THESIS

DEVELOPMENT OF A COST EFFECTIVE AND ENERGY EFFICIENT TREATMENT SYSTEM FOR GRAYWATER REUSE FOR TOILET FLUSHING AT THE MULTI-RESIDENTIAL SCALE

Submitted by

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In partial fulfillment of the requirements

For the Degree of Master of Science

Colorado State University

Fort Collins, Colorado

Fall 2012

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ABSTRACT

DEVELOPMENT OF A COST EFFECTIVE AND ENERGY EFFICIENT TREATMENT SYSTEM FOR GRAYWATER REUSE FOR TOILET FLUSHING AT THE MULTI-RESIDENTIAL SCALE

A growing population increases water demand in many metropolitan areas resulting in the need for projects, like graywater reuse, that free up water supply or decrease water consumption. Plumbing for graywater collection from showers and bathroom sinks has been separated from blackwater collection in 14, two-person units at a residence hall at Colorado State University. Treatment technologies were evaluated for the ability to provide safe and cost effective onsite reuse of graywater for toilet flushing. The goal is to develop a system with low use of energy and consumables capable of treating graywater to a quality safe for toilet flushing. The system analyzed filtration utilizing coarse, sand (20-40 microns), or cartridge (100 microns) filtration and the disinfection potential of ultraviolet (UV) with hydrogen peroxide (H_2O_2), chlorine, UV with chlorine as a residual, or ozonation with chlorine as a residual

Disinfection efficacy was determined by measuring general water chemistry parameters in addition to concentration of *E. coli* and total coliforms. The influent *E.coli* averaged $10^{2.7\pm1.1}$ CFU/100mL and total coliform averaged $10^{7.9\pm1.2}$ CFU/100mL. Effluent *E. coli* was reduced to non-detectable concentrations for UV combined with H_2O_2 and chlorine, but only chlorine measured non-detectable concentrations of total coliform. At the tested doses, ozone combined with chlorine and UV combined with chlorine resulted in limited or no removal of *E.coli* and total coliforms. Higher doses may prove to provide more efficient disinfection but require more

expensive equipment and may impact the projects feasibility. Based on data collected, chlorine appears to be a better approach for disinfection of graywater. None of the disinfectants significantly affected graywater chemistry, but all reduced odors with the exception of UV.

There was no significant change of water chemistry as a result of coarse or cartridge filtration. Sand filtration significantly reduced turbidity, total suspended solids (TSS), total organic carbon (TOC) and biochemical oxygen demand (BOD_5) by 13±11%, 37±12%, 31±17% and 21±9% respectively. Despite the decrease of TSS and TOC, the sand filter resulted in an increase chlorine demand. As a result, it was concluded that the most effective treatment alternative is incorporation of coarse filtration followed by chlorine disinfection. The health and environmental concerns associated with chlorine disinfection can be minimized by utilizing ammonia in graywater to favor monochloramine formation which results in a smaller dose. Additionally, the influent specific UV absorbance of 1.1±0.6 indicates reduced risk of disinfection by-product formation.

The cost, including capital and operation, of implementing various filtration and disinfection approaches along with the total life-cycle project cost at various system sizes were evaluated. At the residence hall scale, the most cost effective disinfection approaches include application of liquid chlorine, ultraviolet with chlorine as a residual, and small-scale ozonation with chlorine as a residual. The cost of the hydrogen peroxide dose rendered its use infeasible. The cost effective filtration approaches were coarse, sand (20-40 microns), and cartridge (100 microns) and the associated capital for each filter did not have a large impact on the life-cycle cost. Graywater reuse for toilet flushing proved financially beneficial particularly in regions with high domestic water costs and at system sizes that reuse ≥1,000 gpd. These projects can be financially feasible and have low payback periods in addition to indoor water use reduction.

ACKNOWLEDGMENTS

I would like to thank my adviser Dr. Sybil Sharvelle for the opportunity to work on this project and the countless support and guidance throughout the process. Additionally, I would like to thank Dr. Larry Roesner for his passion and guidance for graywater reuse and funding me in the pursuit of my master's degree. I am so appreciative of the opportunity that they provided and the ability to further my engineering education.

I would also like to thank Dr. Christopher Goemans, Dr. Susan DeLong and Dr. Ken Carlson for helping me through various technical aspects and their willingness to meet with me on multiple occasions. Finally, I would like to acknowledge the support of multiple graduate students involved with research with Dr. Sharvelle and Dr. DeLong and would like to thank specifically Kristen Wiles and Meg Hollowed. Both of which helped me on many occasions to operate and complete the research project.

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1.0 INTRODUCTION

1.1 Research Motivation

Meeting a population's water demand is an important issue as many areas are approaching or have reached the limit of their water supply (U.S. EPA, 2004). One example of this growing concern is the Environmental Protection Agency (EPA) formation of the WaterSense program in 2006. WaterSense is a partnership that encourages water practices that will decrease water consumption and help protect the nation's water supply (WaterSense, 2012). Water conservation practices address the potential effects of an increasing population on limited water supply. Figure 1.1 shows the United States Geological Survey (USGS) current domestic water use and the U.S. Census Bureau projected population change by 2030.

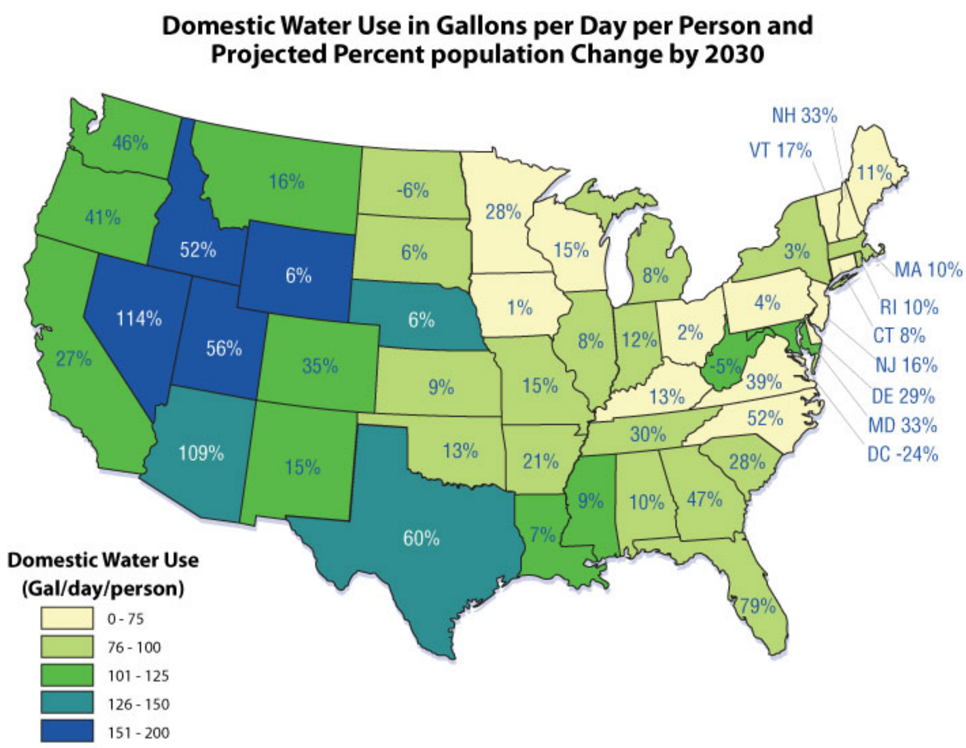

Figure 1.1 Extracted from WaterSense on Domestic Water Use and Projected Population Change (WaterSense, 2012)

This figure shows the dramatic population growth expected throughout the United States, especially in western areas like Texas, Nevada and Arizona. The growing population will result in an increase in water demand. There will be a need for projects and solutions to address how to supply the necessary water to these regions with growing populations.

To address increasing water demand, municipalities are evaluating various water projects that may help increase supply and/or decrease demand. Implementing these projects is very costly and often requires advanced water treatment or major infrastructure improvements. In order to increase the municipal water supply and meet future demand, Aurora Water developed the Prairie Waters Project. This project cost over $6.5 million dollars and has the capacity to treat 50 million gallons per day (gpd) (Aurora Water, 2010). A more cost effective and ecologically beneficial alternative to developing new water supplies is to improve water use efficiency (Cooley et al., 2010). Graywater reuse is one way in which a municipality may address an increase in water demand without having to procure additional water supply or implement costly treatment improvements. Graywater reuse has the potential to decrease water demand on a treatment plant, reduce wastewater generated, free up water supply for other uses and help in times of shortened water availability like drought conditions.

Graywater is defined as the portion of domestic wastewater that is not toilet water and does not contain human waste (Jefferson et al., 2004). In the U.S., dishwater is typically separated from graywater due to high organics and foodborne pathogens (Sharvelle et al., 2012). Graywater sources generally include shower, bath, laundry, sink (excluding kitchen) and wastewater. Graywater is distinguished differently from blackwater because it is lower in organics (Pidou et al., 2007) and pathogens (Elmitwalli and Otterpohl, 2007). For this reason, graywater is easier to treat and there is interest related to practices that utilize graywater as a beneficial water source.

The primary graywater reuse applications are for irrigation and/or toilet flushing. These applications have minimal human contact and require minimum treatment that can be done on-site. Use of graywater can offset demand of domestic fresh water that is used to irrigate or flush a toilet. Graywater reuse for toilet flushing is very beneficial at the multi-residential scale where irrigation demand is minimal (Hanemann, 1998) and graywater can be more easily collected and redistributed.

In order to be successfully implemented, graywater reuse for toilet flushing treatment systems must provide finished water that is safe and aesthetically pleasing for the necessary use (Winward et al., 2008a). Additionally, the systems need to be economically feasible and require little maintenance and energy for operation. These are the necessary social, public health and economic considerations that must be met for the implementation of graywater reuse at a multi-residential scale.

Colorado State University (CSU) is heavily involved in research and innovation and has interest in implementing conservation projects that promote their "green" initiatives. This has included utilizing raw water for irrigation and utilizing ultra-low flow water fixtures in new residence halls (CSU, 2002; CSU, 2007). The university has more than 5,000 students that reside on campus each spring and fall semester. This makes the campus a very large water consumer. The university is proactively reducing consumption by incorporating water saving devices in new facilities and investigating alternative practices. This has included interest in implementing graywater reuse for toilet flushing at the multi-residential scale to offset water use in the residence halls.

There have been many tests conducted on graywater reuse alternatives at multiple scales. These projects are often done in lab, performed at small scales or focus on reuse for irrigation.

There are fewer projects that have been successfully implemented and operated at a multi-residential scale. There is still no widely accepted treatment process or reuse practice for graywater toilet flushing and demonstration scale projects are required to move this concept forward.

1.2 Research Objective

The objective of this project was to determine the most appropriate sequence of filtration and disinfection approaches to treat graywater for supply to toilets. The goal was to ensure high efficacy of disinfection while minimizing consumables, energy input, maintenance, and system cost (capital and operations). A pilot test unit was operated and tested in the Aspen Hall. A series of three different filters and four different disinfectants were tested throughout the course of three academic semesters. The cost to implement graywater treatment options was analyzed at a range of multi-residential scales. Operations of the pilot scale unit guided the design of a prototype system that has been installed at Aspen Hall and the proven system will be connected to toilets in student's rooms in the near future. This project provides an analysis on implementation costs and treatment operations of graywater reuse for toilet flushing at the multi-residential scale.

1.3 Thesis Overview

The next chapter (Chapter 2) will provide background on graywater reuse regulations and a review on technical approaches to graywater reuse filtration and disinfection. Analysis on the filtration and disinfection efficiency is presented in Chapter 3. Based on data collected on treatment approaches, an evaluation of the economic implementation cost was conducted (Chapter 4). Finally, a description of the selected and installed treatment process is described in Chapter 5 and a summary of the research and future work is provided in Chapter 6, the final chapter. The attached appendices provide details of the experiments and calculations that were performed for the project.

2.0 BACKGROUND AND LITERATURE REVIEW

With focus on water supply protection (U.S. EPA, 2004), there has been a growing amount of emphasis on technologies that promote water conservation (WaterSense, 2012). Water use in North America has been declining the past 25 years largely due to low-flow and water conservation appliances (Rockaway et al., 2011). However, this trend is believed to be flattening out as many low-flow appliances are installed and water conservation technology is becoming limited on potential additional water savings (Rockaway et al., 2011).

Graywater reuse at the residential and multi-residential scale has the potential to further water conservation practices and decrease the residential water demand. Graywater accounts for 40% of internal water consumption and requires less treatment than domestic wastewater (Figure 2.1; Rockaway et al., 2011). Graywater is often reused for irrigation or toilet flushing. Reuse for irrigation is beneficial because it requires less treatment and reduces consumption of municipal drinking water. However, graywater reuse for toilet flushing provides year round water savings and reduces the fresh water consumption and wastewater production, which often makes these projects more cost effective. Additionally, regional water rights may have issues with graywater reuse for irrigation because a non-consumptive water source is being reused for a consumptive purpose. For these reasons, graywater reuse for toilet flushing is the more efficient and economic water conservation practice.

In the United States, graywater applications often exclude high organic food waste (dishwasher and kitchen faucets). This report will follow the International Plumbing Code (IPC) definition which states graywater is, "waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays" (IPC, 2012).

This chapter will provide background on graywater quantity and quality. Additionally, an overview of current water reuse and graywater reuse regulations is included. Researched filtration and disinfection alternatives are covered at the end of this chapter as well as a summary of current graywater reuse systems on the market.

2.1 Graywater Quantity

To assess the potential water savings of a graywater project, it is important to understand graywater production rates and toilet water demand. Water use is highly variable based on demographics, economics and single or multi-family residents (Hanemann, 1998). As seen in Figure 2.1, Denver Water estimates single-family graywater production at 25.3 gallons per capita per day (gpcpd) and toilet demand at 15.4 gpcd (Rockaway et al., 2011). This implies that by meeting toilet demand with treated graywater, there can be a 25% savings in indoor water consumption. Many new facilities that may be considering graywater reuse also have low-flow fixtures. Water use when all appliances are low-flow estimate shower and washing machine graywater production at 21.8 gpcpd and toilet demand at 8.0 gpcpd (Commes, 2010). The AWWA conducted a thorough research of water use across residents and found that average indoor water use is 69.3 gallons and 26.7% of that is used to flush toilets (AWWA, 1999a).

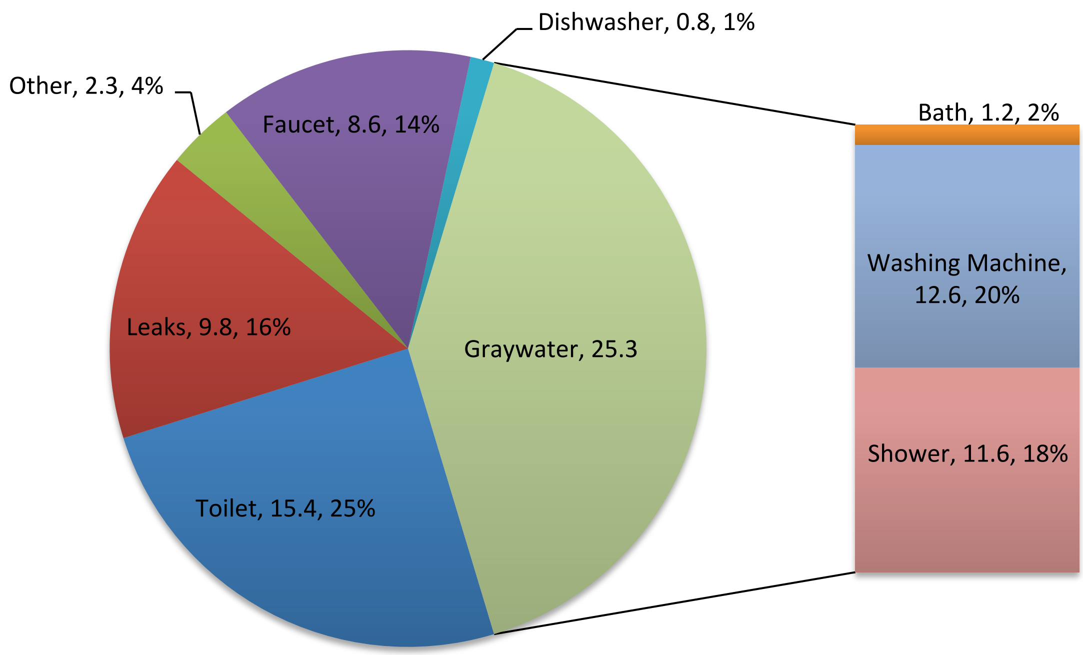

Figure 2.1 Denver Water Residential Water Use adapted from Water Use Trends in North America (units gpcpd; faucet graywater assumed minimal; Rockaway et al., 2011)

2.2 Graywater Water Quality

To design the appropriate treatment process it is important to understand water quality. Graywater quality is highly variable which may complicate the treatment process (Jefferson et al., 2004). When graywater is defined to not include kitchen wastewater, it is often categorized as light or low strength graywater (Winward, 2007).

Table 2.1 provides a summary of graywater influent chemistry based on water use at a residential scale and multi-residential scale (Eriksson et al., 2002; March et al., 2004; Metcalf and Eddy, 2003).

Table 2.1 Graywater Water Chemistry

		Multi-Residential: Hand Sinks, Shower, Bath (March et al., 2004)	**Residential: Bathrooms** (Eriksson et al., 2002)	**Residential: Laundry** (Eriksson et al., 2002)	**Untreated Domestic Wastewater** (Metcalf and Eddy, 2003)
Temperature	Celsius		29	28-32	
pH		7.6	6.4-8.1	8.1-10	
TSS	mg/L	44	54-200	120-280	100-350
Turbidity	NTU	20	28-240	410-1340	
Conductivity	µS/cm		82-250	190-1400	
Alkalinity	mg/L as $CaCO_3$		24-67	83-200	
BOD_5	mg/L		76-200	48-380	110-400
TOC	mg/L-C	58	30-104	100-280	80-290
COD	mg/L	171	100-424	12.8-725	
Total nitrogen	mg/L-N	11.4	5-17	6-21	20-85
Ammonia	mg/L		<0.1-15	.04-11.3	12-50

An important concept in a water reuse is that different demands can be met with different water quality (Gleick et al., 2003). Intensive treatment is not necessary to treat graywater to fresh water quality when reused for toilet flushing. The main chemistry concerns with graywater reuse for toilet flushing include turbidity or total suspended solids (TSS) and biochemical oxygen demand (BOD_5), chemical oxygen demand (COD) or total organic carbon (TOC). Turbidity and suspended solids cause poor aesthetics and may harbor pathogens. BOD_5, COD and TOC may cause a high disinfectant consumption and allow for regrowth in the distribution system.

