

Decentralized Methods of Water Treatment for Reuse of Residential Gray Water

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Abstract

Water shortages continue to cause negative economic, environmental, and social effects. This could be partially solved by reducing residential water consumption. This could be achieved by recycling graywater through an on-site graywater recycling system. Such a system would need to treat graywater to meet local water quality standards, be able to treat the graywater load from a typical home, be compact enough to fit in or near a home, and be relatively affordable. Three systems intended to treat residential graywater were examined: a drawer compacted sand filter, a semi-batch vertical flow wetland, and a moving bed biofilm membrane bioreactor. After an analysis of the three solutions, the semi-batch vertical flow wetland was recognized as the best graywater recycling system to use in residential buildings. This system produced treated graywater with the highest water quality and that contained no detectable escherichia coli. This system also was compact, and could process the highest amount of graywater. If successful, this system could help residential graywater recycling become more common and therefore reduce residential water consumption. This could help reduce the severity of water shortages and the negative effects associated with them.

Executive Summary

In the past few decades, droughts, and the water shortages they create, have been a continuing problem around the world. These create negative economic, social, and environmental effects such as reduced crop output, high unemployment, and the destruction of aquatic plant and animal life. These water shortages will continue in the future and are currently causing severe problems in California and South Africa. Responsible water management can lessen the severity of water shortages. While residential water consumption has been reduced in recent years, this drop in water usage has been small compared to other water usage in other sectors. This shows that there is a potential for greater water savings in residential buildings. An effective way to reduce water consumption is to reuse each household's graywater. Graywater is any wastewater flowing from any fixture besides urinals and toilets. Graywater can be reused in a wide variety of ways including toilet flushing, irrigation, in laundry machines, and vehicle washing. Outdoor irrigation may be particularly valuable for homeowners in regions affected by drought. However, before graywater can be reused, it must first be treated to remove harmful pathogens and substances.

Treating graywater at a centralized wastewater treatment plant would be costly and difficult to implement since new piping infrastructure would need to be created to carry the graywater. Treating mixed residential wastewater for reuse at water treatment plants would be much more energy intensive than treating graywater separately close to its source. A solution to this problem is to create a decentralized graywater treatment system to put in residential buildings. This system would need to meet national, state, or regional water quality standards, be compact enough to fit in a residence or a yard, be able to treat graywater from a residential home in terms of volume and quality, and be easy for homeowner to maintain.

A system that meets all of these requirements is the semi-batch vertical flow wetland. This system takes a previously constructed wetland design and makes it compact enough for use in treating residential graywater. This system consists of a water tank to collect graywater from the home, a filtration system, a second tank to catch the graywater from the filtration system, and a third tank to hold treated graywater before it is ready to be used. After initial collection, graywater is sent through a layered filtration system consisting on wetland plants, compartmentalized soil, spherical plastic beads and gravel. Water is recirculated through the filtration system for several hours. Afterwards, the water is disinfected by adding chlorine and is sent to a third storage tank, ready to be reused.

This system will be installed in new construction homes by home builders in order to market them as environmentally sustainable. Additionally, homeowners trying to reduce their water consumption for economic or environmental reasons will be interested in purchasing such a system. This represents an opportunity for the company that creates this graywater recycling system. Both of these groups will be looking for a system that is practical for a residential building and meets their local graywater quality standards. This system will have a wider economic impact because homeowners will save money on water but have a higher electric bill from the treatment system. If adoption of this system is widespread, there will be a reduced need for centralized water treatment plants.

Problem Statement

The following sections will demonstrate the need for a reduction in domestic, residential water consumption. These sections will explain the benefits of graywater recycling. They will also investigate and explain systems of water recycling in residential homes and their socioeconomic, environmental, and technical implications. Ultimately, these sections will develop a potential solution to the problem of how to reduce residential water consumption as well as its methods of its implementation and possible challenges. This will also touch on the larger implications of this solution.

Initial Problem Description

In recent years, prolonged drought and population growth have led to water shortages in regions around the world. This has led to severe economic and environmental consequences such as high unemployment in rural California (Fitchette, 2014) and the death of freshwater aquatic organisms in Australia (Bond, Lake, & Arthington, 2008). These water shortages can be exacerbated by poor water management practices like high water consumption.

While domestic water usage only accounts for 6.7% of daily U.S. water consumption, its daily usage is not decreasing as fast as other water usage categories. Since 2005, thermoelectric power generation's water usage has decreased by 20% and irrigation use has decreased by 9%. In contrast, domestic water consumption has only decreased by 5% since 2005 (Maupin, et al., 2014). This shows that there is room for improvement in the efficient use of domestic water consumption.

