flow wetland with contaminants being filtered from the water as it goes through the system. The assumptions made for these calculations are based on peer reviewed sources.

Calculations:

Area based on Plug Flow Model

$$A = \frac{Q ln(\frac{C_i - C^*}{C_o - C^*})}{k_A}$$

$$A = \frac{0.1425 ln[\frac{24-(3.5 + (0.053 * 24))}{10 - (3.5 + (0.053 + 24))}]}{0.49}$$

$$A = 0.38\, m^2 = 4.09\, ft^2$$

Hydraulic Loading Rate

$$q = 100\, (\frac{Q}{A})$$

$$q = 100\, (\frac{0.1425}{0.38})$$

$$q = 37.5\, m/day = 123\, ft/day$$

Hydraulic Retention Time

$$V = Area * Depth$$

$$V = 4.09\, ft^2 * 1\, ft = 4.09\, ft^3$$

$$\tau = Vp/Q$$

$$\tau = \frac{4.09\, ft^3\, (0.67)}{(6.68\, ft^3/day)}$$

$$\tau = 0.41\, days = 9.85\, hours$$

Slope using Darcy's Law Variation

$CA = Q/K_f * S$ *(assume k_f is 1956 ft/day) (assume slope is 1%)*

$$CA = \frac{6.68\, ft^3/day}{1956\, ft/day} * 0.01$$

$$CA = 3.42 * 10^{-5}\, ft^2\, (cross\ sectional\ area\ required)$$

Conclusion:

Implementing a HSFW is a feasible option for biological treatment. However, to achieve ideal treatment testing is needed. The slope is a key aspect to moving water through the system at the right place. Currently, the best slope for the system is unknown. The retention time is reasonable, points towards sufficient treatment in a small system. Testing is needed to fill in the blanks as literature emphasizes empirical discovery with small scale treatment wetlands.