One of the largest concerns with graywater reuse is the potential health risk from exposure to pathogens. A variety of indicator organisms have been studied in graywater. A study of a dorm at Cranfield University measured total coliform, *E. coli*, Enteroccoci, Clostridia, *P. aeruginosa*, *S. aureus* (Winward et al., 2008a). However, the *S. aureus* was only present in 25% of the tested samples. Table 2.2 includes the Cranfield findings and a literature review was conducted of multiple graywater sources (Winward et al., 2008a; Winward, 2007).

Table 2.2 Graywater Pathogens

	Dorms: Shower and hand sink Log$_{10}$ CFU/100mL (Winward et al., 2008a)	**Light Graywater** Log$_{10}$ CFU/100mL (Winward, 2007)	**Health Concern** (FDA, 2012)	**Exposure**
Total coliform	5.4	2.7-7.4	Indicator Organism	-
E.coli	2.8	0.5-4.4	Gastrointestinal	Ingestion
Enterococci	2.8	1.9-3.4	Gastrointestinal, nausea, chills, dizziness	Ingestion
Clostridia	3.1		Gastrointestinal	Ingestion
P. aeruginosa(1)	4.4		Dermatitis, Otitis	Dermal
S. aureus	3.4		Gastrointestinal, nausea, headache	Ingestion
Heterotrophic bacteria		5-7.4	Indicator Organism	-

It is important to understand that indicator organisms are not true pathogens, but representative of types of bacteria, protozoa or viruses that may survive and grow in similar conditions. There are not studies on true pathogens in graywater and the presence of these indicator organisms may not be a good representative of pathogens based on the exclusion of toilet and kitchen wastewater (Sharvelle et al., 2012). Actual human health risk will be dependent on pathogen source, applied treatment and exposure route (Ottoson and Stenstrom, 2003).

Additionally, graywater quality will deteriorate over time. Stored graywater will result in exponential total coliform growth from 100 to 8.4*10^6 CFU/100mL after 72 hours (March and Gual, 2009). Dixon et al. observed that storage of 24 hours can provide beneficial TSS and COD removal, but storage over 48 hours may lead to anaerobic conditions and aesthetic issues (Dixon et al., 2000). For this reason graywater storage is sometimes regulated to 72 hours (IPC, 2012).

2.3 Regulations

2.3.1 Graywater Reuse Regulations

Graywater reuse for toilet flushing is not a new concept but it is still without well defined regulations. There are no national regulations on graywater reuse but 20 states (Figure 2.2) have established graywater regulations 17 of which allow reuse for toilet flushing (Sharvelle et al., 2012). The regulations for graywater reuse are highly variable based on the state (Table 2.3). Hawaii, Idaho, Maine and Nevada allow graywater reuse for irrigation but do not specify graywater reuse for toilet flushing, and Montana, South Dakota and Wyoming allow graywater reuse for toilet flushing but have no specified regulations (Sharvelle et al., 2012). Of states that specify graywater reuse for toilet flushing, BOD_5 and TSS are often regulated to <10-30 mg/L and <5-30 mg/L respectively. Pathogen regulations are variable state by state. California is the strictest with a required 5 Log MS2 reduction and total coliform maximum of 2.2 CFU/100mL, while Utah only regulates *E.coli* to 126 CFU/100mL. (Sharvelle et al., 2012)

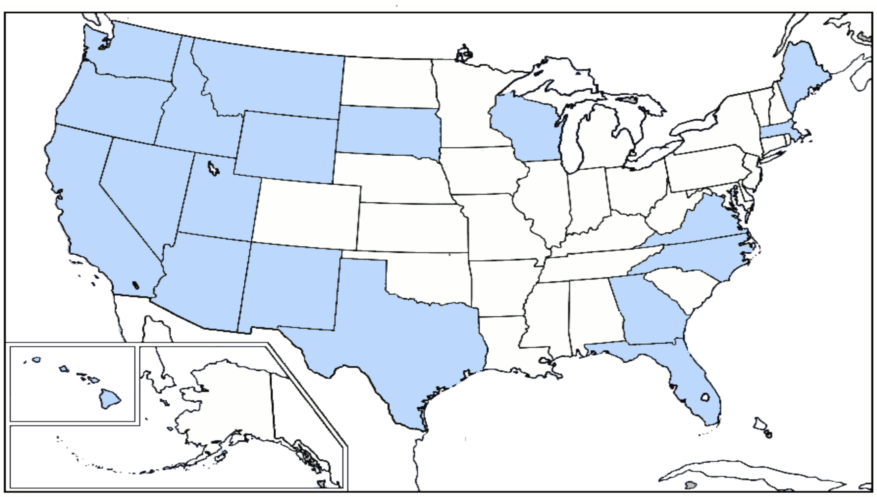

Figure 2.2 Figure extracted from WERF Graywater Regulations on States with Graywater Reuse Regulations (Sharvelle et al., 2012)

Table 2.3 Adapted from WERF Report on Graywater Reuse for Toilet Flushing regulations (Sharvelle et al., 2012; ND means non-detect; N/A means not-applicable)

State	Water Quality Requirements					Disinfection Requirements	Dose/Residual
	TSS mg/L	Turbidity mg/L	BOD mg/L	Total Nitrogen mg/L	pH		
Arizona	N/A	2	N/A	<10	N/A	ND fecal coliform	N/A
California	N/A	N/A	N/A	N/A	N/A	total coliform 2.2 CFU/100mL: MS2>5 Log Removal	Ct 450 mg/L-min with a contact of 90 minutes
New Mexico	30	N/A	30	N/A	N/A	N/A	N/A
Oregon	10	N/A	10	N/A	N/A	total coliform 2.2 CFU/100mL	N/A
Washington	30	N/A	25	N/A	6 to 9	N/A	Chlorine, Iodine or Ozone
Florida	30	N/A	25	N/A	6 to 9	N/A	N/A
Georgia	30	10	25	N/A	N/A	total coliform 500 CFU/100mL: fecal coliform 100CFU/100mL	N/A
Massachusetts	<5	<2	<10	<10	N/A	fecal coliform 14 CFU/100mL	N/A
North Carolina	30	N/A	25	N/A	6 to 9	N/A	N/A
Texas	N/A	N/A	N/A	N/A	N/A	fecal coliform 20 CFU/100mL	N/A
Utah	25	N/A	25	N/A	N/A	*E. coli* 126 CFU/100mL	N/A
Virginia	30	N/A	25	N/A	N/A	N/A	N/A
Wisconsin	<5	N/A	200	N/A	6 to 9	N/A	0.1-4 mg/L Free Chlorine Residual

N/A is defined as not applicable

2.3.2 Water Reuse Regulations

While many states do not address graywater reuse for toilet flushing specifically, many do address water reuse applications. Most of these regulations are for irrigation uses but some states also include reuse for toilet flushing, fire protection, decorative ponds, construction or car washing. In 2002, the EPA surveyed states that have regulations that allow for water reuse for toilet flushing. These findings are summarized in the Guidelines for Water Reuse (U.S. EPA, 2004) and are outlined below (Table 2.4). There is a broad range of water quality, disinfection and treatment regulations.

Table 2.4 Unrestricted Urban Reuse Regulations compiled from Guidelines for Water Reuse (U.S. EPA, 2004; ND means non-detect; N/A means not-applicable)

State	Water Quality Requirements				Disinfection Requirements	Disinfection Dose/Residual
	TSS mg/L	Turbidity mg/L	BOD mg/L	pH		
Arizona	N/A	2	N/A	N/A	ND fecal coliform	N/A
Arkansas	None Specified					
California	N/A	2	N/A	N/A	total coliform 2.2 CFU/100mL	N/A
Delaware	10	5	10	N/A	fecal coliform 20 CFU/100mL	N/A
Florida	5	20	N/A	6 to 8.5	ND fecal coliform	Total chlorine residual of 1 mg/L after 15 minute contact
Georgia	5	3	5	6 to 9	fecal coliform 23 CFU/100mL	Detectable disinfection residual
Hawaii	N/A	2	N/A	N/A	fecal coliform 2.2 CFU/100mL and 5 Log virus reduction	Chlorine residual of 5 mg/L after 90 minutes contact
Illinois	None Specified					
Indiana	5	N/A	10	6 to 9	ND fecal coliform	Total chlorine residual of 1 mg/L after 30 minute contact
Massachusetts(1)	10	5	30	6 to 9	fecal coliform 100 CFU/100mL	
New Jersey(1)	5	N/A	N/A	N/A	fecal coliform 2.2 CFU/100mL	Chlorine residual of 1 mg/L after 15 minute contact
North Carolina(2)	5	10	10	N/A	fecal coliform 14 CFU/100mL	N/A
South Dakota	None Specified				total coliform 200 CFU/100mL	N/A
Texas	N/A	3	5	N/A	fecal coliform 20 CFU/100mL	N/A
Utah	N/A	2	10	6 to 9	ND fecal coliform	Total chlorine residual of 1 mg/L after 30 minute contact
Washington	30	5	30	N/A	total coliform 2.2 CFU/100mL	Chlorine residual of 1 mg/L after 30 minute contact

(1)Total Nitrogen requirment of 10 mg/L, (2)Ammonia requirement of 4 mg/L, ND stands for Non-Detect

There is a wide range of regulations when it comes to both graywater and water reuse practices. There is no consistency between states on what is the proper organism to regulate and what degree of disinfection is necessary. Some states, like California, require similar water reuse and graywater reuse regulations requiring 2.2 CFU/100mL total coliform maximum levels. While other states, like Utah, recognize a difference between general water reuse and graywater reuse requiring non-detect of fecal coliform for water reuse while more lenient regulations of 126 CFU/100mL of *E. coli* for graywater reuse. Most states do require less strict water standards for graywater reuse versus urban water reuse. Based on this large variability, there is need for research to further investigate what treatment is necessary and appropriate for graywater reuse.

The current regulations often require treatment that includes removal of organics and solids followed by disinfection in order to meet the established standards. These regulations are based on a wide variety of use and may be too strict when it comes to reuse applications for toilet flushing. The City of Guelph analyzed water quality of toilets flushed with fresh water and graywater to compare the health risks of switching to graywater. The graywater toilets had a fecal coliform concentration of 2-770 CFU/100ml and chlorine residual of 0.24-3.53 mg/L. The fresh water toilets had a fecal coliform concentration of 11-998 CFU/100ml and 0.22-0.33 mg/L. This shows that graywater may actually pose less of a health risk based on the lower indicator organisms measured. This is likely to because of the larger chlorine residual that is introduced when utilizing graywater reuse. (City of Guelph, 2012)

2.4 Graywater Filtration

All graywater treatment systems need to utilize filtration to remove solids that may harbor pathogens or make the water aesthetically unpleasing. The types of filtration practiced have ranged from as simple as a coarse strainer to remove large hair particles to membrane filtration that remove organic carbon and suspended solids. Christova-boala et al. studied a strainer, mesh and fine (0.2mm) filter in series and found that weekly maintenance was required for each filter (Christova-boala et al., 1996). A hotel in Spain utilized nylon and sand filter and achieved an improvement of TSS, turbidity and TOC of 28%, 18% and 20% respectively. Every 5-6 days the nylon and sand filter required backwashing (Gual et al., 2008). Another hotel used a nylon sock filter (0.3mm) and achieved a reduction of TSS from 44 to 18.6 mg/L (March et al., 2004). There have been other advanced graywater filtration approaches that include Ultrafiltration (UF), nano-filtration, and UF + Reverse Osmosis (RO) (Li et al., 2009). The efficiency of these filters is highly dependent on the pore size and ranged from 56% to 98% BOD removal (Li et al., 2009). These membranes are typically more efficient but will have a higher operation cost and require more maintenance (Pidou et al., 2007). Filters that have low capital cost, minimal maintenance and energy consumption increase the potential for the implementation of graywater reuse. If a system is to intensive in any of these areas, the consumer may prefer to maintain the utilization of the current municipal water source and utilities will not benefit if treatment costs are not more efficient than conventional water and wastewater systems.

2.5 Graywater Disinfection

To ensure that treated graywater is safe for contact that may occur in water reuse applications, graywater must be sufficiently disinfected removing any potentially harmful pathogens. As discussed previously, the necessary level of inactivation and proper disinfection design is yet to be well defined. It is also necessary to maintain a disinfectant residual in the distribution system to prevent pathogenic regrowth in the pipes or while the water sits in the toilet tanks. Proper disinfection has the additional aesthetic benefit of odor reduction. Chlorine is one of the most extensively used disinfectants with graywater, but there are negative environmental and health associations with it (March and Gual, 2009). Chlorine disinfection may result in the formation of disinfection by products (DBPs) that may be harmful to human health (Yen, 2007).

Since chlorine disinfection can require very high doses, undesirable disinfection by-product formation and potential health hazards, there is interest in investigating cost-effective and efficient alternatives. Three alternative disinfectants that have been considered are ozone, ultraviolet (UV), and hydrogen peroxide. Ozone and UV do not provide a residual and, therefore, chlorine would still need to be added for the distribution system. Hydrogen peroxide does provide a potential residual that could be used in place of chlorine.

2.5.1 Chlorine

The most widely utilized disinfectant in water treatment is chlorine (Yen, 2007). Graywater reuse projects often utilize sodium hypochlorite (NaOCl) as a chlorine source. NaOCl disassociates in water to Hypochlorite (HOCl). HOCl is cost effective, easy to manage and efficient at disinfecting a variety of pathogens (March et al., 2005). Depending on the treatment process, graywater will have a variety of constituents that will readily consume HOCl (March et al., 2005). Inorganics and organics in water will consume the chlorine as it is dosed up until breakpoint chlorination (Figure 2.3).

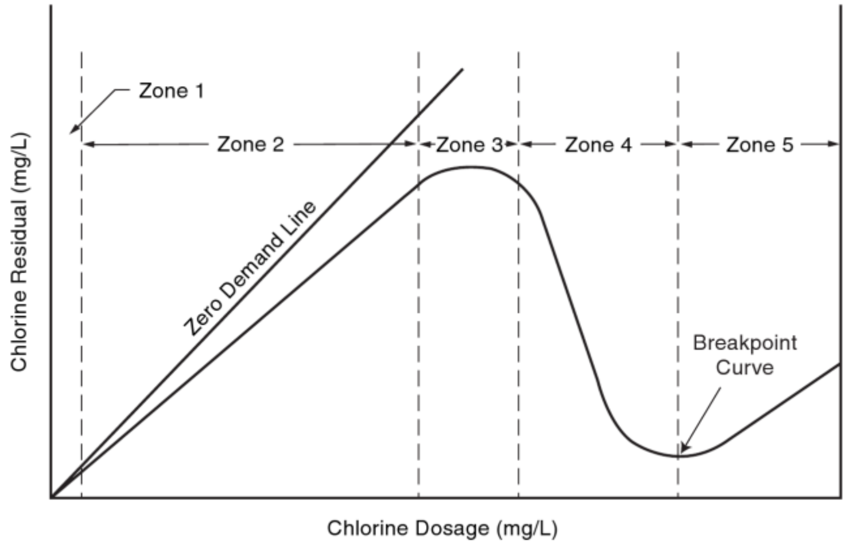

Figure 2.3 Breakpoint Chlorination Curve (Connell, 1996)

The breakpoint chlorination curve will be widely variable depending on graywater quality and the treatment process utilized. The first zone represents reactions that occur with inorganic reductants like iron and nitrate/nitrite which can be present in graywater in concentrations of 0.34-1.1 mg/L and <0.05-6.3 mg/L-N respectively (Eriksson et al., 2002). Inorganic reactions can be beneficial and provide odor reduction through oxidation of hydrogen sulfide (Weiner, 2008).

In Zones 2-4 chlorine is reacting with ammonia to form chloramines. Ammonia is often present in graywater between <0.1-15 mg/L-N depending on graywater source (Erikkson et al., 2002). HOCl reacts with NH_4 based on the following reactions (AWWA, 2006):

Monochloramine reaction:

Equation 2.1: $$HOCl + NH_3 = NH_2Cl + H_20$$

Dichloramine reaction:

Equation 2.2: $$HOCl + NH_2Cl = NHCl_2 + H_20$$

Nitrogen Trichloride:

Equation 2.3: $$HOCl + NHCl_2 = NCl_2 + H_20$$

Monochloramine will be the primary chlorine residual in Zone 2 up to a mass chlorine to ammonia ratio of 5:1 mg Cl_2: mg NH_4-N (Weiner, 2008). As additional chlorine is added, there is an increase in dichloramine formation resulting in a plateau of chlorine residual formation (Zone 3). At this point all free ammonia has reacted with chlorine and additional chlorine further reduces the chloramine species and reacts with any remaining nitrogen rapidly decreasing the chlorine residual (Zone 4). This occurs until a mass chlorine to ammonia ratio of 7.6:1 (Weiner, 2008).

The final zone, Zone 5, results in the formation of free chlorine and a linear relationship between disinfection dose and chlorine residual is established. Throughout chlorine disinfection there are side reactions with organics. Starting in Zone 2, chlorine will react with organic nitrogenous material and form organic chloramines. The reactive organic material is often protein or amino acids and the resulting chloramines have very little disinfection potential (AWWA, 2006). Additionally, these reactions may result in the undesirable formation of DBPs, like trihalomethanes, which may be carcinogenic (AWWA, 2006). Interactions with organic material will occur in Zones 2, 3 and 4. These conditions result in chlorine disinfection to be highly variable not only between different graywater reuse projects but also potentially within the same project based on variations on influent inorganics, ammonia concentrations and reactive organic constituents.

The effectiveness of a disinfectant is based on the necessary contact time multiplied by the residual dose (Ct) to achieve a determined log inactivation. Free chlorine is the most reactive chlorine species with a Ct of .034-.05 mg-min/L Cl_2 for a 2 Log *E. coli* reduction (Siemens, 2009). Monochloramine is also a beneficial disinfectant that is less reactive than free chlorine and requires a Ct of 95-180 mg-min/L Cl_2 for a 2 Log *E. coli* reduction (Siemens, 2009). However, monochloramine provides a more stable residual in the distribution system and can be more effective in the prevention and disinfection of biofilms (Weiner, 2008). Dichloramine has little disinfection benefit while nitrogen Trichloride has little to no disinfection benefit (AWWA, 2006). The chlorine compound formed during disinfection will be dependent on an application's influent graywater, treatment process and chlorine dose. The necessary dose and contact time will be very different dependent on whether free chlorine or monochloramine formation is favored. Chlorine doses in graywater have been highly variable with a range from as low as 13.15 mg/L Cl_2 to as high as 75 mg/L Cl_2 (Tal et al., 2011; March et al., 2004).

The mechanism for chlorine disinfection is the same despite the effective disinfectant. Chlorine is an oxidant that will penetrate the cell and deactivate essential enzymes (Yen, 2007). Free chlorine is a more effective disinfectant than monochloramine, but monochloramine provides a more stable residual in the distribution system (Weiner, 2008). Disinfecting with free chlorine will achieve more rapid disinfection. However, based on the large amount of consumptive material in graywater, monochloramine disinfection will require a lower chlorine dose and a more stable residual.