There are several methods to reduce residential water such as water efficient fixtures, educating the public about water conservation, and water recycling. These water efficient fixtures take the form of low water toilets, showerheads, and appliances. Educating people makes them more

conscious about their water usage and decreases water consumption ("Low Flow Water Fixtures (Sinks, Shower Heads, Toilets) - A Better City", 2016). In addition to these methods, water recycling offers a promising way to reduce overall domestic water consumption, particularly because it is currently underutilized.

Before water can be reused, it must undergo a treatment process. A typical suburban or urban home produces wastewater which fails to meet safe water regulations. Bacteria from residential wastewater far exceeds EPA standards for surface reuse which require no detectable fecal coliform/100 mL (Asano, 2007, p. 170). Treating this wastewater water can be complex and expensive. However, different appliances and fixtures in residential homes produce wastewater with varying levels of contaminants and bacteria. Since blackwater contains more contaminants than graywater, it is easier to treat graywater to an acceptable standard for reuse. Blackwater only accounts for between 11% and 17% of water usage in typical American and Canadian households, so graywater recycling could significantly reduce residential water consumption (Mayer et. al, 1999).

In 2005, it was estimated that 2600 millions of gallons per day of municipal wastewater were being reclaimed and reused in the United States at centralized water treatment facilities (Asano, 2007, p. 47). This represents only a small portion of 42000 million of gallons of water used every day by public water supplies throughout the country (Maupin, et al., 2014). While it is difficult to estimate the number of homes that currently have water recycling systems, there is the potential for expansion into new homes. Currently, 60 million Americans live in homes served by decentralized water treatment systems such as septic systems (Asano, 2007, p. 767). Additionally, in developing nations, there is no water supply infrastructure in the periphery of rapidly growing cities such as Bangkok (Jiawkok, Ittisupornrat, Charudacha, & Nakajima, 2012). A decentralized graywater system would be well suited for these homes.

Overall Analysis and Objectives

Water shortages have been shown to cause many negative economic, environmental, and social problems. In order to reduce water shortages, water consumption must fall across all industries and usage sectors. Residential water consumption could be reduced by implementing a practical decentralized graywater recycling system in homes, helping reduce the severity of water shortages.

This graywater recycling system would need to meet several criteria to be feasible. This system would need to be compact enough to fit in an unfinished area or yard of a residential home. A larger system would require the construction of an additional structure, increasing the cost of installing the graywater system. In dense urban areas, a large system simply could not fit on a property. Ideally, a graywater system should be economical enough that home owners and home builders can afford to purchase and install one. If the graywater system is prohibitively expensive to create and install, less people will opt to purchase one. This system would also need to be able to process the peak graywater outflow from a typical residential home, otherwise graywater would be diverted to traditional wastewater outflows, reducing the water saving potential of the treatment system. Based on typical water consumption in North American homes, a graywater system should be able to process at least 40-50 gallons (151-189 liters) of water per day per resident (Mayer et. al, 1999). Additionally, a residential graywater system should not require intensive or frequent maintenance. Frequent maintenance would be cumbersome for residents and would likely discourage the adoption of a graywater treatment system. The system would minimally have to meet water safety standards

for outdoor non-potable reuse. There could be a larger potential for water reuse if a treatment system were able to meet water safety standards for indoor reuse (toilet flushing, washing machine, shower, etc.). These standards vary between countries and subnational jurisdictions as demonstrated in Table 1. This system would ideally not be very energy intensive to operate. An energy intensive system would increase costs to the homeowner, making the graywater recycling system less appealing. Since this energy would sometimes come from sources that produce greenhouse gases and pollutants, this would offset the environmental benefits of saving water.

Table 1: Comparison of Water Quality Standards

Regional Standard	Reuse Application	Water Quality Criteria
United Kingdom (Environmental Agency 2011)	Sprinkler, car washing, toilet flushing, garden watering, washing machine use	<10 ntu turbidity; pH 5-9.5; <2 mg/L residential chlorine; <0.5 mg/L residential chlorine for garden watering
Wisconsin (WDOC 2015)	Toilet and urinal flushing	pH 6-9; BOD ₅ ≤200 mg/L; TSS ≤5 mg/L; Free chlorine residual ≤4mg/L
Wisconsin (WDOC 2015)	Surface irrigation except food crops, clothes & vehicles washing, air conditioning, dust control, soil compaction	pH 6-9; BOD ₅ ≤10 mg/L; TSS ≤5 mg/L; Free chlorine residual between 1 mg/L and 10 mg/L
New South Wales, Australia (NSW Health Department 2011)	Toilet flushing, cold water supply to washing machines, garden irrigation with local approval	BOD ₅ <20 mg/L; TSS<20 mg/L; Fecal coliforms <10 cfu/100 mL
Western Australia, Australia (Government of Western Australia, Department of Health 2010)	Toilet flushing, cold water supply to washing machines, irrigation	BOD ₅ <10 mg/L; TSS<10 mg/L; E. coli 1 MPN /100mL; Coliphages <1 pfu/100mL; Clostridia <1 cfu/100 mL
Victoria, Australia (EPA Victoria 2013)	Toilet flushing, cold water supply to washing machines,	BOD ₅ <10 mg/L; TSS<10 mg/L; Fecal coliforms <10 cfu/100 mL