2.5.2 Ozone

Ozone is a strong oxidant and potent disinfectant (Weiner, 2008). Chlorine is a weak disinfectant of protozoa, while ozone is effective against bacteria, viruses and protozoa (U.S. EPA, 1999). It is stronger than chlorine and requires lower Ct values for disinfection. Ozone requires a low Ct of 0.02 and 0.5-0.6 mg-min/L for 2 Log inactivation of *E.coli* and *Giardia* respectively (Siemens, 2009). Compared to chlorine that requires a Ct of 47-150 mg-min/L for 2 Log inactivation of *Giardia*. Ozone disinfects by attacking the bacterial membrane and disrupting enzymatic activity (U.S. EPA, 1999).

Additionally, dissolved ozone is highly reactive with oxidizable organics and inorganic compounds (Weiner, 2008). In graywater, these constituents may be in high concentration since TOC typically ranges between 30-104 mg/L-C (Eriksson et al., 2002). Therefore, use of ozone as a disinfectant in graywater can provide water quality benefits including BOD_5 and COD reduction, turbidity improvements and odor inhibition (Weiner, 2008). Ozone does not provide a stable residual and off gassed ozone is hazardous at low concentrations (Weiner, 2008). This makes the maintenance and management of ozone disinfection potentially more hazardous than other alternatives. The potential health hazard may complicate the implementation of ozone at multi-residential scale depending on the expertise and available maintenance of the reuse application.

2.5.3 Ultraviolet

UV disinfection provides another alternative to chlorine. The UV light penetrates into the pathogen and damages the DNA and RNA thus inhibiting cellular transcription and replication preventing growth (Hijnen et al., 2006). Most UV lamps operate at 254 nm, the peak wavelength absorbed by DNA (Hijnen et al., 2006). The effectiveness of the UV dose is determined by the quantity of time the pathogen is in contact with the light and the distance the pathogen is from the light source. UV disinfection can require a short contact time, and a UV dose between 20-40 mJ/cm^2 is effective at inactivating bacteria and viruses (Weiner, 2008). The effective dose will vary depending on influent water quality. The primary water quality concern is percent ultraviolet transmittance (UVT). UVT is defined as the fraction of incident light transmitted through a sample (U.S. EPA, 2006). Common constituents that absorb light include inorganic iron and sulfite and organic material (U.S. EPA, 2006). These constituents may be present in high quantities in graywater and, sufficient treatment processes may need to be implemented to improve the %UVT. Suspended solids may also be a concern for the effectiveness of UV disinfection in graywater.

Pathogens may be particle associated and thus be shielded from UV light causing an increased resistance (Hijnen et al., 2006). UV has shown to be effective in graywater with low transmittance and suspended solids where a 2.4 Log *E.coli* reduction was achieed at a low dose of 5.8 mJ/cm^2 and 47% UVT (Winward, 2007). UV is less efficient against spores and viruses (Chevrefils et al., 2006). UV is a beneficial alternative because it has no chemical addition into the water and it can be more effective than chlorine against *Giardia* and *Cryptosporidium* (Hijnen et al., 2006).

2.5.4 Hydrogen Peroxide

Hydrogen peroxide (H_2O_2) is a beneficial disinfectant because it can provide a residual like chlorine without the negative environmental impacts (Ronen et al., 2010). It is an oxidant that is utilized in water treatment for odor control and COD reduction (Clark, 1999). It reacts with organics and inorganics similar to ozone. Despite the fact that hydrogen peroxide is a stronger oxidant than chlorine, it shows mild antimicrobial activity (Clark, 1999). One graywater application used a stabilized form of hydrogen peroxide (HPP) and required a 125 mg/L H_2O_2 dose and 35 minute contact time to achieve 2 Log fecal coliform reduction (Ronen et al., 2010). This is a higher initial dose compared to graywater projects that utilize chlorine and required a dose between 13.15-75 mg/L Cl_2 (Tal et al., 2011; March et al., 2004). The disinfection efficiency can be improved by coupling hydrogen peroxide with UV. This is an Advanced Oxidation Process (AOP) and results in the formation of hydroxyl radicals that are very strong non-selective oxidants (Clark, 1999). The disinfection efficiency of UV+H_2O_2 is primarily dependent on UV and not hydroxyl radicals (Mamane et al., 2007), but there is an added benefit of a residual disinfectant.

2.6 Commercial Graywater Systems

There are a growing amount of commercial systems that reuse graywater. Internationally, graywater reuse is more popular than it currently is in the US where there are still a limited amount of domestic systems. Sharvelle et al. performed a thorough analysis of current reuse systems on the market (Sharvelle et al., 2012). SinkPositive is a basic diversion system that performs no treatment but directly collects hand wash water into the toilet bowl. This strategy is simple but has potential health risks and has minimal water savings, as the system is unable to collect shower or laundry water, the two largest sources of graywater in the home (Figure 2.1). Water Savings Technologies produces the AQUS system that collects, filters and disinfects hand sink water. This system provides more treatment but is still limited to water savings from hand sinks only. Water Legacy provides a larger graywater reuse system that collects shower, laundry and hand sink water, filters and disinfects using UV and hydrogen peroxide. This system has lower maintenance but larger operational costs associated with the disinfection method. BRAC Systems manufactures a graywater reuse system that utilizes 100 micron filtration and chlorine tablet disinfection to achieve *E. coli* and fecal coliform <100 CFU/100mL but customers have stated issues with properly controlling the chlorine dose. BRAC also makes other systems that can incorporate a sand filter, UF membrane or UV disinfection. Wahaso manufacturers a commercial system that includes 5 micron filtration and automated backwashing. The system is new to the market and was released onto the market after the start of this project. Similarly, AquaRecycle makes commercial graywater reuse systems that includes 3-micron filtration, ozone disinfection and is completely automated. Equaris manufactures the most extensive graywater reuse system in the US and treats graywater to fresh water quality. The system utilizes aeration, filtration, ozonation and reverse osmosis. (Sharvelle et al., 2012)

There is increasing interest in graywater reuse at the multi-residential scale but there is not a system that is proven to be the most efficient and economic. Some of the more basic systems do not provide sufficient water treatment or water conservation and only utilize hand sink water. In contrast, some of the more sophisticated systems have large costs and require frequent maintenance and/or energy input. Additionally, only the AquaRecycle, BRAC and Wahaso systems are sized to handle volumes at the multi-residential scale. The concerns with these systems are that they are relatively new to the market and have potentially high capital and operational costs due to over treating the graywater. For this reason, a system is needed that is both efficient and cost-effective is desired in order to successfully implement graywater reuse at the multi-residential scale. (Sharvelle et al., 2012)

2.7 Summary

Graywater reuse for toilet flushing is a growing area of interest for municipalities and developers. States are starting to establish regulations specific to graywater reuse. There have been a variety of experiments on potential filtration and disinfection options. Most of these projects are laboratory based or at the residential scale. The approach for filtration of graywater ranges from coarse to sophisticated membrane filtration. Chlorine disinfection is the most common and efficient disinfectant for graywater but there is interest in alternative approaches depending on the treatment process. There is a need for increased research of graywater treatment at the multi-residential scale. Additionally, the cost and benefits of these projects are often not incorporated into the treatment consideration and thus it is hard to evaluate the potential for project implementation.

3.0 OPERATION OF A PILOT-SCALE TREATMENT SYSTEM EMPLOYING VARIOUS APPROACHES FOR FILTRATION AND DISINFECTION

3.1 Introduction

Graywater reuse for toilet flushing has the potential to save 26.7% of the indoor water consumption (AWWA, 1999a). This is a substantial savings that could help decrease the strain on urban water supplies and free up demand for other uses.

There has been substantial research on graywater disinfection and filtration in lab settings, but there is still a need for additional investigation on disinfection and filtration options at a larger scale. There are very few commercially available graywater treatment systems in the United States (US) for toilet reuse. A pilot scale project with sample collection and analysis over an extended duration (more than 3 months) will provide beneficial knowledge that may guide the potential implementation of disinfection and filtration alternatives.

The objective of this study was to analyze disinfection and filtration alternatives for graywater reuse for toilet flushing at the multi-residential scale. The first step of this process was to analyze a series of disinfectants (UV+H_2O_2, chlorine, UV and ozone) for disinfection efficacy. In addition, three cost effective filtration options (coarse, sand and cartridge) were tested for improvement to water quality and effect on disinfectant dose. This study was conducted in Aspen Hall at CSU where actual graywater was collected from 28 residents and was tested with the various treatment systems.

3.2 Materials and Methods

3.2.1 Experimental Set-Up

A pilot scale graywater treatment system was operated over the course of three semesters testing different disinfection and filtration alternatives. The first phase of the project was in the spring 2011 and tested a manufactured graywater reuse system utilizing UV + H_2O_2 for disinfection efficiency and water chemistry aesthetics. The second phase, fall 2011, analyzed the disinfection efficacy and water chemistry of chlorine, UV and ozone. The final phase was conducted, spring 2012, tested a coarse, sand and cartridge filter on water chemistry improvements and effects on chlorine consumption. The phases and measured parameters are outlined in Table 3.1. The sample tests varied based on which parameters where most important for each phase.

Table 3.1 Experimental Set-Up

Experiment		Semester	Days of Operation	Number of Samples	Parameters[1]
1	H_2O_2 + UV	Spring 2011	76	17	DO, Temperature, pH, Conductivity, Turbidity, Total, Suspended and Dissolved Solids, BOD_5, COD, DCOD, *E. coli*, Total coliforms, Hydrogen peroxide
2	Chlorine	Fall 2011	34	8	DO, Temperature, pH, Conductivity, Turbidity, Total, Suspended and Dissolved Solids, BOD_5, COD, DCOD, *E. coli*, Total coliforms, Total chlorine
3	UV	Fall 2011	23	6	DO, Temperature, pH, Conductivity, Turbidity, Total, Suspended and Dissolved Solids, BOD_5, COD, DCOD, *E. coli*, Total coliforms
4	Ozone	Fall 2011	17	6	DO, Temperature, pH, Conductivity, Turbidity, Total, Suspended and Dissolved Solids, BOD_5, COD, DCOD, *E. coli*, Total coliforms, Ozone
5	Coarse	Spring 2012	61	6	DO, Temperature, pH, Conductivity, Turbidity, Total Hardness, Total Alkalinity, UVT, SUVA, Total, Suspended and Dissolved Solids, BOD_5, TOC, DOC, *E. coli*, Total coliforms, Chlorine consumption, Ammonia
6	Sand	Spring 2012	18	8	DO, Temperature, pH, Conductivity, Turbidity, Total hardness, Total alkalinity, UVT, SUVA, Total, Suspended and Dissolved Solids, BOD_5, TOC, DOC, *E. coli*, Total coliforms, Chlorine consumption, Ammonia
7	Cartridge	Spring 2012	13	6	DO, Temperature, pH, Conductivity, Turbidity, Total hardness, Total alkalinity, UVT, SUVA, Total, Suspended and Dissolved Solids, BOD_5, TOC, DOC, *E. coli*, Total coliforms, Chlorine consumption, Ammonia

3.2.2 Analytical Methods

The water sampling collection, storage and parameters were tested according to standard methods (Standard Methods for the Examination of Water and Wastewater, 2005). Dissolved oxygen (DO) and temperature were read using an YSI DO field probe (YSI, Yellow Springs, Ohio). BOD_5 was analyzed by measuring DO with a YSI BOD_5 probe and HACH nutrient buffer solution (HACH, Loveland, CO). Turbidity was analyzed with a Hach 2100N nephelometric turbidimeter. Total alkalinity, total hardness, and total, suspended and dissolved solids were measured according to Standard Methods (Methods 2320, 2340, 2540). Ammonia was analyzed using HACH high range ammonia method 10031 and a HACH DR2500 spectrophotometer. TOC and dissolved organic carbon (DOC) were analyzed via combustion and acidification with a Shimadzu TOC-V CSH/CSN (Shimadzu, Japan) and the DOC samples were filtered through 0.45 micron filter. UVT and dissolved absorbance were measured using a Thermo Scientific Genesys Spectrophotometer at 254nm and the dissolved samples were passed through a 0.45 micron filter. COD and dissolved COD (DCOD) were measured using HACH High Range COD vials method 8000 and a Hach DR2500 spectrophotometer and the dissolved samples were passed through a 0.45-micron filter. Total chlorine was measured according to the DPD colorimetric method using the HACH total chlorine test kit method 8210 and HACH DR2500 spectrophotometer. Ozone was measured based on the indigo method using a HACH ampule kit method 8311 and DR2500 spectrophotometer, while hydrogen peroxide was measured using HACH thiosulfate titration field kit 22917. Pathogens were quantified using U.S. EPA approved Colilert-24 hour powder pillow indicators and incubated at 35^{o} Celsius for 24 hours before samples were quantified for total coliform and *E. coli* (IDEXX, Westbrook, Maine).

Specific UV absorbance (SUVA) was calculated (U.S. EPA, 2005) in order to assess the potential disinfection by-product formation from chlorine disinfection of graywater. This was accomplished using the DOC and dissolved absorbance at 254nm.

Equation 3.1: $$SUVA\ (L/mg-M)_{@254nm} = \frac{Dissolved\ Absorbance\ (cm^{-1})_{@254nm}}{Dissolved\ Organic\ Carbon\ (mg/L-C)} * 100\ (cm/M)$$

3.2.3 Pilot Scale Testing Unit

The pilot scale graywater reuse system was installed on the Colorado State University campus to assess the feasibility of graywater reuse for toilet flushing at the multi-residential scale. The system was installed in the Aspen Hall, constructed in 2008. The first floor of the dorm was dual plumbed so that graywater (shower and hand sink) could be collected separately from blackwater. Additionally, the toilets were plumbed with the ability to use the graywater after treatment. The first floor has 14 double occupancy rooms; therefore, graywater (shower and sink water) was collected from 28 students. The dorm is vacant in the summer and all tests were conducted while school was in session over the spring 2011, fall 2011 and spring 2012 semesters.

Graywater collected from hand sinks and showers generated 10.7 gpcpd or 300 gallons per day (gpd) and the estimated toilet use by the CSU facilities is 5 flushes/person/day or 224 gpd. The system was sized to collect and process the graywater with a 24-hour storage time. A 24-hour storage time was selected to minimize pathogen growth and odor issues but still achieve beneficial settling (Dixon et al., 2000). Graywater was collected and composited in a 250-gallon vertical tank (Figure 3.1). There was a second collection tank installed, but it was not utilized to prevent prolonged storage. All installations were plumbed to code and the tanks were equipped with ventilation, overflow and drain. The system and major components are depicted below in Figure 3.1. The collection tank composited the graywater to a uniform quality and provided settling of large solid particles. The collected graywater was then filtered and disinfected.

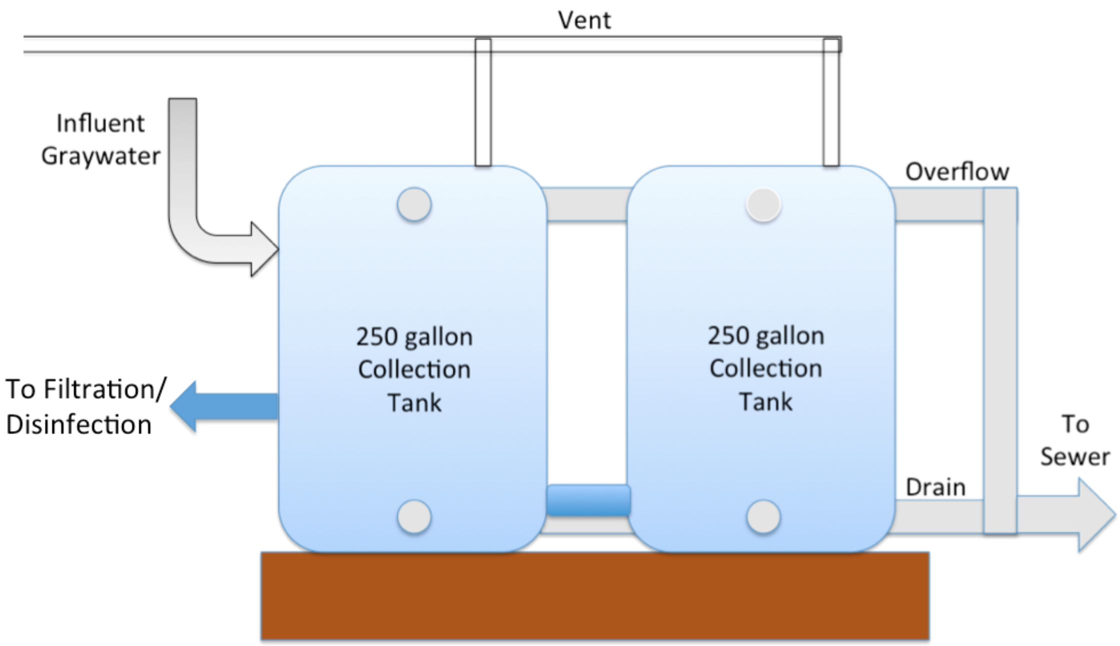

Figure 3.1 Graywater Collection System in the Aspen Hall

3.2.4 Manufactured Reuse System

The first set of tests (Experiment 1, Table 3.1) were performed on a manufactured graywater treatment system (Water Legacy, Boulder, CO) and had some key operational differences than the other disinfection and filtration tests. The system was meant to treat all incoming graywater; therefore the 250-gallon collection tank was not utilized. The system was comprised of an influent septic bristle filter, 100-gallon collection/disinfection tank and UV + H_2O_2 disinfection. The bristle filter was low maintenance and provided coarse separation of large incoming solids. The system collected and processed all incoming graywater and any excess water not used for toilet flushing would overflow to the sewer. Water was collected as it was generated and was processed through the coarse filter and into the disinfection tank. The system set-up is shown in Figure 3.2 and a schematic of the treatment process is shown in Figure 3.3.

Figure 3.2 Manufactured Reuse System

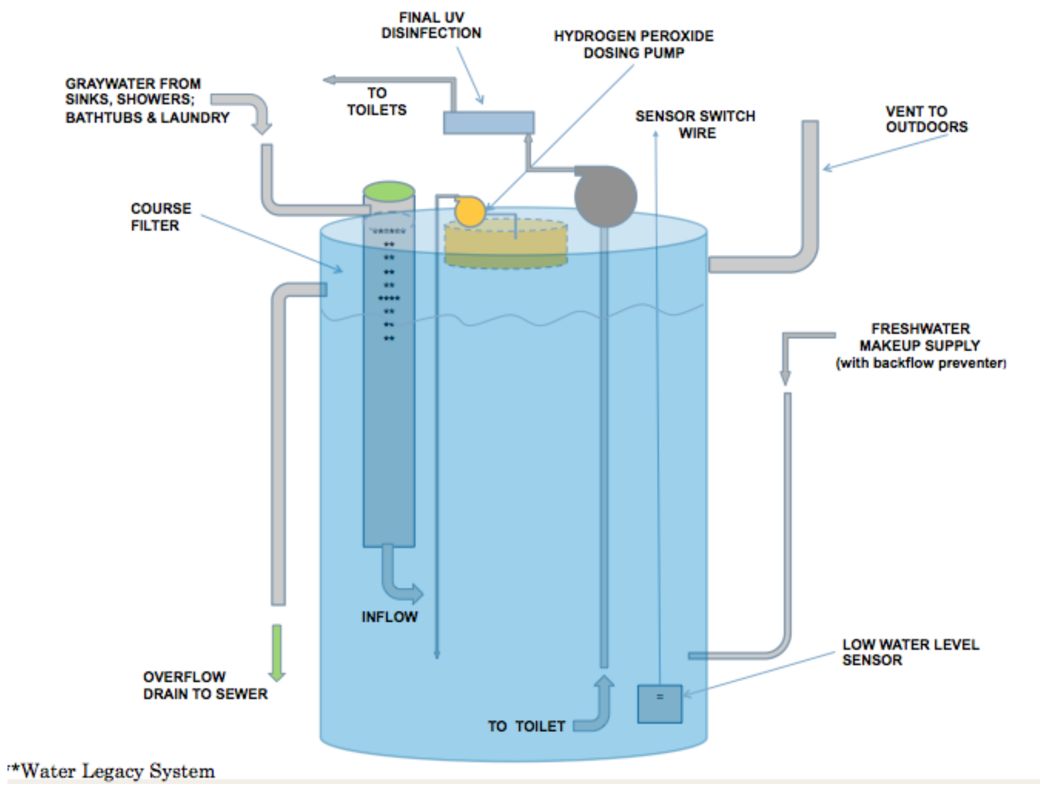

Figure 3.3 Water Legacy System Schematic

Once in the tank, water was disinfected based on a controlled recirculation schedule. During a disinfection cycle, the system would recirculate water through a Sterilight Silver S5Q-PA UV lamp (Viqua, Guelph, Ontario) and dose in-line with a constant volume of 30% hydrogen peroxide and then reintroduce the water back into the tank. The chemical dosing was accomplished utilizing a fixed output Stenner 45MP1 peristaltic pump (Stenner, Jacksonville, FL) and a timer with a set duration controlled the dosed volume. The tank would recirculate 8 times a day for 30 minutes at 3.3 gallons per minute (gpm). This system utilized UV as the primary disinfectant and established a residual hydrogen peroxide concentration in the tank. The S5Q-PA was sized to deliver a 40 mJ/cm^2 dose at 75% UVT and a flow rate of 3.5 gpm. The manufacture would not provide dose information on UVT lower then 75%. The consumption of hydrogen peroxide in graywater was analyzed based on the difference between the dosed and measured effluent concentrations during system operation. The system was designed to have a long minimum contact time of 420 minutes in the disinfection tank. All graywater would pass through the UV lamp one final time before leaving treatment tank. A Grundfos MQ 3-35 booster pump (Grundfos, Olathe, KS) operated the recirculation and simulated flushing (see Section 3.2.7).

3.2.5 Evaluation of Various Disinfection Approaches

To test other disinfection approaches, the manufactured system was altered, but the same coarse filter was utilized throughout all of the tests. The storage tanks were utilized as described above providing time for water compositing and solids settling. Settled graywater has shown to have a beneficial reduction in TSS and TOC (Winward et al., 2008b). The stored graywater would gravity flow from the collection tanks, through a coarse septic bristle filter and finally into a 120-gallon vertical tank (Figure 3.4). The volume in the tank was controlled to 70-gallons so that the total system storage was 320-gallons. Utilizing only one of the collection tanks and limiting the disinfection volume ensured that graywater was not stored more then 24 hours. The minimum contact time in the disinfection tank was 110 minutes for the three disinfectants tested. The Grundfos booster pump was again used as a recirculation and distribution pump. Throughout the Fall 2011 semester chlorine, UV and ozone were tested for disinfection efficacy. Additionally, samples treated by UV and ozone were collected from the pilot scale system and were dosed with sodium hypochlorite to analyze the disinfection potential of primary disinfection with chlorine as the secondary residual disinfectant. One Liter samples were dosed with 10 mg/L Cl_2 and allowed 30 min contact time before enumeration of *E. coli* and total coliform. The influent graywater was profiled (see Table 3.1) from samples taken from the collection tank while disinfected samples were collected from the simulated flush line leaving the tank (not pictured).

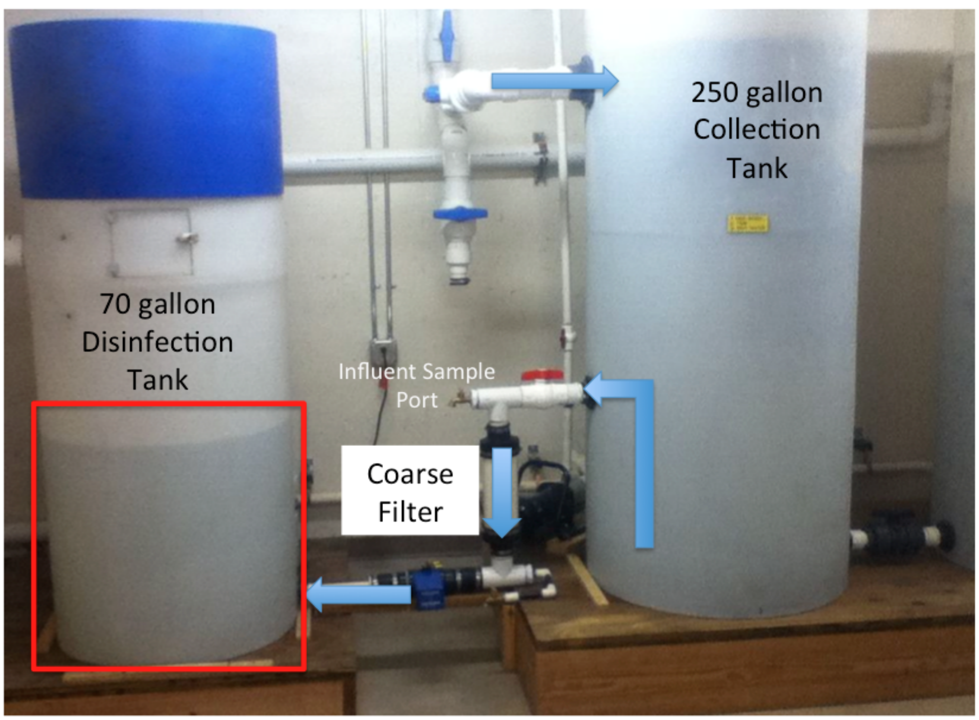

Figure 3.4 Pilot Scale Testing Unit

Chlorine

Chlorine disinfection (Experiment 2, Table 3.1) was tested using liquid sodium hypochlorite. The filtered water was recirculated 8 times for 30 min at 3.3 gpm and the graywater was dosed in-line with 6% NaOCl using the same Stenner peristaltic pump. The sample was than reintroduced into the disinfection tank where a residual chlorine concentration was established. The sodium hypochlorite consumption in graywater was determined based on the difference between dosed and measured effluent concentrations during the system operation.

Ultraviolet

Ultraviolet disinfection (Experiment 3, Table 3.1) was tested using the same recirculation schedule. The filtered water would recirculate through the Sterilight Silver S5Q-PA UV lamp at 3.3 gpm and be reintroduced back into the disinfection tank. This was the same lamp utilized in the manufactured reuse system which was sized to deliver a 40 mJ/cm^2 dose at 75% UVT and a flow rate of 3.5 gpm. There was no residual chemical used in this test to ensure that all achieved disinfection was from UV. The water was recirculated through the UV lamp to provide primary disinfection and prevent bacterial growth in the disinfection tank. During a scheduled flush simulation (see Section 3.2.7), water would pass through the UV lamp one final time.

Ozone

The final disinfectant tested was ozone (Experiment 4, Table 3.1). A Del Ozone APG-120 hot tub scale ozonater (Del Ozone, San Luis Obispo, CA) was installed that was capable of producing ozone from air at a rate of 60 mg/hr. The ozone production rate was controlled by an air pump and the produced ozone was introduced into the graywater by two bubble diffusers at the bottom of the tank. The ozone process ran continuously throughout the day. Based on the daily ozone production rate and volume of water treated, the graywater was dosed at an ozone concentration of 1.3 mg/L. The system did not recirculate and the Grundfos booster pump only operated the simulated flushing.

3.2.6 Filtration

After completion of the disinfection analysis, different filtration processes were tested in the spring of 2011. The filters tested needed to be low maintenance, low energy and economically feasible. This resulted in the selection of a coarse, sand and cartridge filter. The graywater composited and settled in the primary collection tanks and then gravity flowed through the filter. Chlorine was dosed in-line after filtration before the disinfection tank. The disinfection tank allowed for 110 minutes contact time to adequately reduce pathogens and establish a chlorine residual. Influent samples were taken from the collection tank and filtered samples were taken post filtration before chlorine disinfection. Disinfectant effluent samples were taken for aesthetic observations and analysis of chlorine consumption as a result of filtration.

Coarse Filter

The first filter (Experiment 5, Table 3.1) tested was a coarse Matala medium density filter (Matala, Laguna Hills, CA). Matala is a plastic material that is often used in ponds and in some wastewater applications. The media was installed in a PVC pipe between the storage tank and disinfection tank (Figure 3.5). The material is very affordable and easy to clean or replace when necessary with a very low frequency maintenance schedule. The filter consumes no energy and requires no back flushing. The function of this filter was to catch large particles, like hair or debris, which failed to settle out in the collection tank. The coarse filter implemented in the disinfection tests was a septic bristle filter. The Matala filter was chosen instead because it is lower in cost and has the ability to be rinsed where the bristle filter required disposal.

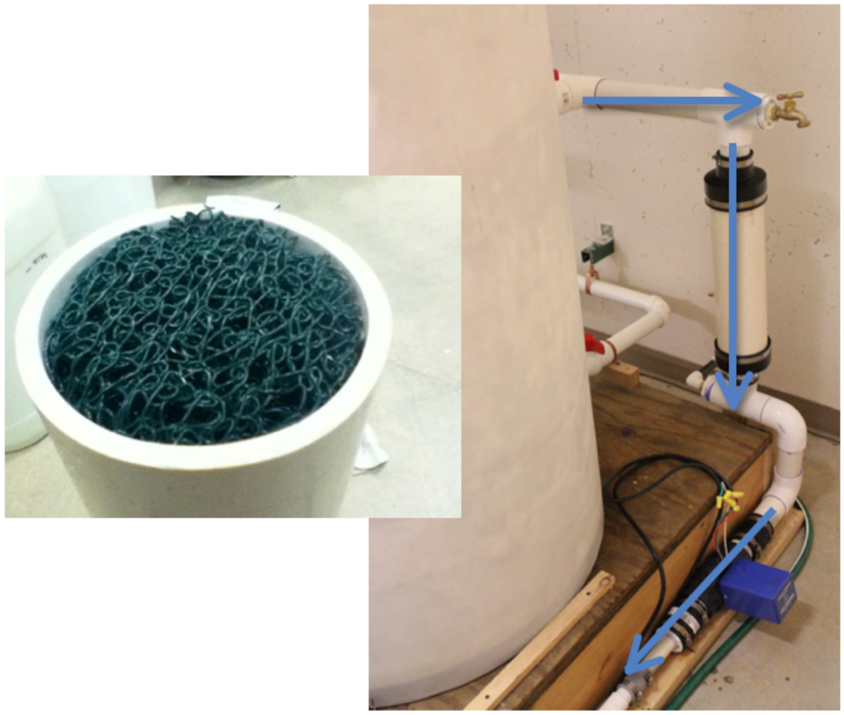

Figure 3.5 Coarse Matala Filter

Sand Filter

The second filter tested (Experiment 6, Table 3.1) was a Hayward S144T pool sand filter (Hayward, Elizabeth, NJ). The sand filters primary purpose was particle removal and provides filtration in the range of 25-50 microns. The system was designed to utilize the pressure head of the collection tanks to pass the water through the sand filter. A pump was incorporated to provide the ability to backwash the sand filter when clogged. The maintenance associated with this filter is backwashing and sand replacement. Energy was only consumed when backwashing the filter. Influent graywater came through the hose on the right and left the hose on the bottom of the screen while backwashed graywater left out of the green hose in the top (Figure 3.6).

Figure 3.6 Hayward Pressure Sand Filter

The Hayward filter is a pressure pool filter that is sized according to NSF standards with a hydraulic loading rate of 20 gpm/ft^2 (Hayward, 2012). At Aspen, the water passed through the sand filter at a rate of 7.5 gpm. The necessary surface area at that flow rate would be 0.375 ft^2. The Hayward filter had a surface area of 1 ft^2 and was more then sufficiently sized according to the NSF standards for pool sand filters. An alternative sand filter is a rapid filtration that allows for bacterial growth and higher organic removal. The EPA suggests an organic load of 5 lbs. per 1000 ft^2 per day for onsite wastewater treatment systems with rapid sand filtration (U.S. EPA, 2002a). Based on the measured influent BOD of 105±17.1 mg/L (Table 3.9) this would require a filter surface area of 51.6 ft^2. Additionally, the sand filter needs to be aerobic requiring the addition of DO into the graywater. The large footprint and aeration requirements affect the feasibility for rapid sand filtration for graywater reuse.

Cartridge Filter

The last filter tested (Experiment 7, Table 3.1) was a PurFlo 2418 cartridge filter (PurFlo, Chicago, IL). The cartridge provided filtration of particles >100 microns (Figure 3.7). The filter required no pumping and therefore consumed no energy. The filter also included a 1.5-pound granular activated carbon (GAC) insert that can adsorb dissolved compounds but requires replacement or carbon regeneration. The maintenance of this filter is periodic cleaning of the cartridge and replacement when necessary. This filter is higher in cost and maintenance than the coarse, but lower than the sand.

Figure 3.7 PurFlo Cartridge Filter

Activated carbon can adsorb a variety of organic compounds common in graywater. Typically GAC applications suggest a maximum TSS of 5 mg/L and fats, oil and grease be less than 10 mg/L (Davis, 2011). A general estimate for sizing an activated carbon system suggests 0.2 to 0.8 grams COD per gram of carbon (Reynolds and Richards, 1996). Based on the average influent COD of 212±61.1 mg/L (Table 3.6), the carbon was exhausted in 0.6 to 2.3 days. The quantity of carbon necessary for a maintenance period of 1 month would be 19.2 to 76.8 pounds. The cartridge filter was chosen for the 100-micron filtration and no significant benefit is expected from the activated carbon insert. The quantity of activated carbon is too small to be effective against the high influent load of graywater.

3.2.7 Flush Simulation

For safety purposes the treated graywater was not used in toilets during the testing process. A flush schedule was developed to mimic the usage pattern that is expected by the residence. This pattern is similar to usage peaks observed in single-family homes with higher use in the morning and evening (AWWA, 1999a). Figure 3.8 depicts the flush schedule and the number of flushes during each flush event. The system was limited to 20 flush events (the maximum the timer allowed) and the times in which those occurred were staggered throughout the day to provide variable flushing that would be more representative of a real world system. Every day 295 gallons of graywater was processed and flushed. A water meter was installed on the effluent line to verify daily treated water volume. Graywater flow through the system was controlled by an electronic ball valve connected to a float in the disinfection system. The water level in the disinfection tank would decrease as water was flushed out of the system. Once 17 gallons were flushed out of the system, the ball valve opened and the tank was refilled.

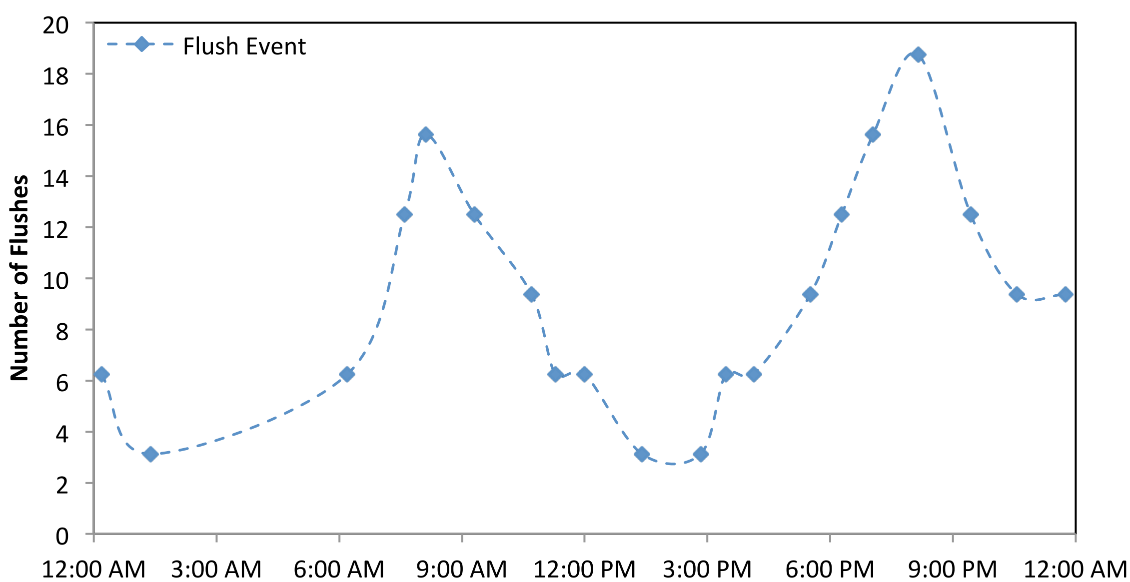

Figure 3.8 Flush Simulation Schedule

3.2.8 Disinfection Batch Set-Up

Concurrent to this project, graduate research assistant, Kristen Wiles, performed a series of batch tests on the disinfection efficacy of a series of filtration and disinfection options in graywater on a variety of pathogens. This analysis is currently being conducted. Portions of these results were included in this paper for comparisons between the pilot results and laboratory disinfectant efficacy. Graywater was collected from the Aspen Hall after it had been coarse filtered. Lab strand *E. coli* was added to the graywater and the total coliform and *E. coli* were enumerated. The samples were disinfected with chlorine, ozone and UV and a Log_{10} reduction was measured. For a detailed description of the experimental analysis and reported results, reference Kristen Wiles thesis on batch disinfection of graywater.