	surface irrigation, subsurface irrigation		
NSF/ANSI 350R (NSF 2011)	Restricted indoor and unrestricted outdoor water reuse		pH 6-9; CBOD ₅ ≤10 mg/L (avg.) & ≤25 mg/L (max.); TSS ≤10 mg/L (avg.) & ≤30 mg/L (max.); Turbidity 5 ntu (avg.) & 10 ntu (max.); E. coli 14 MPN/100mL (mean) & 240 MPN/100mL (max.)
Jordan (Jordan Standards and Metrology Organization 2008)	For irrigation vegetables cooked	restricted and eaten	BOD ₅ <60 mg/L; COD <120mg/L; TSS 50mg/L; pH 6-9; E. coli <10 MPN/100mL

Source: (Yu, Rahardianto, Stenstrom, & Cohen, 2016) & (Assayed, Chenoweth, & Pedley, 2015).

It is worth noting other ways of treating graywater from residential buildings. Water from homes can be reused in a traditional, centralized way by sending combined wastewater to a water treatment facility. Currently, some centralized wastewater treatment plants treat water to reuse for irrigation in public parks and golf courses (Asano, 2007, p. 46). Treated municipal wastewater can also be used for aquifer recharge (Asano, 2007, p. 154). Homes would be best served by a decentralized system of water treatment rather than building new infrastructure to connect these homes to the public water supply. Even in areas connected to the public water supply, it would be costly to install new pipes bringing treated water effluent from a centralized treatment plant to reuse areas (Asano, 2007, p. 768). Additionally, centralized plants can affect the water recycling capability of thousands of households when there is an event that damages the plant. The impact from a nonfunctioning decentralized water treatment center would be much less severe (Asano, 2007, p. 768). Centralized wastewater treatment plants needlessly use more energy to treat water from the same number of homes. This is because the combined wastewater requires a higher level of treatment than treating graywater. It is estimated that decentralized greywater recycling systems use between 11.8% and 37.5% of the energy a centralized wastewater treatment plant uses to treat the waste from the same number of residents (Matos, Pereira, Amorim, Bentes, & Briga-Sá, 2014). Because of the advantages offered by decentralized graywater systems, the remaining sections will focus on them.

Historical and Economic Perspectives

During the late 1990s and 2000s, Australia suffered its most severe drought on record causing large environmental and economic damage (Bond, Lake, & Arthington, 2008). Last year, in 2015, South Africa experienced its driest year on record. This is causing a water shortage and has led to water restrictions in Johannesburg ("South Africa Drought: No End in Sight", 2016). Specifically in California, a five year drought has led to strain on water resources. The current drought is the worst drought event in the last 1200 years (Griffin & Anchukaitis, 2014). While uncertainties exist,

climate change will ensure there will be more severe droughts like this in the future that will impact future water resources and supply around the world (Griffin & Anchukaitis, 2014).

A severe reduction in water supply has negative economic impacts. For example, in 2013, 14000 acres of lettuce fields could not be planted in Fresno County, California because the severe drought could not support its growth. The lack of productive fields led to a decrease in the amount of work available and increased unemployment. The local unemployment rate was 34% in December 2013, higher than typical during December. (Fitchette, 2014). This phenomenon has been repeated in other areas with water shortages and is a serious problem for those who work in the agricultural sector.

During periods of drought, flora and fauna in the area comes under stress because of habitat destruction and increased competition for resources. Human activity can exacerbate this problem by siphoning off water from above-ground sources. Aquatic life is especially vulnerable to these impacts. High water usage during drought leads to a loss of habitat and an increase in habitat fragmentation as water levels drop. Water quality becomes poorer as oxygen levels decrease and salinity increases. All these factors contribute to population decline in aquatic organisms (Bond, Lake, & Arthington, 2008).

A lack of surface water in 2013 and 2014 forced California farmers to further deplete underground aquifers (Fitchette, 2014). This creates a long-term negative consequence because as aquifers are depleted, the agricultural industry must consume more energy to pump out remaining groundwater (Christian-Smith, Levy, & Gleick, 2014). Continued high water usage during prolonged periods of drought can lead to other negative consequences. During a water shortage, water resources used for hydroelectric power are redirected to water consumption, reducing hydroelectric power production. This is especially harmful because fossil fuels are often used to produce electricity to match continued demand. For example, during the 2007-2009 California drought, California replaced its losses in hydroelectric power production by burning natural gas and importing electricity (Christian-Smith, Levy, & Gleick, 2014). This releases more fossil fuels which further contribute to climate change. These severe and negative consequences justify efforts to reduce water shortages by recycling water.

While wastewater reuse has existed since ancient Greece, it has only been since the early 20th century that there has been a proliferation of water recycling systems (Asano, 2007, p. 41). An early example of wastewater recycling is Grand Canyon National Park's reuse of water for toilet flushing and lawn irrigation starting in 1926. Other early adopters of reusing wastewater for garden irrigation include the town of Pomona, California in 1929 and San Francisco's Golden Gate Park in 1932 (Asano 2007, p. 42). After 1960, water treatment and reuse increased substantially in the United States because of high population growth in the arid western states, stricter wastewater treatment, effluent discharge regulations, and the creation of water reuse guidelines and regulations in many states. (Asano 2007, p. 41).

Candidate Solutions

There are several different systems, besides the candidate solutions in the sections below, which could potentially treat household graywater for reuse on-site. One example is a constructed wetland, with layers of plants, silica sand, and gravel. This system has with a subsurface horizontal flow. This produces treated graywater that meets reuse standards including a common requirement of <10

mg/L of BOD₅ (Yu, Rahardianto, Stenstrom, & Cohen, 2016). However, this system has serious drawbacks. It is estimated that in order to treat a typical home's daily graywater effluent of 340 L, the constructed wetland would occupy 4.3-8.5 m². This would be difficult to accommodate in homes with small or non-existent yards. Additionally, it would require a long retention time of 4 to 8 days (Yu, Rahardianto, Stenstrom, & Cohen, 2016). These factors eliminate the horizontal flow constructed wetland as a viable treatment system.

Another potential greywater recycling system is using an activated sludge membrane bioreactor. This produces high quality treated graywater that meets most water reuse criteria for indoor and outdoor use. It meets safe water standards in criteria such as turbidity, TSS, and BOD₅ (Jong, et al., 2009). However, a study focused on using a membrane bioreactor to treat residential graywater detected unacceptable quantities of E. coli in the treated graywater (Jong, et al., 2009). In order to solve this problem, the treated water would need to be disinfected after treatment by the membrane bioreactor. Also, this system uses three tanks for water treatment, not including holding tanks before and after treatment (Jong, et al., 2009). The size of this system may become too large to be practical to be used in a home. For these reasons, membrane bioreactors are not well suited to treat household graywater for reuse.