3.3 Results and Discussion

Disinfection

3.3.1 Determination of Disinfection Dose

The dose of all analyzed disinfectants is provided below in Table 3.2. The influent UVT was measured to analyze the potential UV dose. The ozone dose was limited by the maximum production of the ozone generator. Hydrogen Peroxide and chlorine dose were determined based on the chemical consumption during system operation. Chemical consumption was determined on-site by measuring the difference between the dosed chemical concentrations and measured effluent concentration during system operation. The observed hydrogen peroxide consumption and chlorine consumption are reported in Table 3.3.

Table 3.2. Disinfection Dose Determination

Disinfectant	Operation	Dose
UV + H_2O_2	Scheduled recirculation through UV lamp and hydrogen peroxide dosed in-line	40±6% UVT and 140 mg/L H_2O_2
6% NaOCl	Dosed periodically In-line	12 mg/L Cl_2
UV	Scheduled recirculation through UV lamp	40±6% UVT: 40 mJ/cm^2 at 75% UVT and 3.5 GPM
Ozone	Constant bubble diffusion with controlled air flow	60 mg/hr = 1.3 mg/L

Table 3.3. Disinfection Consumption and Ammonia Concentration (Mean ± SD)

Disinfectant	Parameter
H_2O_2 consumption (mg/L as H_2O_2)	135.3 ± 1.7
Chlorine consumption (mg/L as Cl_2)	10.2 ± 1.6

The %UVT was measured to be 40 ± 6. This is a low UVT consistent with other literature reported graywater values of 47% (Winward, 2007). This greatly reduces the effectiveness of UV disinfection and would result in doses significantly <40 mJ/cm^2 based on manufacture's information for the UV lamp used in these experiments. The manufacture does not provide information on the UV dose at the measured UVT values. The low transmittance is likely a result of inorganics like iron and magnesium (Christova-boala et al., 1996) and the high DOC levels (19.9 ± 8.8 mg/L-C) that were measured in the influent graywater. This will greatly limit the potential for UV disinfection without filtration or degradation of the organic and inorganic compounds. The large concentration of organics resulted in a high consumption of hydrogen peroxide (Table 3.3). The consumption of 135.3 ± 1.7 mg/L H_2O_2 is consistent with other reported values of 125 mg/L H_2O_2 in graywater (Ronen et al., 2010). The ozone production was limited by the maximum the generator could produce, but the disinfection efficiency would be affected by the large concentrations of organics and a residual ozone concentration was not observed.

Chlorine was dosed until a total chlorine residual was measured with a resulting consumption of 10.2±1.6 mg/L Cl_2. This resulted in a necessary dose of 12.6 mg/L for a residual of 2.4 mg/L±1.6 Cl_2. The average influent ammonia concentration was 8.4±2.2 mg/L-N and the mass ratio of chlorine to ammonia was calculated to be 1.2:1. Based on the discussion in chapter 2, monochloramine formation is highly favored until a mass ratio of 5:1 (Weiner, 2008). This suggests that the effective disinfectant formed during chlorine disinfection was monochloramine. Other studies have shown the preferential formation of chloramine in graywater in the presence of ammonia (March et al., 2005). The chlorine consumption that was observed is likely a result of iron, manganese and organic material in graywater (Jefferson et al., 2004).

Some regulations require disinfection dose with free chlorine residual. In this case dosing to free chlorine residual requires a mass ratio of chlorine to ammonia of 7.6:1 (Weiner, 2008). Based on the measured ammonia values this would require a chlorine dose of 71.5 mg/L Cl_2. The dose would have to be even higher because of reactions with inorganic and organic compounds (AWWA, 2006). At this dose there would be a free chlorine residual and complete removal of ammonia (AWWA, 2003). A hotel in Spain disinfected graywater at a dose of 75 mg/L in order to achieve free chlorine residual higher than 1 mg/L (March et al., 2004). Without extensive pretreatment of graywater, disinfection to the formation of free chlorine with graywater is undesirable due to the potentially large concentration of ammonia that can range between <0.1-15 mg/L-N (Eriksson et al., 2002). This results in a large dose and an increase in operational cost. Additionally, there are more reactions with organic matter that may result in the formation of halogenated organic compounds and potentially disinfection by-products when dosing at such high chlorine concentrations in the presence of organics (March et al., 2009). Monochloramine disinfection resulted in a much lower necessary dose.

3.3.2 Aspen Disinfection Efficiency

The disinfection efficiency was tested using *E. coli* as the indicator organism. *E. coli* is commonly used in water treatment to indicate the presence of pathogenic bacteria and is often regulated in water reuse applications. A summary of the disinfection efficiency of *E. coli* for each disinfectant is shown in Table 3.4 and a graph of *E. coli* reduction is included in Figure 3.9.

Table 3.4. *E. coli* Disinfection (Geometric Mean ± SD; N/A means non-applicable)

	Influent *E. coli* Log CFU/100ml	**n**	**Effluent *E. coli*** Log CFU/100ml	**n**
Influent Average	2.7 ± 1.1	30	N/A	N/A
UV + H_2O_2	3.2 ± 0.6	7	0.1 ± 0.2	10
6% NaOCl	2.0 ± 0.5	4	0.2 ± 0.3	4
UV	2.4 ± 1.1	2	0.65 ± 0.92	2
UV + Cl	2.4 ± 1.1	2	0.5 ± 0.58	6
Ozone	1.9 ± 0.3	5	1.6 ± 0.6	5
Ozone + Cl	1.9 ± 0.3	5	0.83 ± 0.44	4

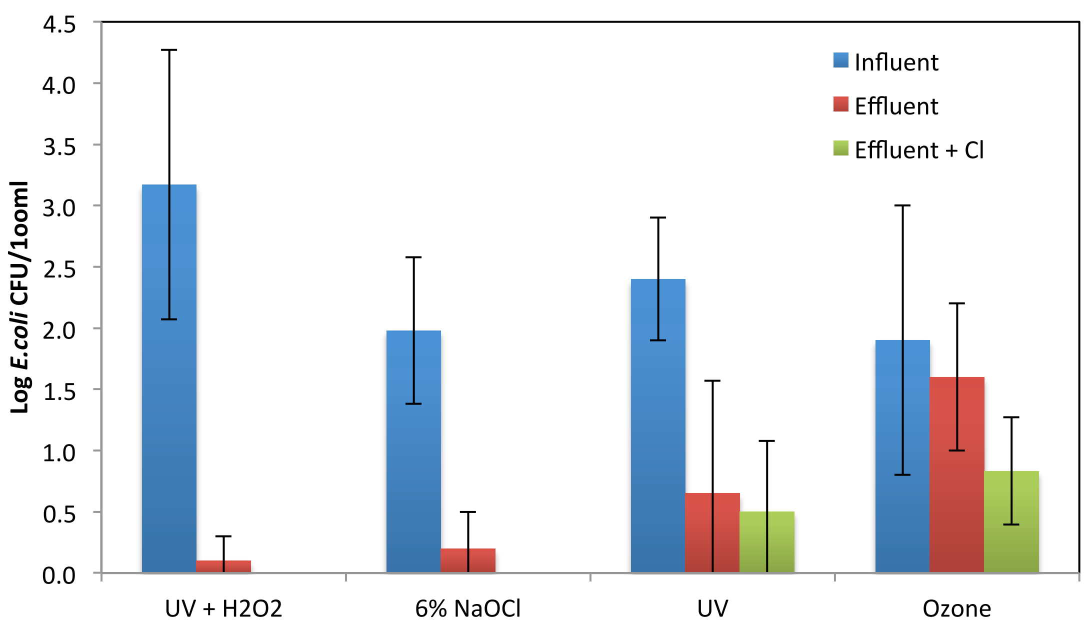

Figure 3.9. *E. coli* Disinfection Efficiency

UV+H_2O_2 and NaOCl were very effective at disinfection of *E. coli* with almost a complete reduction, while ozone was ineffective (Figure 3.9). Unfortunately, only two samples were collected successfully for UV disinfection of *E.coli* (Table 3.4). Based on the two samples UV may have been effective against *E. coli,* but that cannot be concluded without a more complete sample set. Literature review shows UV is efficient against *E. coli* requiring a low dose of 1-10.5 mJ/cm^2 to achieve a 3 Log_{10} reduction depending on the strand (Chevrefils et al., 2006). In graywater, Winward achieved 2.4 Log_{10} disinfection of *E. coli* with a dose of 5.8 mJ/cm^2 at a 47% UVT (Winward, 2007). H_2O_2 + UV had a hydrogen peroxide dose of 135.3 ± 1.7 mg/L and a minimum contact time of 420 minutes. This resulted in a 2.2±1.7 mg/L H_2O_2 residual and *E. coli* was disinfected to <2 CFU/100mL. Similarly, Ronen et al. required a large dose of 125 mg/L H_2O_2 and contact time of 35 minutes to achieve a 2 Log_{10} reduction of fecal coliform in graywater (Ronen et al., 2010). Chlorine was dosed at 12.6±1.6 mg/L Cl_2 and had a minimum contact time of 110 minutes. This resulted in a total chlorine residual of 2.4±1.6 mg/L Cl_2 or a Ct of 144 mg-min/L and achieved <2 CFU/100mL *E. coli*. Literature reports monochloramine Ct value of 95-180 mg-min/L to achieve a 2 Log_{10} *E. coli* reduction (Siemens, 2009). Ozone did not prove to be an efficient disinfectant despite its strong effectiveness against *E. coli* requiring a Ct of only 0.3 mg/L-min for a 2 Log_{10} reduction (Siemens, 2009). This is due to the large amount of organics in graywater competing with disinfectants. A much higher ozone dose or further pre-treatment would have been necessary based on the large amount of ozone consumption.

Table 3.5. Total Coliform Disinfection (Geometric Mean ± SD; N/A means non-applicable)

	Influent total coliform Log CFU/100ml	**n**	**Effluent total coliform** Log CFU/100ml	**n**
Influent average	7.9 ± 1.2	11	N/A	N/A
UV + H2O2	>5.4	5	>4.4	5
6% NaOCl	>4.9	3	0.2 ± 0.3	4
UV	6.5	1	>4.4	3
UV + Cl	6.5	1	2.1 ± 2.1	3
Ozone	6.3	2	>4.7	4
Ozone + Cl	6.3	2	3.3 ± 1.3	6

Additionally to *E. coli*, some states regulate total coliform in water reuse projects. The only disinfectant that showed effective disinfection of total coliform was NaOCl with an average of <2 CFU/100 mL (Table 3.5). UV + H_2O_2, UV and ozone all had total coliform numbers higher than the detection range, which suggests little to no disinfection. The average influent graywater total coliform concentration was Log_{10} 7.9 CFU/100mL (Table 3.5). A hotel in Spain utilizing chlorine as a graywater disinfectant observed when chlorine residual was >1 mg/L, samples were negative for total coliform (March et al., 2004).

The overall effectiveness of a primary and residual disinfectant was tested for UV and ozone. The average effluent *E. coli* concentration for UV and ozone with chlorine as a secondary disinfectant was 0.5 and 0.83 Log_{10} CFU/100mL respectively (Table 3.4). The effluent total coliform concentration was 2.1 and 3.3 Log_{10} CFU/100mL respectively (Table 3.5). The combined disinfection approach proved to be only slightly better than the primary disinfectant alone and not better than NaOCl disinfection due to the ineffectiveness of UV and ozone individually and limited chlorine contact time of 30 minutes (Figure 3.9).

3.3.3 Disinfectant Effects on Water Chemistry

During the disinfection tests, spring 2011 and fall 2011, the influent water chemistry was monitored. This was done to understand the quality of the graywater from the residence hall and assess the effect of the disinfection alternatives on graywater chemistry. The average influent concentrations are provided in Table 3.6. A complete summary of all measured influent and effluent water quality parameters is provided in Appendix B.

Table 3.6 Influent Water Chemistry Spring 2011 and Fall 2012

	Influent
DO (mg/L)	1.1 ± 0.5
pH	7.0 ± 0.4
Turbidity (NTU)	39 ± 9.8
Conductivity (µS/cm)	204 ± 35.8
BOD_5 (mg/L)	144 ± 41.9
COD (mg/L)	212 ± 61.1
dCOD (mg/L)	119 ± 45.1
TS (mg/L)	175 ± 44.2
TSS (mg/L)	31 ± 8.4
TDS (mg/L)	144 ± 40.5

The effluent water chemistry was monitored simultaneous to the influent for all of the tested disinfectants. For each disinfectant, a Satterthwaite's t-test was performed to determine if the influent and effluent water chemistry was significantly different (U.S. EPA, 2000). Additionally the percent change between the average influent and average effluent concentration was calculated. A summary of the disinfectant effect on graywater chemistry and the statistical significance is provided in Figure 3.10 where indicates "**" indicates a statistical significance $p<0.05$ and "*" indicates a statistical significance at $p<0.1$.

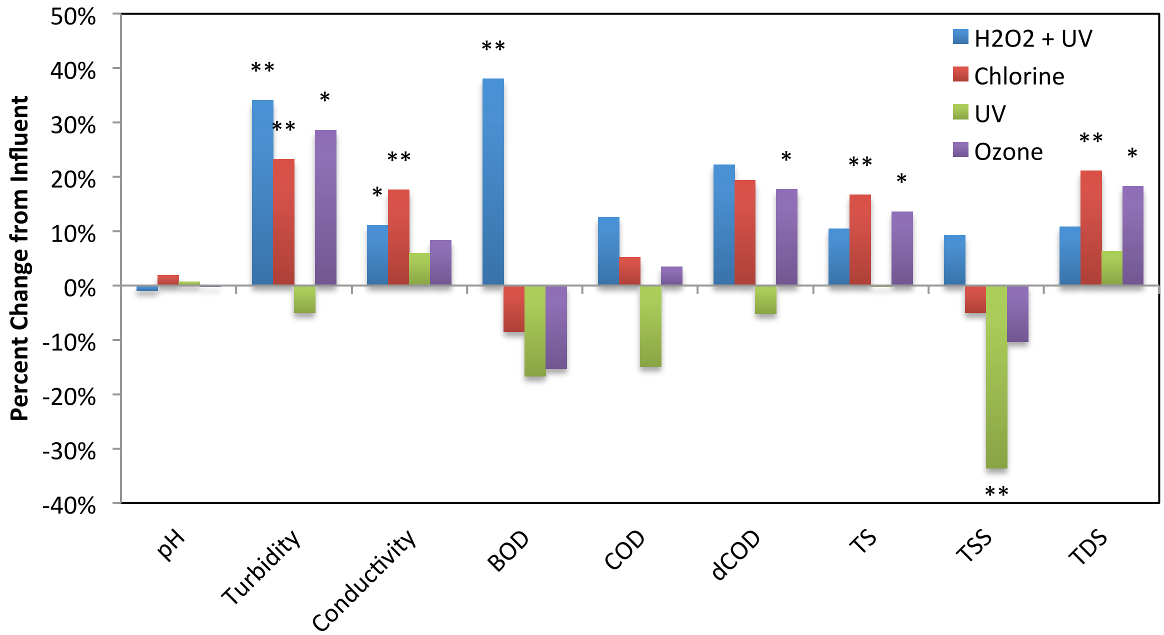

Figure 3.10 Water Chemistry Percent Change from Influent to Effluent (**indicates a statistically significant change from influent at $p<0.05$; *indicates a statistically significant change from influent at $p<0.1$)

All samples were collected during the fall 2011 except for the H_2O_2+UV that was collected during the spring 2011. H_2O_2 + UV did not have a settling process before the disinfection which resulted in a significantly higher ($p<0.5$) turbidity and BOD_5 effluent (Figure 3.10). This shows the importance of compositing and settling in a separate tank before filtration and disinfection.

Chlorine disinfection had a significant ($p<0.5$) increase in dissolved compounds (TDS and conductivity) due to the increase of sodium from the hypochlorite solution. Additionally, chlorine did result in a 23% increase in turbidity ($p<0.05$) as a result of chemical reactions in the graywater, but this did not lead to aesthetic issues as the TSS was unchanged (Figure 3.10).

The only water chemistry parameter significantly ($p<0.05$) affected by ozone was an increase in TDS. This indicates that some reactions with ozone were possibly occurring with smaller compounds but no other parameter was significantly affected indicating little overall impact by ozone. Similarly, UV had no significant effect on water chemistry. The exception to this was significant ($p<0.5$) reduction in TSS. This was possibly a result of the lack of chemical reactions that occurred during UV disinfection and not a result of UV reduction of TSS. For all of the disinfectants, the influent and effluent DO concentration was significantly different (Table 3.7).

Table 3.7 Effluent Dissolved Oxygen Concentration (mg/L; **indicates a statistically significant change from influent at $p<0.05$)

	DO (mg/L)
Influent	1.1 ± 0.5
H_2O_2 + UV	$7.5 \pm 2.6^{**}$
Chlorine	$3.5 \pm 1.9^{**}$
UV	$3.3 \pm 0.3^{**}$
Ozone	$2.7 \pm 0.5^{**}$

Figure 3.11 H_2O_2 + UV Effluent Water Quality

Figure 3.12 Chlorine Effluent Water Quality

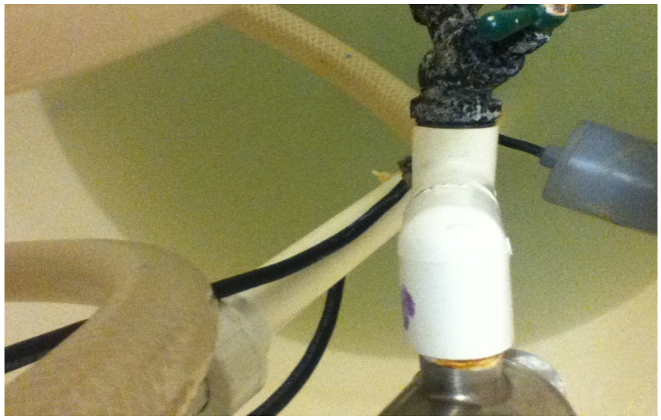

Figure 3.13 UV Effluent Water Quality

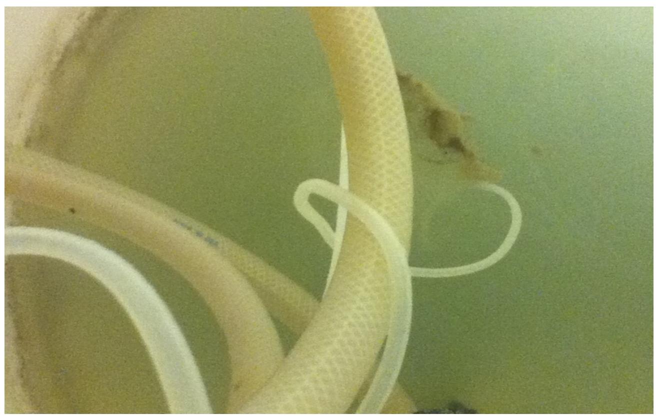

Figure 3.14 Ozone Effluent Water Quality

There were observed aesthetic and odor differences between disinfectants. The H_2O_2 resulted in a saturated DO concentration of 7.5±2.6 mg/L (Table 3.7). This beneficially prevented anaerobic storage conditions and there were no undesirable odors. However, it does increase the potential for bacterial growth in the distribution system providing an aerobic environment in the presence of organics. Additionally, the saturated DO caused what appeared to be fats and oils to coagulate and suspend in the disinfection tank (Figure 3.11). This is primarily an aesthetic issue that would be undesirable if it occurred in the toilet tanks. Ozone resulted in an increased DO (2.7±0.5 mg/L) as a result of the ozonation process. To a lesser extent, this resulted in similar suspended material as observed with H_2O_2 (Figure 3.14). UV and Chlorine resulted in an increased

DO as a result of the recirculation process but that did not appear to have any affects on water chemistry. UV alone resulted in a visually darker effluent (Figure 3.13). Additionally, odor issues arose without a residual disinfectant maintained in the tank. Chlorine had the best effluent appearance visually. Suspended matter was not as observable and the water had a slight blue color instead of gray (Figure 3.12). The chlorine did help to reduce odors unlike UV, but not as efficiently as ozone or hydrogen peroxide.