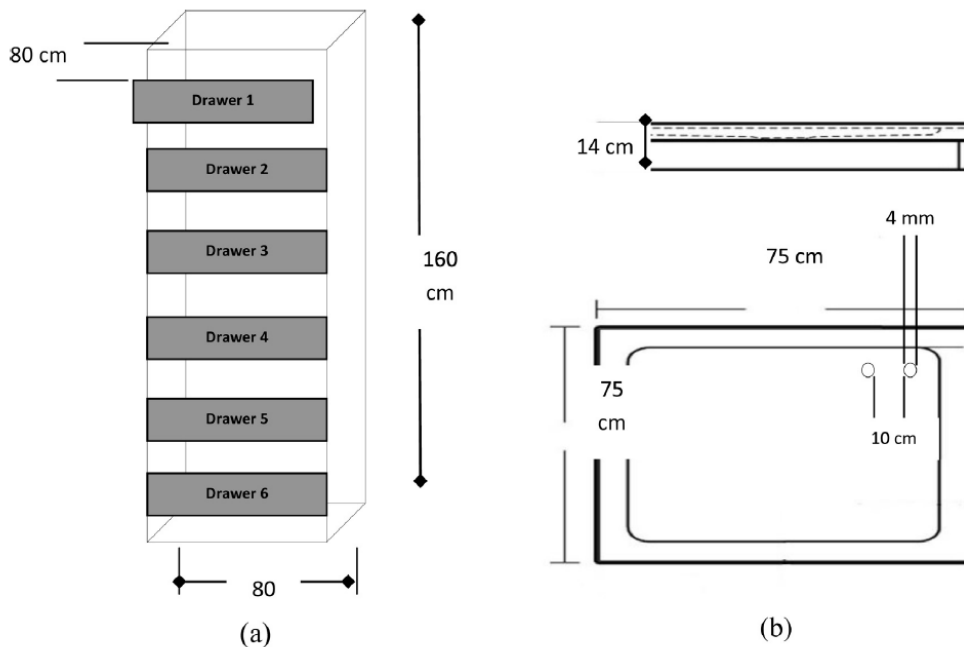
Drawer Compacted Sand Filter

A drawer compacted sand filter aims to filter graywater using a more traditional sand filter in a relatively compact space. Additionally, this system seeks to ease maintenance requirements compared to a traditional sand filter system. This is because each drawer can be easily removed and replaced without dismantling the entire filtration system. After graywater is produced in a house, it flows to a large collection tank, which also acts as a sedimentation tank. From here, a sump pump pushes water to the water distribution system on top of the drawer compacted sand filter. This distribution system consists of a series of plastic tubes which drips water directly above the first drawer of the drawer compacted sand filter. The filtration system itself consists of six PVC drawers stacked on top of each other, with a 10 cm vertical gap between each of them. Each drawer is perforated on the bottom with evenly spaced 4 mm holes to allow water to drip through the drawer (Assayed, Chenoweth, & Pedley, 2015). Water flows through the first drawer and drips through the next five drawers until it reaches the bottom. Drawer 1 is filled with 2.5 mm gravel. The second and third drawers are filled with 1.3 mm silica sand. The fourth and fifth drawers are filled with finer 0.7 mm silica sand. The sixth drawer has two different layers of material. The top layer is composed of 2.5 mm gravel and the bottom layer is filled with granular activated carbon. Once the water drips through the sixth drawer it is collected by a series of pipes and pumped to a third reservoir that holds the treated graywater until it is reused (Assayed, Chenoweth, & Pedley, 2015).

An advantage of the drawer compacted sand filter is that is compact. Excluding tanks (which may vary by household water usage), it is .75 m in length, .75 m in width, and 1.6 m in height. It occupies a floor area of 0.5625 m². This system also has a low cost of installation. In a study with this system in Jordan, a drawer compacted sand filter was estimated to cost 633 JD (\$895) to install in homes retrofitted for graywater recycling (Assayed, Chenoweth, & Pedley, 2015). This system does not require the use of chlorination which means there is virtually no residual chlorine in this treated graywater. It is easy to maintain this system as well, because any single drawer can be accessed or replaced without the need to dismantle other parts of the filtration system. This system has also been

shown to treat 350 liters of graywater per day (Assayed, Chenoweth, & Pedley, 2015). Since graywater only flows through the filtration system once, this system has a much lower electricity demand than other graywater treatment solutions.

A disadvantage of this system is that it has difficulty removing high amounts of organics and total solids from graywater. Since kitchen sinks are the source of most organics and solids, this system could only be effective by treating graywater from other sources. Because effluent from kitchen sinks cannot be treated by drawer compacted sand filters, this limits its potential to reduce water usage. In applications with residential graywater that excluded kitchen sinks, this system was able to produce treated graywater with a maximum BOD₅ of 19.0±8.0 mg/L, a maximum COD of 47±28 mg/L, a maximum TSS of 11.0±6.0 mg/L, pH of 7.9±0.4, and an E. coli count between 2 and 12 CFU/100 mL (Assayed, Chenoweth, & Pedley, 2015). This treated water is not of a high enough quality to meet some jurisdiction's above-ground potable reuse requirements, limiting its use to less stringent jurisdictions or to irrigation.



Source: (Assayed, Chenoweth, & Pedley, 2015).
Semi-Batch Vertical Flow Wetland

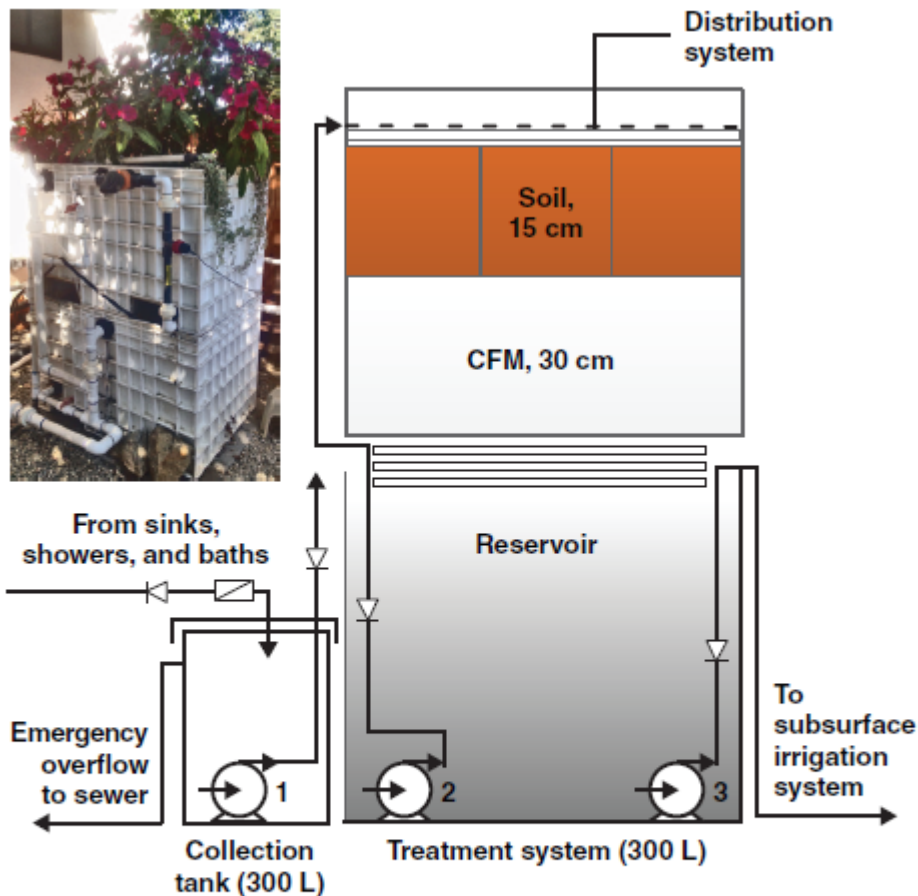
Traditionally in graywater treatment, a horizontal flow constructed wetland is used. As discussed previously, a large drawback of this graywater treatment solution is that it consumes a large area. This makes it relatively impractical for use in residential buildings, especially for urban environments with limited yard space. The semi-batch vertical flow wetland solves that drawback by stacking the treatment area, while achieving similar treatment results (Yu, Rahardianto, Stenstrom, & Cohen, 2016). This system functions through a series of multiple tanks and sump pumps. After use, the effluent graywater from the house is passed through a 1 mm by 1 mm filter screen before it moves to a collection tank. From there it is pumped to the top of the semi-batch vertical flow wetland