3.3.4 Batch Disinfection Results

The batch analysis showed similar disinfection performance to the Aspen pilot system. The tests were performed by Kristen Wiles and looked at the efficiency of chlorine, UV and ozone against *E .coli* (Figure 3.16) and total coliform (Figure 3.15).

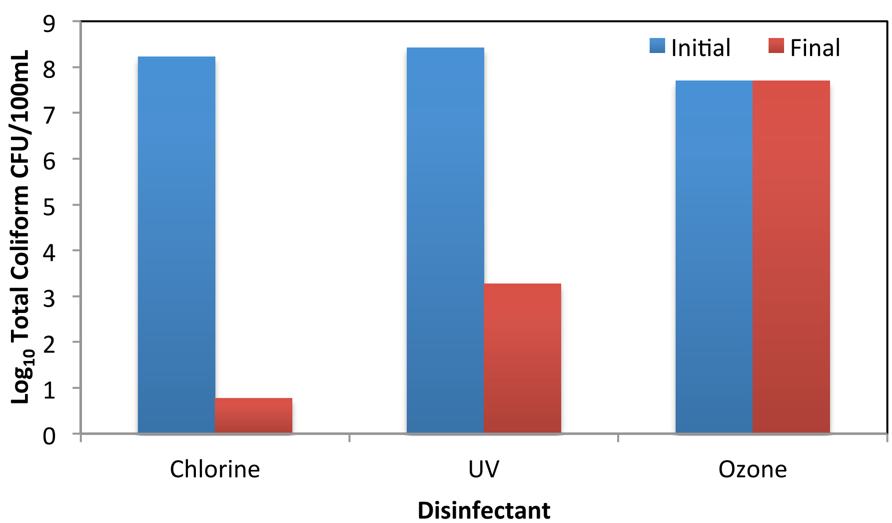

Figure 3.15 Total Coliform Coarse Filtered Graywater Batch Disinfection

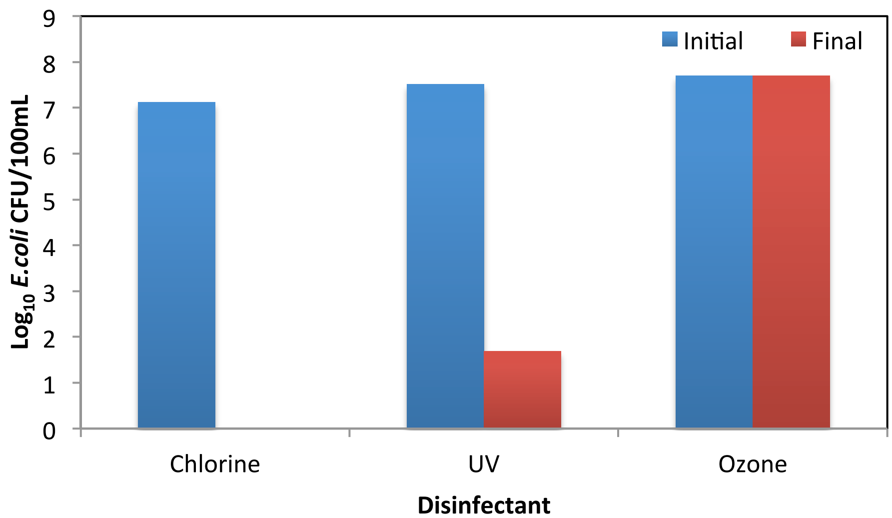

Figure 3.16 *E. coli* Coarse Filter Graywater Batch Disinfection

Ozone did not provide inactivation of *E. coli* or total coliform at a dose of 1 mg/L and contact time of 60 minutes (Figure 3.15 and Figure 3.16). UV was dosed at 28 mJ/cm^2 and achieved total coliform and *E. coli* reduction of 5.2 and 5.8 Log_{10} CFU/100mL respectively (Figure 3.15 and Figure 3.16). The batch UV dose was higher than the pilot unit operated in Aspen Hall and the batch tests indicate more efficient UV disinfection. This increased performance of UV is likely the result of a higher dose and inactivation of suspended bacteria. UV disinfection has two phases, a linear phase followed by a tailing phase (Hijnen et al., 2006). In the linear phase, the suspended coliforms are easily disinfected, but in the tailing phase the particle associated coliforms are shielded from the UV light (Winward, 2007). The batch tests were based on the disinfection of added lab-strain bacteria that were likely primarily suspended. Additionally, some pathogens have the ability to repair after UV disinfection. This is accomplished by dark repair or photo-reactivation (Hijnen et al., 2006). The batch samples were enumerated immediately after disinfection, but in the pilot system there were periods of time before quantification. This time may have provided opportunity for repair to occur.

At a dose of 12 mg/L Cl_2 and a contact time of 60 minutes, *E. coli* and total coliform were reduced by >7.1 and 7.4 Log_{10} CFU/100mL (Figure 3.15 and Figure 3.16). Figure 3.17 is a second chlorine batch analysis that shows the linear phase of disinfection achieved in the first 15 minutes followed by the tailing phase over the remaining 45 minutes. Chlorine consumption followed the same model of rapid initial consumption and a stabilized residual by 60 minutes. Winward et al. observed similar graywater disinfection kinetics (Winward et al., 2008b).

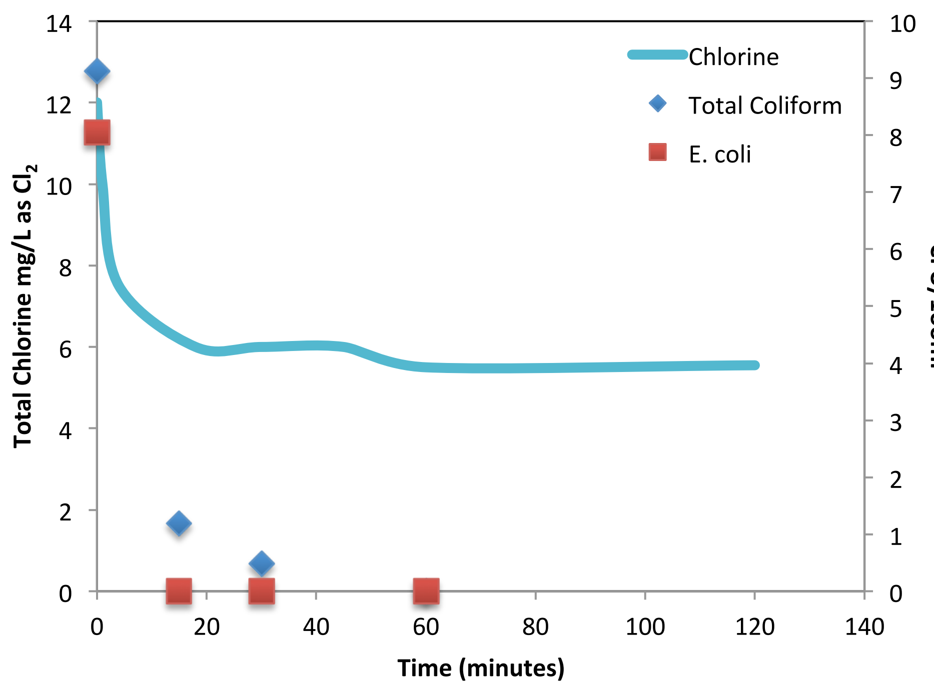

Figure 3.17 *E. coli,* Total Coliform, and Chlorine Consumption Over Time

3.3.5 Chlorine Disinfection Efficiency

During the fall 2011 and spring 2012 semesters' graywater disinfection was tested with different filters and chlorine. The resulting measured influent and effluent total coliform and *E. coli* concentrations are presented in Table 3.8.

Table 3.8 Chlorine Disinfection Efficiency (NM means not measured)

Date	**Total Coliform**		***E. coli***		**Total Chlorine Residual** mg/L as Cl_2
	Influent Log CFU/100ml	**Effluent** CFU/100ml	**Influent** Log CFU/100ml	**Effluent** CFU/100ml	
10/14/11	>5.38	0	2.0	0	2.8
10/17/11	>3.38	0	2.61	0	8.0
10/21/11	>4.68	0	2.02	0	5.1
10/26/11	>4.68	0	<1.3	0	2.4
4/2/12	8.19	0	<3	0	1.0
4/5/12	8.38	0	4.35	0	2.4
4/6/12	NM	0	NM	0	2.6
4/20/12	8.81	0	0.8	0	1.5
4/24/12	NM	0	NM	0	2.0
4/25/12	NM	0	NM	0	2.0
5/1/12	8.51	1	3.76	0	0.3
5/2/12	>9.38	44.1	5.19	0	0.6
5/4/12	8.23	0	1.3	0	1.4
5/11/12	NM	1	NM	0	6.5

In all of the filters tested, dosing based on total chlorine residual of 1-4 mg/L Cl_2 provided efficient inactivation of *E. coli* and total coliform. This suggests that monochloramine will sufficiently disinfect graywater. The benefit of this is that there is lower cost and decreased DBP formation potential compared to dosing until free chlorine formation. Similar projects observed that samples with >1 mg/L Cl_2 free chlorine residual resulted in a negative test for total coliforms (Gual et al., 2008; March et al., 2004). Chlorine disinfection in the presence of ammonia results in a considerably lower chlorine dose and a more stable residual (March et al., 2005). Graywater dosed at ammonia : chlorine molar ratios of 1-8 resulted in a more stable chlorine residual compared to chlorine dosed in graywater with no or trace concentrations of ammonia present (March and Gual, 2009). Chlorine disinfection is efficient in the presence of organic matter, and the TOC concentrations in graywater will affect the chlorine consumption but not the disinfection efficiency (Winward et al., 2008).

Filtration

3.3.6 Filtration Water Chemistry Results

A coarse, sand and cartridge filter were individually tested for the effect on water chemistry. The graywater was sampled throughout the spring 2012 semester and an ANOVA analysis was performed on the influent concentrations for each filter to ensure the water quality was not significantly different between for any filter. Results showed that the influent concentrations were not significantly ($p<0.05$) different between sample groups for TOC, DOC, BOD and TSS. The average influent concentrations are reported below in Table 3.9. The influent concentrations were consistent with the reported light graywater quality (Eriksson et al., 2002). Appendix A provides a complete summary of all measured influent and effluent water chemistry.

Table 3.9 Influent Water Chemistry During Spring 2012

	Influent
DO (mg/L)	0.3 ± 0.3
pH	7.1 ± 0.3
Turbidity (NTU)	32 ± 4.2
Conductivity (µS/cm)	255 ± 71.3
BOD_5 (mg/L)	105 ± 17.1
TOC (mg/L-C)	44 ± 12.2
DOC (mg/L-C)	19.9 ± 8.8
TS (mg/L)	167 ± 22.3
TSS (mg/L)	25 ± 4.7
TDS (mg/L)	142 ± 21.8

A Satterthwaite’s t-test was performed on influent and effluent concentration for each filter to determine significant changes in water chemistry (U.S. EPA, 2000). The percent change between the average influent and average effluent concentration was calculated for each water chemistry parameter and is reported along with statistical significance in Figure 3.18.

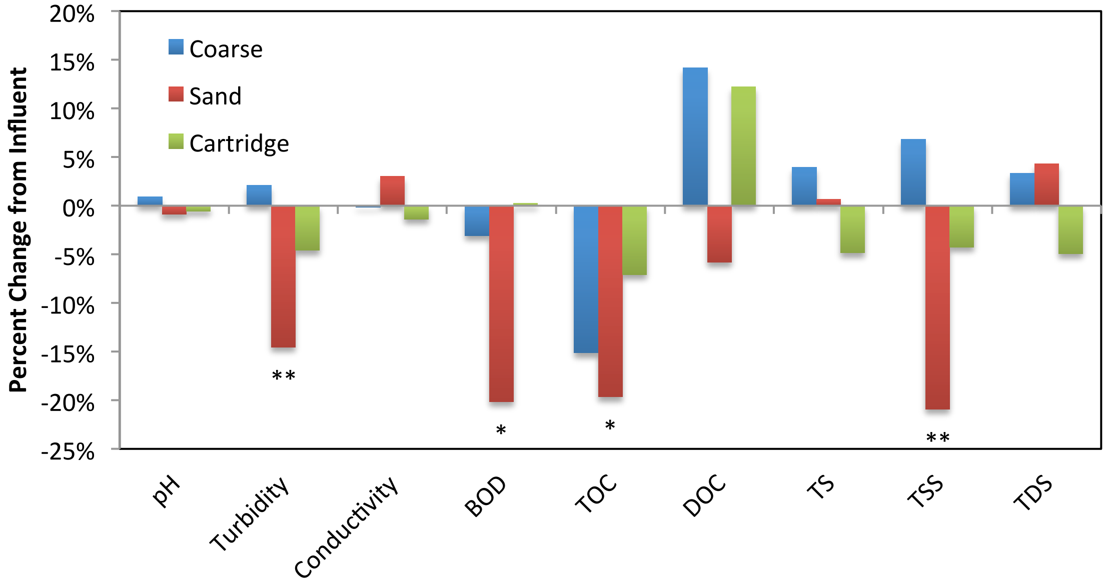

Figure 3.18 Water Chemistry Percent Change from Influent to Post-Filtration (**indicates a statistically significant change from influent at $p<0.05$; *indicates a statistically significant change from influent at $p<0.1$)

The coarse and the cartridge filter did not achieve any statistically significant ($p\geq0.1$) change in water quality. The sand filter did show to have a significant reduction in solids (TSS and turbidity) with a $p<0.05$ and organics (BOD5 and TOC) with a $p<0.1$. For these parameters a percent removal was calculated for each individual sample. The TOC, BOD_5, TSS and turbidity removal rates are reported in Table 3.10.

Table 3.10 Filtration Percent Removal ((**indicates a statistically significant change from influent at $p<0.05$; *indicates a statistically significant change from influent at $p<0.1$)

	Percent Removal		
	Coarse	**Sand**	**Cartridge**
TOC	15 ± 10	31 ± 17*	5 ± 20
BOD_5	2 ± 8	21 ± 9*	-3 ± 20
TSS	-3 ± 17	37 ± 12**	6 ± 12
Turbidity	-1 ± 7	13 ± 11**	5 ± 10

The coarse and cartridge filter proved to have little to no significant ($p\geq0.1$) change on solids (TSS and NTU) or organic content (TOC and BOD_5) of graywater (Table 3.10). When the filters were removed at the end of the experiment, each filter did collect some of the larger debris, but did not significantly remove the suspended solids. Other graywater projects have shown coarse filtration will effectively remove large particles in graywater (Winward et al., 2008b). The majority of particles in graywater range in size from 10-100 microns (Jefferson et al., 2004). The pore size of both filters was larger then 100 microns allowing the majority of the solids to pass through. The coarse and cartridge filters operated for 61 and 13 days respectively and neither filter required maintenance during the testing period. A similar project utilized a strainer and mesh filter and required weekly maintenance (Christova-boala et al., 1996). As expected, the activated carbon in the cartridge filter was undersized and provided no additional DOC removal (Figure 3.18)

The sand filter efficiently removed a portion of the solid and organic content of graywater. The sand filter significantly ($p<0.05$) reduced the TSS and turbidity with an average calculated removal rate of 37±12% and 13±11% respectively (Table 3.10). Additionally, the sand filter significantly ($p<0.1$) removed a portion of the organic content (BOD_5 and TOC). The average calculated removal rate of BOD_5 and TOC was 21±9% and 31±17% respectively (Table 3.10). This removal likely accounts for the suspended portion of the graywater organic compounds and the filtration had no effect on the DOC (Figure 3.18) The sand filter was in operation for 18 days and filtered 5,144 gallons. The initial sand filtration rate was 7.9 gpm, but the filtration rate slowed to 1.9 gpm in the final days signifying the need to backwash the filter. A hotel in Spain utilized a sand filter and reduced TSS, turbidity and TOC by 28%, 18% and 20% respectively and required backwashing every 5-6 days processing on average 7,053 gpd (Gual et al., 2008).

The efficiency of solids removal increased over time as suspended solids collected on the sand and reduced the pore size (Figure 3.20). In contrast, the TOC removal appeared to decrease over time as the suspended organic mater was filtered out. The accumulation of organics in the sand seemed to lead to biologic growth on the media. Eventually the collected solids sloughed off the sand. This resulted in a decrease in efficiency of TOC and TSS removal after 17 days (Figure 3.19 and Figure 3.20). This is when the media began to clog and backwashing was necessary. A frequent backwash schedule would reduce this occurrence and maintain the filters performance.

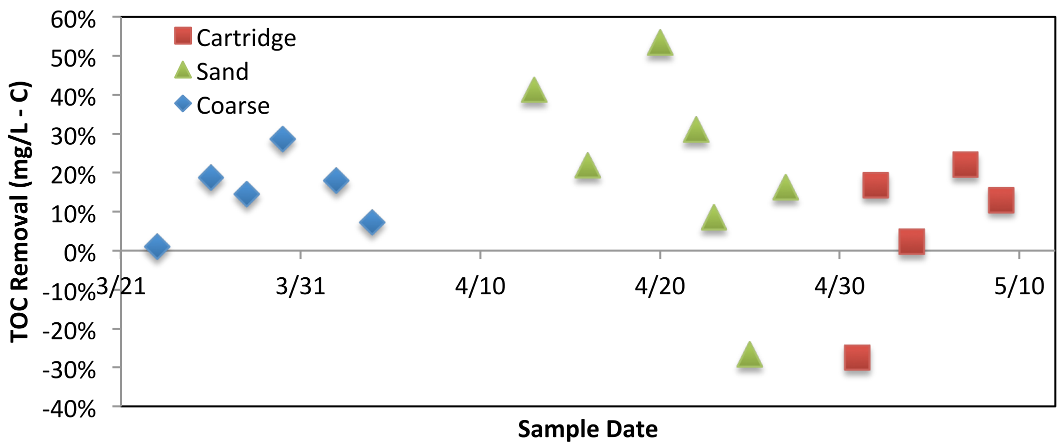

Figure 3.19 TOC Removal

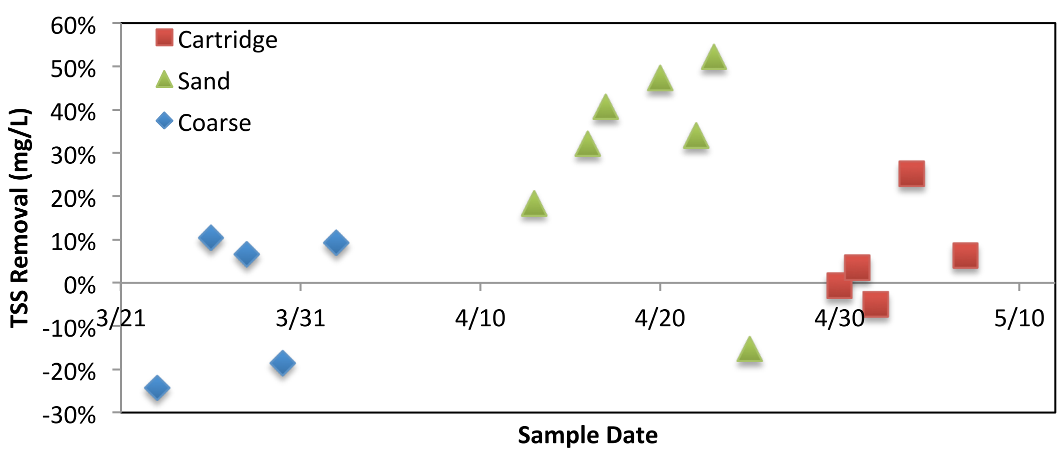

Figure 3.20 TSS Removal

The retention time in the sand filter was highly variable based on the flush schedule and when the graywater was being utilized. Overnight, simulated flushing was not occurring resulting in long retention times. The retention in the sand filter was 4 minutes while the tank was refilling and 5 hours overnight when the schedule was not flushing. The operational retention time for this study likely enabled some microbial growth clogging the filter and decreasing filter rate, but did not provide sufficient time for complete degradation of organic compounds to CO_2. Therefore the sand filter beneficially removed solids, but was limited in organic removal based on the operated retention times and filter size.

3.3.7 Filtration Chlorine Consumption and SUVA

Each filter was tested for the potential impact on disinfection performance. Figure 3.21 and Figure 3.22 shows the chlorine consumption for each filter. Additionally, Table 3.11 provides filtration effect on UVT and SUVA to understand the potential of UV disinfection and possible change in disinfection by-product formation.

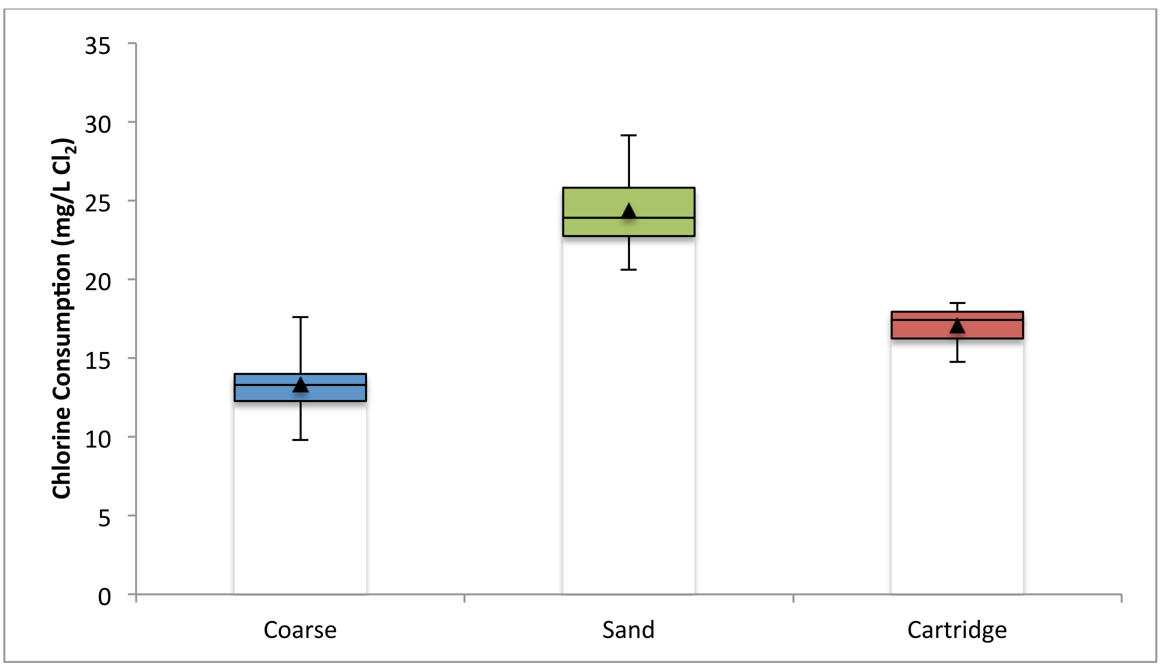

Figure 3.21 Chlorine Consumption Based on Filtration

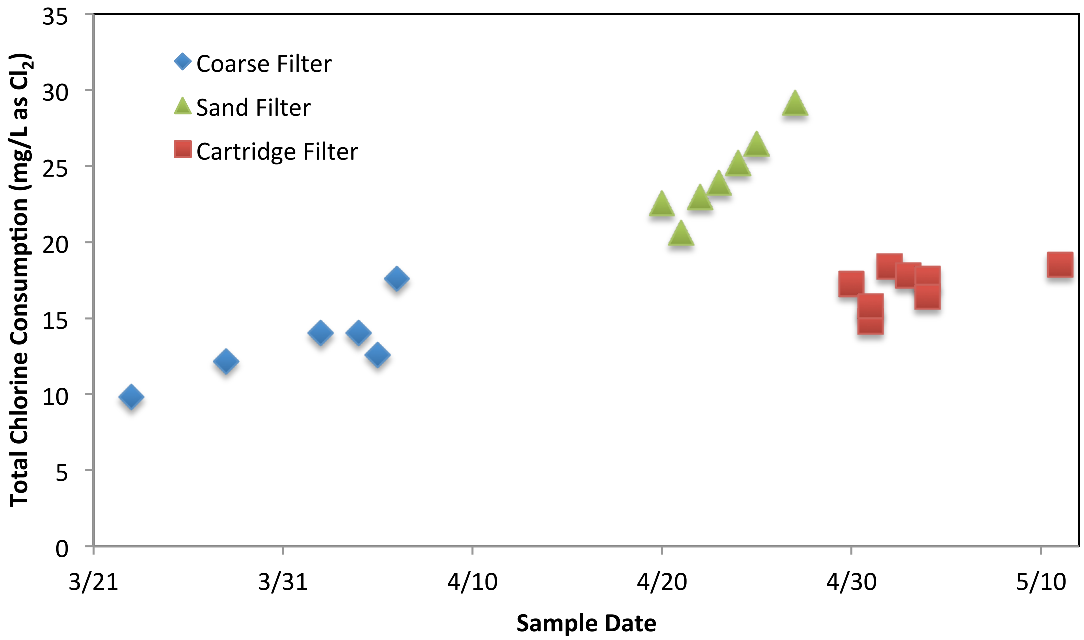

Figure 3.22 Chlorine Consumption Associated with Tested Filters

Table 3.11 Filtration Effect on UVT, SUVA and Chlorine Consumption (**indicates a statistically significant change from influent at $p<0.05$)

	Influent	Coarse	Sand	Cartridge
%UVT	40 ± 6	39 ± 6	41 ± 6	36 ± 6
SUVA	1.1 ± 0.6	1.1 ± 0.6	1.0 ± 0.6	1.1 ± 0.3
Ammonia (mg/L-N)	8.4 ± 2.2	8.2 ± 3.0	9.0 ± 1.7	9.1 ± 2.2
Chlorine Consumption (mg/L Cl_2)	N/A	13.4 ± 2.6**	24.4 ± 2.8**	17.1 ± 1.3**

The UVT was not significantly ($p\geq0.1$) improved by any of the filters (Table 3.11). This is because most of the absorbing compounds are dissolved inorganics or organic species that were unaffected by filtration. To efficiently improve the transmittance, a biological or membrane filtration process would be necessary to remove the DOC. Friedler et al. tested a rotating biological contactor (RBC) and improved the UVT from 52.5% to 92.9% (Friedler et al., 2011).

The chlorine consumption between each filter was statistically significant at $p<0.5$ according to an ANOVA analysis (Appendix C). The chlorine consumption increased with improved filtration. The coarse had the least filtration and least chlorine consumption, while the sand had the most filtration but the largest chlorine consumption (Figure 3.21). The coarse, sand and cartridge filter had a consumption of 13.4±2.6, 24.4±2.8 and 17.1±1.3 mg/L Cl_2 respectively (Figure 3.21). March and Gual also looked at filtration effect on chlorine consumption and reported that no significant change was observed between non-filtered graywater and samples filtered between 25-200 microns (March and Gual, 2009).

As stated earlier, the sand filter likely had biological growth that was observed on the surface of the media upon completion of experiments. This growth may have resulted in partial degradation of organic content and formation of intermediate compounds that were more reactive with chlorine. Researchers have observed in wastewater treatment that soluble microbial products (SMP) formed during biodegradation of carbohydrates and starches may result in a more reactive organic species and a higher disinfection by-product formation potential (DBPFP) (Liu and Li, 2010). These soluble microbial products occur during the early stages of organic degradation (Liu and Li, 2010). The sand filter was not operated for biological removal and there was a variable residence time from 4 minutes to 5 hours. The sand filter chlorine consumption increased over time (Figure 3.22). This suggests that as the bacterial growth increased, soluble microbial products were produced in the filter and were more reactive with chlorine causing an increase in demand. Krasner et al. showed wastewater treatment resulted in biological activity that preferentially removed DOC over UVA meaning the non-humic compounds were more easily degraded than the humic (Krasner et al., 2009). This suggests that the influent non-humic organics common in graywater are more reactive for initial degradation resulting in higher fraction of reactive DOC. This is a hypothesis of what may be occurring in the sand filter based on the resulting observed parameters and literature review of biological degradation processes. It was clear that a statistically significant change in chlorine consumption was observed with the sand filter.

The cartridge filter also showed had a significant ($p<0.05$) different chlorine consumption, (17.1±1.3 mg/L Cl_2) compared to the coarse filter (13.4±2.6 mg/L Cl_2). The cartridge filter did not show signs of biological growth; therefore, the change in chlorine consumption is likely for different reasons than the sand filter. The cartridge filter was 100 microns with a GAC insert. As discussed earlier, the GAC was undersized based on the influent graywater load so there was no beneficial DOC reduction (Figure 3.18). The higher chlorine consumption is likely due to the variation of influent graywater (Table 3.9). The cartridge filter was operated over the final weeks of the semester. During this time there is a large amount of cleaning which may have resulted in additional compounds that entered the graywater system and led to a spike in chlorine consumption. Additionally, the activated carbon may have resulted in additional chlorine consumption. The finer GAC was washed off the filter and residue was observed in the pipes and walls of the filter. Activated carbon can react with chloramines and result in a higher chlorine consumption (AWWA, 1999b). These two factors are likely the cause for the observed difference in chlorine consumption between the cartridge and coarse filter.

An increase in chlorine consumption results in a higher operational cost and an increase in potential reactions with organic compounds. One of the biggest concerns with utilizing chlorine disinfection is the formation of DBPs. Therefore, minimizing these reactions is beneficial. One way to measure potential reactions of organic compounds in graywater is SUVA. SUVA values > 4 L/mg-min are said to be humic while < 2 L/mg-min are non-humic (Krasner et al., 2009). Humic compounds are more likely to form DBPs. The influent SUVA for graywater was 1.1±0.6 L/mg-min and was not affected by filtration (Table 3.11). Wastewater is often chlorinated and the SUVA of the effluent organic matter (efOM) from wastewater treatment is 1.65-6.06 L/mg-min (Sirivedhin and Gray, 2005). This suggests that the organic matter from graywater is no more reactive than organic content in treated wastewater.

SUVA is not a perfect DBP measurement and other parameters must be considered. Another equally important indicator is the organic matter concentration (Liu and Li, 2010). Graywater has a high concentration of DOC at 19.9±8.8 mg/L-C (Table 3.9). Higher DOC results in more opportunities for chlorine reactions and DBP formation (Liu and Li, 2010). Advanced treatment processes may reduce the DOC to a concentration where this is of less concern. In another treatment process, a rotating biological contactor and filtration reduced DOC in graywater to 5 mg/L and required a chlorine dose of 5 mg/L (Friedler et al., 2011). However, these processes can be very costly and labor intensive making implementation more difficult and wide scale adoption less likely. Other researched treatment systems use coarse filtration but a high chlorine dose of 75 mg/L Cl_2 to establish a free chlorine residual (March et al., 2004). Operating a system in this range incurs a large cost and has the potential to form a considerable amount of DBPs.

An alternative practice to minimize chlorine dose is by operating disinfection to favor monochloramine disinfection. The effect of filtration on chlorine consumption was studied based on the formation of monochloramine and not breakpoint chlorination (Figure 3.22). Minimizing the chlorine dose will decrease the potential chlorine and organic reactions. Approximately 90 percent of chlorine and organic matter reactions do not produce halogenated organic compounds and are redox reactions (AWWA, 2003). The coarse filter proved to be the best option for minimizing dose resulting in a consumption of 13.4±2.6 mg/L Cl_2 (Table 3.11).

3.4 Summary and Conclusions

The tests showed that coarse filtration and chlorine disinfection may be one of the better options for graywater reuse applications. Hydrogen peroxide proved to be efficient at *E. coli* disinfection but at a very high operational cost (see Chapter 4). Ozone and UV did not prove to be sufficiently effective at the scale tested. Utilizing ammonia present in graywater to preferentially form monochloramine can minimize chlorine demand. This will reduce operational cost and decrease the potentially negative environmental effects of breakpoint chlorination. Monochloramine proved to sufficiently disinfect graywater and provides a stable residual. Coarse filtration proved to have no notable effect on water chemistry but does collect major solids and requires minimal maintenance. The cartridge filter had a higher cost than the coarse filter but no added water chemistry or disinfection benefits. The sand filter did prove to have an effect on the suspended solids and organics of graywater but requires more maintenance and results in organic compounds that are more reactive with chlorine. More advanced filtration processes may result in improved water chemistry, but may come at a cost rendering it unfeasible to implement.

4.0 ECONOMIC ANALYSIS OF GRAYWATER REUSE AT THE MULTI-RESIDENTIAL SCALE

4.1 Introduction

Projects that decrease water consumption, like graywater reuse, provide potential benefits for both the utilities and consumer. While there has been an increase in graywater treatment technologies, there is still a limited amount of information on cost and energy requirements associated with these technologies (Pidou et al., 2007). A proper cost analysis is necessary to assess the potential financial benefit a graywater reuse project.

Water conservation projects require an initial investment, but often translate into long-term capital and operational savings (U.S. EPA, 2002b). A city or utility may be looking at ways to stretch the current water supply, prevent the need for costly treatment upgrades, free up water supply for an alternative use or to prepare for drought potential. A consumer would consider graywater reuse project to decrease monthly water bill, be environmentally conscience or potentially gain credit for building certification (LEED).

The value of water conservation and reuse projects is not limited to capital and operational savings. Benefits of these projects include watershed protection, local economic development and improvement of public health (Sheikh et al., 1998). Many groups may benefit from water reuse project, but the burden of cost is typically not shared (Cooley et al, 2010). Therefore, projects that are financially beneficial to the consumer are more likely to be implemented.

Federal facilities are required to incorporate innovative and cost-effective water efficiency strategies (FEMP, 2012). As a result, the Federal Energy Management Program (FEMP) was developed to provide resources on how to assess the financial benefit of different energy and water projects (Fuller and Peterson, 1995). This financial analysis was performed on graywater reuse for toilet flushing at a range of system scales and for a variety of disinfection alternatives. This section provides a calculation of the present value lifetime and annualized costs between the alternatives of utilizing graywater reuse for toilet flushing (Alternative 1) or maintaining use of freshwater for toilet flushing (Alternative 2).

4.2 Material and Methods

4.2.1 Life-Cycle Cost Analysis

A life cycle cost (LCC) analysis was performed in order to assess the implementation cost of a graywater reuse project at the multi-residential scale. The analysis was done according to the FEMP Life-Cycle Costing Manual (Fuller and Peterson, 1995). All terms were discounted to present value to determine the life cycle cost of a project. An economic analysis was first performed to consider the cost of implementing different disinfectants at Aspen Hall. Next, an economic analysis of implementing chlorine disinfection with coarse, sand and cartridge filtration was calculated. This analysis was performed on a range of multi-residential scales to understand the cost-benefit of graywater reuse at different applications. The multi-residential scales, or system size, tested refers to the amount of graywater reused for toilet flushing in a day.

4.2.2 Disinfection Cost Analysis

In order to address the feasibility of graywater disinfection alternatives, an implementation cost for chlorine, hydrogen peroxide, ozone and UV was calculated. The disinfection alternatives needed to be cost effective at a range of treatment volumes, easy to maintain and be safe for use at a multi-residential scale. Capital investment, annual operation and electrical use were calculated. Disinfectants were compared based on a 10-year life cycle cost discounted to terms of present worth. All costs were calculated based on implementation at Aspen Hall treating 300 GPD of graywater and assuming maintenance was equal across disinfectants. Costs were derived from current market prices during the time of the analysis. A list of the selected component manufacture, model and cost for each disinfection alternative is provided in Appendix D.

Hydrogen Peroxide

Hydrogen peroxide costs were calculated for chemical injection at a dose of 140 mg/L H_2O_2, the dose determined necessary for graywater (see Chapter 3). The capital costs include a peristaltic pump and volume controlled timer. The annual operation cost was the consumption of hydrogen peroxide. The only electrical consumption was from the peristaltic pump.

Chlorine

Chlorine disinfection costs were calculated for chemical and tablet disinfection. Chemical disinfection analysis was based on 6% NaOCl and had capital costs that included a peristaltic pump and volume controlled timer. The annual cost was the hypochlorite consumption at a dose of 14 mg/L Cl_2 and the only electrical consumption was from the peristaltic pump.