and is distributed equally across the surface through a series of pipes. These pipes have their outflows very near to the soil layer. The water then flows through a soil layer made of silica or a similar substitute. Coconut coir may be substituted for soil. This soil layer is separated into compartments with fabric. Wetland plants are also planted in the soil which aid in the filtration process of the graywater. Below this soil layer, is a layer of cross flow media composed of spherical plastic beads and gravel that provide a surface area for biofilm growth. Water collects in a reservoir below the filtration layers. Another sump pump pushes the water back to the top of the semi-batch vertical flow wetland and flows through the layers again. This water is continuously recirculated through the system as the first collection tank continues to collect graywater effluent from the house. When the collection tank is full, the reservoir empties into another tank where it is further treated with chlorine at a chlorine concentration of 4 mg/L to disinfect the recycled graywater. After this, the treated graywater is ready for reuse.

An advantage of the semi-batch vertical flow wetland is that it is relatively compact. Discounting storage tanks, it occupies a floor area of 0.68 m² (Yu, Rahardianto, Stenstrom, & Cohen, 2016). It can treat graywater to acceptable quality standards within 3 hours, showing marginal improvement afterwards. In a study of graywater from a single family home, the semi-batch vertical flow wetland was able to significantly improve water quality. Effluent from the system showed turbidity levels of 0.30±0.27 ntu, TSS of 0.5±0.12 mg/L, COD of 16.37±2.92 mg/L, and a BOD₅ of 3.1±1.18 mg/L (Yu, Rahardianto, Stenstrom, & Cohen, 2016). The pH of the water became slightly less basic, going from an average of 7.35 to an average of 6.90. This treatment process has been shown to virtually eliminate coliform bacteria. After filtration combined with disinfection with chlorine, the total number of coliforms decreased from an estimated average of 1.35*10⁸ per 100 mL to an undetectable level (Yu, Rahardianto, Stenstrom, & Cohen, 2016). Based on a three hour filtration time, this system can process 2100 L of graywater per day (Yu, Rahardianto, Stenstrom, & Cohen, 2016).

A disadvantage of this solution is that it consumes a large amount of electricity to operate its sump pumps. This may make the system uneconomical in areas with a high electricity cost. It is estimated that it would cost about \$2500 to purchase and install an automated version of this system not including retrofitting the home for graywater recycling. Because this system has wetland plants on top of the soil layer, this system would need to have access to sunlight, limiting its placement to an outdoor space or area of the home with adequate sunlight. Also, the chlorine used in the disinfection process would need to be replaced occasionally, adding to the cost of maintenance.

Figure 2: Diagram and Photograph of Vertical Flow Wetland



CFM—cross-flow media

The upper wetland unit consists of a soil layer and CFM. Graywater intake (pump 1), recirculation (pump 2), and discharge (pump 3) are controlled by three submerged pumps.

Source: (Yu, Rahardianto, Stenstrom, & Cohen, 2016).

Moving Bed Biofilm Membrane Bioreactor

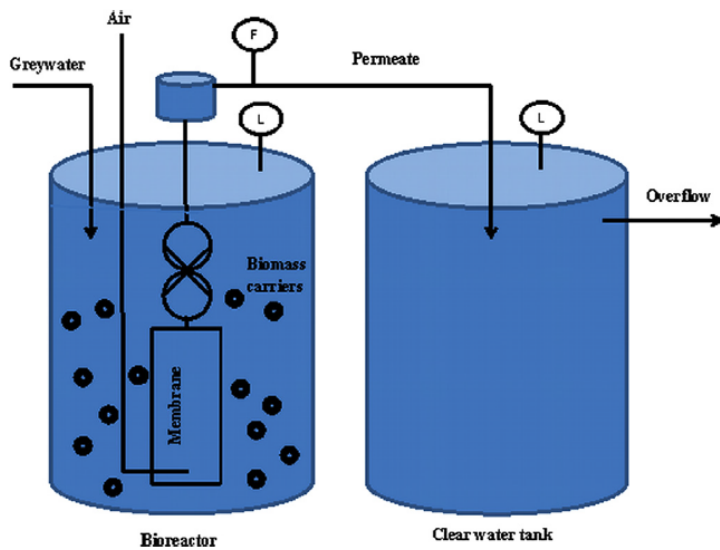
Moving bed biofilm membrane reactors offer the opportunity to solve the problems associated with conventional activated sludge membrane bioreactors, while still reaping the benefits of membrane bioreactors. Moving bed biofilm membrane reactors have a lower suspended solid concentration in the bioreactor and therefore a lower incidence of membrane clogging (Jabornig & Favero, 2013). Additionally, the biofilm reactor and membrane filtration system can be combined into one tank to reduce the amount of space required for a graywater recycling system (Jabornig & Favero, 2013). This makes it much more practical for homes in urban areas. Since only one tank is required, this also reduces the energy and maintenance requirements compared to an activated sludge membrane bioreactor, making this system more appropriate for residential use (Jabornig & Favero, 2013). The system functions by collecting graywater through a 1 mm by 1 mm screen into a tank that serves as a bioreactor. This tank contains moving bed biomass carriers. These carriers are

made of HDPE, have a high specific area, and are cylindrical in shape. These carriers serve as a place for biofilm to grow which break down organic compounds and pollutants in the graywater. An air compressor aerates the graywater for a minute once every ten minutes. Twice a day, during non-peak water use times, the system is flushed using a suction pump that pulls the water through a cylindrical 0.2 μ m membrane in the center of the tank. Here, the water is pulled up through a tube to another tank where the treated water is ready to be reused. During a flush, the water is pulled through the membrane for 15 minutes followed by 30 seconds of back flushing to prevent membrane fouling (Jabornig & Favero, 2013)..

An advantage of the moving bed biofilm membrane bioreactor is that is relatively compact and fits inside the water collection tank itself. Another advantage is that the system produces treated water that meets many water quality standards. In a study with synthetic graywater simulating a four person household, this system produced treated water with a COD of 86.1 ± 39.93 mg/L, a BOD₅ of 8.40 ± 2.80 mg/L, a pH of 8.34 ± 0.46 , a turbidity of 0.98 ± 1.28 ntu, and a TSS of 1.75 ± 1.85 mg/L (Jabornig & Favero, 2013). Additionally, after treatment *E. coli* was undetectable in the treated water (Jabornig & Favero, 2013). This system is also very flexible as to where it can be placed in a home. It is completely enclosed and therefore could be placed either in an unfinished area of the home or outside. Another advantage of this system is that it does not use chlorination so there is no residual chlorine in the water after treatment.

A drawback of this system is that it has a moderate rate of power consumption because of the air compressor and the suction pump. It is estimated that such a system would consume 1.26 kW*h per cubic meter of treated water produced. This system also only processes 200 L of graywater per day. Additionally, it takes upwards of two weeks after the installation for the biofilm to grow sufficiently to produce high quality treated water (Jabornig & Favero, 2013). Homeowners must also perform regular maintenance on this system because sludge builds up on the bottom of bioreactor tank at rate of about 2 L per week (Jabornig & Favero, 2013). This must be removed every few weeks otherwise the capacity of the bioreactor will be diminished. Another disadvantage of this system is its high installation. It is estimated that it will take about 15 years of use before this becomes cost effective for the homeowner (Jabornig & Favero, 2013).

Figure 3: Diagram of Moving Bed Biofilm Membrane Bioreactor



Source: (Jabornig & Favero, 2013).

Comparison of Solutions

Table 2: Table Comparing the Qualities of Each Candidate Solution

	Drawer Compacted Sand Filter	Semi-Batch Vertical Flow Wetland	Moving Bed Biofilm Membrane Bioreactor
Size (Floor Area m ²)	0.5625	0.68	Varies on tank size
Cost (\$)	895	~2500	-
Water Treated Daily (L)	350	2100	~200
Maintenance	Low	Low	High
Electricity Consumption	Low	High	Medium
BOD ₅ of Treated Water (mg/L)	19.0±8.0	3.1±1.18	8.40±2.80
COD of Treated Water (mg/L)	47±28	16.37±2.92	86.1±39.93
Turbidity of Treated Water (ntu)	-	0.30±0.27	0.98±1.28
TSS of Treated Water (mg/L)	11.0±6.0	0.5±0.12	1.75±1.85

E. coli in Treated Water (CFU/ 100mL)	2 - 12	<1	<1
Waiting Period After Installation (days)	0	0	~ 14
pH of Treated Water	7.9±0.4	6.90	8.34±0.46
Residual Chlorine in Treated Water (mg/L)	0	4	0
Is able to treat graywater from kitchen sinks?	No	Yes	Yes

Proposed Solution

Based on the findings in the candidate solutions section, semi-batch vertical flow wetland system offers the best opportunity for residential graywater recycling when compared to the other candidate solutions. This is a compact graywater treatment system, which makes it ideal for use in residential homes. Its small size means that it can be placed in an unfinished area of the house or in a small yard, even in an urban area with moderate density. The semi-batch vertical flow wetland system produced treated graywater that was of the highest quality when compared to the other two systems. The treated effluent from this system contained lower levels of BOD₅, COD, turbidity, and TSS than either the drawer compacted sand filter or the moving bed biofilm membrane bioreactor. Like the moving bed biofilm membrane bioreactor, the semi-batch vertical flow wetland also had undetectable levels of E. coli in the treated graywater. This allows the treated graywater from the semi-batch vertical flow wetland to be used for a greater number of reuse applications than treated graywater from the drawer compacted sand filter system. This system also has the potential to be used in a greater number of regions around the world since it meets more stringent water quality standards. For example, this system meets water quality standards for toilet flushing, cold water laundry, and surface irrigation in Western Australia, New South Wales, and Victoria. It also could be used in Wisconsin for the same uses except that irrigation could not be used on food crops. This treated water also meets NSF/ANSI standards for restricted indoor use as well as Jordan’s standards for restricted irrigation. Also, this system can treat graywater produced by kitchen sinks, allowing more water from the house to be reused. This will allow the household to use less water compared to the drawer compacted sand filter system.

Major Design and Implementation Challenges

There are some apparent difficulties in implementing the semi-batch vertical flow wetland graywater treatment system. This system is one of the more expensive graywater solutions to install. This may discourage homeowners from purchasing this system. Some possible solutions to this problem include reducing its cost, or working with local and regional governments to provide subsidies. This system also consumes a high amount of electricity. In areas with high energy costs and low water costs, such as Mexico, the time to make a return on investment for this system is too long to be attractive to homeowners. In regions with extremely high electricity costs, this system will not be economically beneficial at all (Yu, Rahardianto, Stenstrom, & Cohen, 2016). Additionally, treated graywater from this system cannot meet certain water quality standards because it contains residual chlorine from the disinfection process. For example, its treated graywater contains too much chlorine to be able to use for both indoor use and garden irrigation in the United Kingdom. Since the semi-batch vertical flow wetland uses plants as a part of its filtration process, this system need to have access to sunlight. A team would need to find a way to bring sunlight to the top of this system in urban areas with small yards or yards with limited sunlight. This system would need to be kept warm throughout the year to ensure both the wetland plants would not go dormant and that the water inside the system does not freeze. If the plants in the system are dormant, it could negatively affect the quality of the treated water because the plants will not be able to act as a biological filter. If the water freezes inside the system, it could lead to graywater backup inside the residence and would also prevent the filtration system from operating.

Implications of Project Success

If the project is successful, more residential buildings will have graywater treatment systems and will reuse graywater for more purposes than they currently do. This will reduce water consumption in residential homes.

This system will appeal to environmentalist homeowners who are interested in reducing their water consumption. In areas with high water costs, such as Denmark and Germany, this system could be a serious economic benefit (Yu, Rahardianto, Stenstrom, & Cohen, 2016). Economic minded homeowners would be interested in purchasing this system from our company. Home builders trying to market their homes as environmentally friendly would want to install this graywater recycling system in their homes. An all-in-one graywater recycling system will reduce the need for homeowners to have to design their own system and will make buying a graywater recycling system more consumer friendly. New competitors may emerge to compete with this system and try to take some of its market. As graywater systems like this become common in water stressed regions, new regulations may require graywater recycling systems in new homes, further growing this market. This system will increase overall demand for chlorine because it needs to be used in the system's disinfection process.

There are several benefits from this decrease in residential water consumption. For example, this will also reduce demands on municipal sewers and sewage treatment systems in areas that have homes with these systems. In water-stressed regions, this reduction in water consumption will ease water shortages because less water will need to be diverted for use in residential homes. This will reduce the negative effects associated with water shortages such as high rural unemployment, habitat destruction of aquatic flora and fauna, and an overuse of underground aquifers. This system will have an additional environmental benefit because it will save electricity compared to treating

graywater at a centralized wastewater treatment plant. However, this will shift the electric cost of treating water from a water treatment plant to homeowners.

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