Ultraviolet

Ultraviolet disinfection was calculated based on a residential scale UV unit capable of delivering a dose of 40 mJ/cm^2 at a flow rate of 3.5 gpm and 75% UVT. The associated capital was the cost of the lamp, ballast and control assembly. The annual cost was the UV lamp replacement. The electrical cost was the power consumed to operate the UV lamp 24 hours a day. No pump capital or electrical use was included with the assumption that the pump is required for all systems in order to distribute the graywater.

Ozone

Ozone disinfection was analyzed at three different scales: spa, lab and industrial. These scales were based on the resulting ozone output of the generator. As ozone output increase there are additional capital costs associated with implementation of O_3 at higher concentrations. The spa scale capital was an air pump and spa ozonater with a maximum output of 0.06 grams/hr. The lab scale capital included an air pump and a bench top ozonater with a maximum output of .75 grams/hr. The industry scale generator had a maximum output of 10 grams/hr. In order to generate ozone at this high concentration, an oxygen concentrator and ozone destruction unit were included along with the ozone generator in the capital cost. The annual cost included manufacture required replacement of components in the ozone generator. Electrical use was calculated assuming the ozone system was in operation 24 hours a day.

4.2.3 Multi-Residential Scale Economic analysis

An economic analysis was performed on a range of multi-residential sizes to understand the affect of scale on graywater reuse for toilet flushing. Sodium hypochlorite was chosen as the disinfectant based on the inactivation efficacy and economic considerations outlined above. Three different filters (coarse, sand and cartridge) were included to assess the effect of increased filtration on implementation cost. Fourteen different scales ranging from 50-5,000 gpd of graywater reuse were analyzed. This range would account for a single residence of 3 people to a multi-residential apartment of 335 people. Considered costs included capital investment and annual operation and maintenance. All costs were derived from current market prices. A life cycle cost analysis was performed discounting annual costs and bringing all costs to present worth. This economic analysis does not include costs associated with dual plumbing a building for graywater collection and distribution or the cost of a backflow prevention device. These costs may very significantly regionally and depending on new developments or retrofits. These are important costs to consider and are capital investment costs that may be calculated for individual applications. These costs may be added to the total life cycle cost defined below in order to understand the feasibility of a particular project. This cost analysis is specific to the treatment process.

The capital costs included pumps, tanks, filters, disinfection components and miscellaneous piping and control devices. The annual costs included chlorine consumption, system electrical use and scheduled maintenance. The scheduled maintenance was estimated by allotting a certain number of hours based on the system size. This is a very hard thing to estimate and is highly dependent on the durability of a treatment system.

4.2.4 Municipal Water Rates

Graywater toilet reuse at the multi-residential scale provides an alternative to utilizing municipality water. In order to consider the potential for reuse in different geographic areas, eight major cities were selected randomly to consider the potential for a reuse project based on current regional water and wastewater rates. The assumption is that one gallon of graywater reused for toilet flushing saves the consumer the cost of one gallon of fresh water and one gallon of wastewater. The actual billed water savings will be based on how a city accounts for wastewater generation. This is because, unlike freshwater, wastewater is not billed by a meter so customer use is estimated using different strategies. The water and wastewater rates were determined based on the utilities published rates of each city. When a multi-residential rate was stated it was selected. If a city did not specify or clearly define the water rate structure (ex. tiered rate structures), the lowest value was utilized for a conservative estimate. The collected water + wastewater rates are shown below in Table 4.1. The past five years, Chicago has had significant rate increases. For that reason, an evaluation of Chicago rates in 2008, 2012 and 2015 was included to understand the impact of increasing rates on implementation of graywater reuse projects. A life cycle cost analysis was performed on the gathered water rates over the next ten years. The calculation used a modified uniform present value to account for escalating water prices. The calculated life-cycle cost would be the total cost to flush toilets for the next ten years.

Table 4.1 Municipal Water Rates

	Rate Structure	Water Rates ($ per TH gal)	Wastewater Rates ($ per TH gal)	Current Water + Wastewater ($ per TH gal)
Fort Collins[1]	Seasonal Flat Rate for Multi-Residential	$2.08	$3.10	$5.18
San Diego[2]	Flat Rate Multi-Residential	$5.24	$6.72	$11.96
Phoenix[3]	Seasonal Flat Rate	$4.33	$2.96	$7.29
Portland[4],[5]	Flat Rate	$4.44	$10.88	$15.32
Boston[6]	Tiered	$5.73	$7.41	$13.14
Orlando[7],[8]	Tiered	$1.54	$4.10	$5.64
Denver[9],[10]	Tiered	$3.38	$3.25	$6.63
Chicago 2008[11]	Flat Rate	$1.53	$1.29	$2.82
Chicago 2012[11]	Flat Rate	$2.51	$2.23	$4.74
Chicago 2015[11]	Flat Rate	$3.82	$3.82	$7.64

(1)fcgov.com, (2)sandiego.gov, (3)phoenix.gov, (4)portlandoregon.gov, (5)portlandonline.com, (6)bwsc.org, (7)ouc.com, (8)cityoforland.net, (9)denverwater.org, (10)denvergov.org, (11)cityofchicago.org

4.2.5 Calculations

The life cycle cost analysis takes all costs to own, operate and maintain a project and discounts the costs into common terms of present worth in order to account for the time-value of money. The capital investment costs are already in terms of present value. Total annual costs were calculated for the product life and assumed annually constant over the entire duration. The annual cost included component replacement, energy consumption and operation and maintenance. No residual system value was included providing a more conservative estimate. The life cycle cost was calculated based on the following equation (Fuller and Petersen, 1995):

$$\text{Equation 4.1:} \quad LCC = I + Repl - Res + E + W + OM\&R$$

LCC = Life-Cycle Cost
I = Present-Value Investment
Repl = Present-value capital replacement cost
Res = Present-value residual value
E = Present-value energy costs
W = Present value water costs
OM&R = Present-value non-fuel operating, maintenance and repair costs

A 10-year life cycle was assumed which is conservative compared to other graywater systems with estimated life of 6-50 years (Sharvelle et al., 2012) and in the range of other comparable home components with a life of 8.5-15 years (Seiders et al., 2007). There is no municipal water (W) used in the treatment process. The annual costs were calculated over ten years and brought back to present value based on the NIST 2011 discount factor of 3% and the following equation (U.S. NIST, 2011; Fuller and Petersen, 1995).

$$\text{Equation 4.2:} \quad Uniform\ Present\ Value\ (UPV) = A_0 \times \frac{(1+d)^n - 1}{d(1+d)^n}$$

UPV = Uniform Present Value
A_0 = Annual Cost (ex. energy, chemicals or maintenance)
Repl = Present-value capital replacement cost
d = Discount factor (3%)
n = Time of interest (10 years)

The life cycle cost of maintaining the use of freshwater for toilet flushing (Alternative 2) was calculated over the same ten-year period of time. There was no capital investment. The only cost was water use and wastewater generated to flush toilets. This cost was calculated for each year and brought back to present worth using a discount of 3% (U.S. NIST, 2011). Water costs show an escalating growth rate of 5.5% (Bureau of Labor Statistics, 2012). This is a conservative estimate compared to other graywater economic analysis that included a 5% and 10% escalation rate (City of Guelph, 2012). The life cycle cost was calculated using the modified uniform present value (UPV*) to account for the escalation rate of water over the next ten years (Fuller and Petersen, 1995).

Equation 4.3: $UPV^* = A_0 \frac{(1+e)}{(d-e)} \left[1 - \left(\frac{1+e}{1+d}\right)^n\right]$

UPV* = Modified Uniform Present Value
A_0 = Annual Cost (ex. energy, chemicals or maintenance)
Repl = Present-value capital replacement cost
d = Discount factor (3%)
n = Time of interest (10 years)
e = Escalation rate (5.5%)

All life cycle costs in terms of present worth were converted to cost per water unit. Water rates are in terms of dollars per thousand gallons ($ per TH gallon) so it was desired to turn the total life cycle cost into a common water rate term. This was accomplished by taking the calculated life cycle cost and dividing it by the total graywater reused over the ten-year period.

Equation 4.4: $Water\ Rate\ (\$\ per\ TH\ gallon) = \frac{LCC_{10yr}}{Volume\ Treated_{10yr}}$

Finally, a payback period was calculated to understand how long it would take an implemented graywater reuse project to payback the total life cycle cost. The payback was calculated based on simple payback calculation that used the discounted annual costs that were calculated with the LCC analysis (Fuller and Petersen, 1995). The reuse system capital investment was divided by the savings per year from utilizing graywater instead of freshwater.

Equation 4.5: $Net\ Savings = LCC_{Freshwater} - LCC_{Potable}$

Equation 4.6: $Simple\ Payback = \frac{\Delta I}{\Delta E + \Delta W + \Delta OM\&R}$

I = Present-Value Investment
E = Present-value energy costs
W = Present value water costs
OM&R = Present-value non-fuel operating, maintenance and repair costs

The economic analysis included an observation of energy use. Energy use was monitored at Aspen Hall throughout the duration of the experiments. Energy costs were calculated for each system based on energy consumption of published system components and estimating the duration that each component is on based on use and flow rates.

4.3 Results and Discussion

4.3.1 Disinfection Cost Analysis

The first calculation was a life cycle cost analysis for each disinfectant individually (Table 4.2). A complete breakdown of all the disinfection product costs and calculations is included in Appendix E. All costs were performed relative the pilot-scale at Aspen Hall which is a system size of 300 gpd.

Table 4.2 Individual Disinfection Cost Calculation

	Liquid NaOCl	Hydrogen Peroxide	UV	Ozone Spa Scale	Ozone Lab Scale	Ozone Industrial Scale
Capital Cost	$587	$587	$259	$230	$679	$6,000
Annual Cost	$82	$563	$106	$28	$44	$638
10-year Life Cycle Cost Analysis	$1,289	$5,386	$1,162	$466	$1,051	$11,442

The individual disinfection calculations showed chlorine to have the lowest LCC of $1,289 (Table 4.2). Tablet chlorine disinfection was also considered but the dose is difficult to control may become problematic; therefore, liquid chlorine was selected as the appropriate chlorine disinfectant. Individually UV, spa ozone and lab ozone had comparable LCC's to liquid chlorine of $1,162, $466 and $1,051 respectively (Table 4.2). Hydrogen peroxide and industrial ozone had much larger life cycle cost of $5,386 and $11,442 respectively. These large costs are associated with the high annual cost of hydrogen peroxide while industrial ozone equipment requires a large capital cost. From this information, a life cycle analysis for primary and residual disinfection calculation is included in Table 4.3 and Figure 4.1.

Table 4.3 Total Disinfection Cost Calculation

	UV + H_2O_2	Liquid NaOCl	UV + Cl	Spa O_3 + Cl	Lab O_3 + Cl	Industrial O_3 + Cl
Capital Cost	$846	$587	$846	$817	$1,266	$6,587
Annual Cost	$668	$82	$188	$110	$126	$720
Primary and Residual Disinfection Life-Cycle Cost Analysis (10-yr life)	$6,548	$1,289	$2,450	$1,755	$2,340	$12,731
Energy Use (kWh/TH gal)	3.1	0.6	3.1	1.5	3.1	51.5

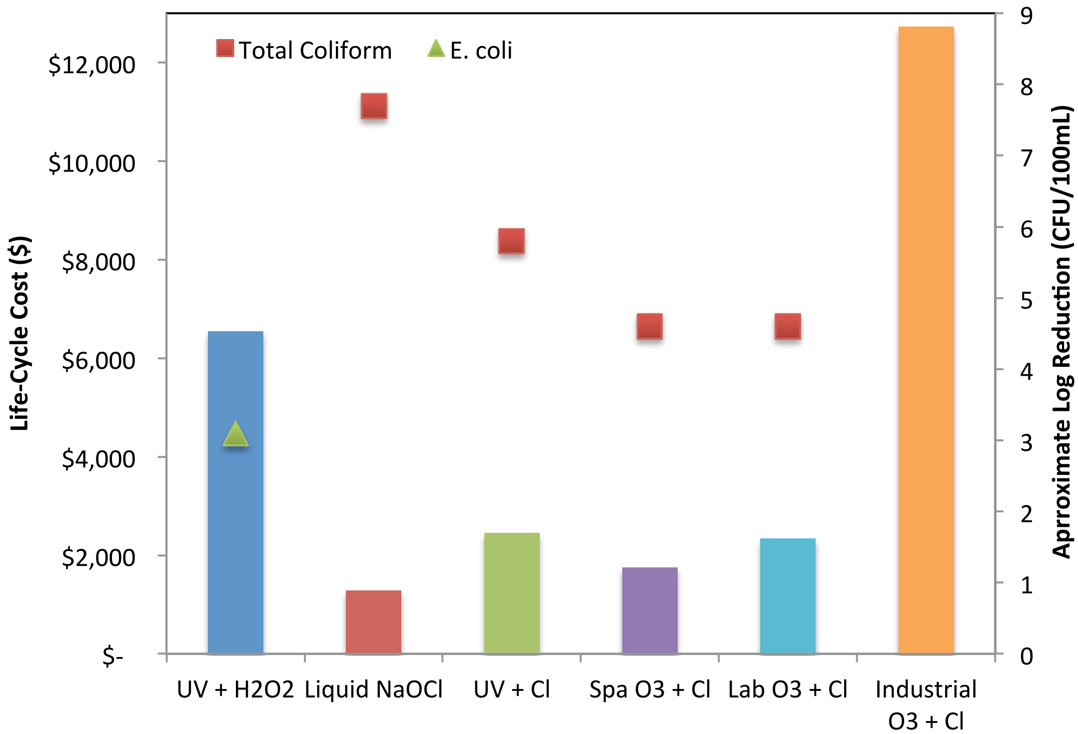

Figure 4.1Total Disinfection Cost Calculation

A residual disinfectant is required in the distribution system. A complete cost analysis must include the cost of a residual. The residual disinfectants considered were hydrogen peroxide with UV or liquid chlorine with ozone or UV. Chlorine can act as a primary and residual disinfectant and it alone was still considered as an alternative. Figure 4.1 shows the resulting life cycle cost for each disinfection option. The large annual cost of hydrogen peroxide consumption makes it economically unfavorable as a residual disinfectant. A treatment process that decreases organics may make H_2O_2 more feasible as a residual disinfection. Liquid chlorine alone was the most economically feasible but UV, spa ozone or lab ozone combined with chlorine still proved to be economically viable alternatives (Figure 4.1). Additionally, spa ozone and lab ozone with chlorine had a small life cycle cost difference of $585 dollars which may suggest that lab ozone is the better selection because of the relatively small cost associated with the increased ozone production (Table 4.3). Industrial ozone had such a large LCC that it is economically less feasible even if other pretreatment measures were implemented (Table 4.3). Larger multi-residential applications that would benefit from the large ozone production may be able to offset the initial capital cost.

Additionally to LCC, it is important to understand the energy use by the disinfection alternatives. A summary of the energy use per thousand gallons is included in Figure 4.2.

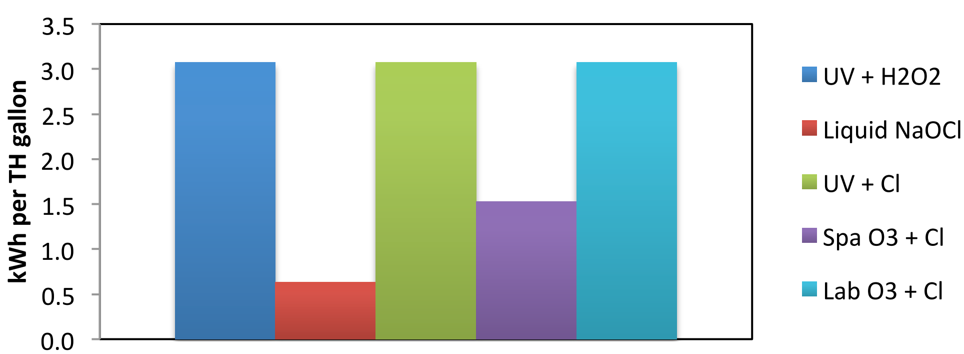

Figure 4.2 Energy Use from Disinfection

Liquid chlorine and spa ozone proved to have the least energy consumption. UV + residual and lab scale ozone + Cl had equivalent energy consumption of 3.1 kWh/TH gallon (Figure 4.2). However, industrial ozone had by far the largest energy consumption of 51.5 kWh/TH gallon (Table 4.3).

4.3.2 Multi-Residential Cost Analysis

The life cycle cost was calculated for the entire treatment system and 3 different filter options. In order to compare the alternatives, a system size of 1,000 gpd was selected and a table was compiled with the resulting LCC, treated water cost and net savings (Table 4.4). A complete list of product costs and calculations is included in Appendix E.

Table 4.4 Life-Cycle Cost Analysis based on Filtration and a System Size of 1,000 GPD in Fort Collins

	System Size: 1,000 GPD		
	LCC	**$/TH gal**	**Net Savings**
Coarse	$15,210	$4.17	$6,649
Sand	$17,186	$4.71	$4,673
Cartridge	$16,019	$4.39	$5,840
Fort Collins Municipal	$21,859	$5.99	$0

Table 4.4 shows that there is little difference in total life cycle cost based on filter utilized. Therefore, filter selection should be based on maintenance and water quality efficiency. Compared to the Fort Collins water rates, the coarse, sand and cartridge filter all proved to provide an overall net savings of $6,649, $4,673 and $5,840 respectively on a treatment scale of 1,000 gpd (Table 4.4). Coarse filtration was selected for the rest of the economic considerations because it proved to have minimal maintenance, low chlorine demand (see Chapter 3) and the most economic LCC.

The next consideration was the affect of system size on implementation potential. The system LCC was calculated for 14 different scales (Table 4.5). A simple cost of water was calculated by dividing the LCC by lifetime water saved and plotted against system size (Figure 4.3). Current utility water rates rang from $4.74-$18.76 (**Error! Reference source not found.**) so for graywater reuse to be economically feasible the treated water costs must be in this range.

Table 4.5 System Cost of Coarse Filter as a Function of System Size

Coarse	System Size						
	50	75	85	100	150	300	500
Capital	$2,030	$2,030	$2,180	$2,180	$2,258	$2,251	$3,026
Annual Chemical and Energy	$17	$25	$28	$33	$53	$106	$177
Annual Maintenance	$240	$240	$240	$480	$480	$480	$720
$/TH gal	$23.12	$15.68	$14.41	$17.97	$12.43	$6.62	$5.85
	750	900	1000	2000	3000	4000	5000
Capital	$3,579	$4,008	$4,008	$5,007	$6,562	$8,336	$11,815
Annual Chemical and Energy	$265	$318	$353	$707	$1,060	$1,413	$1,766
Annual Maintenance	$720	$720	$960	$1,920	$2,880	$3,840	$4,800
$/TH gal	$4.38	$3.92	$4.17	$3.76	$3.67	$3.64	$3.72

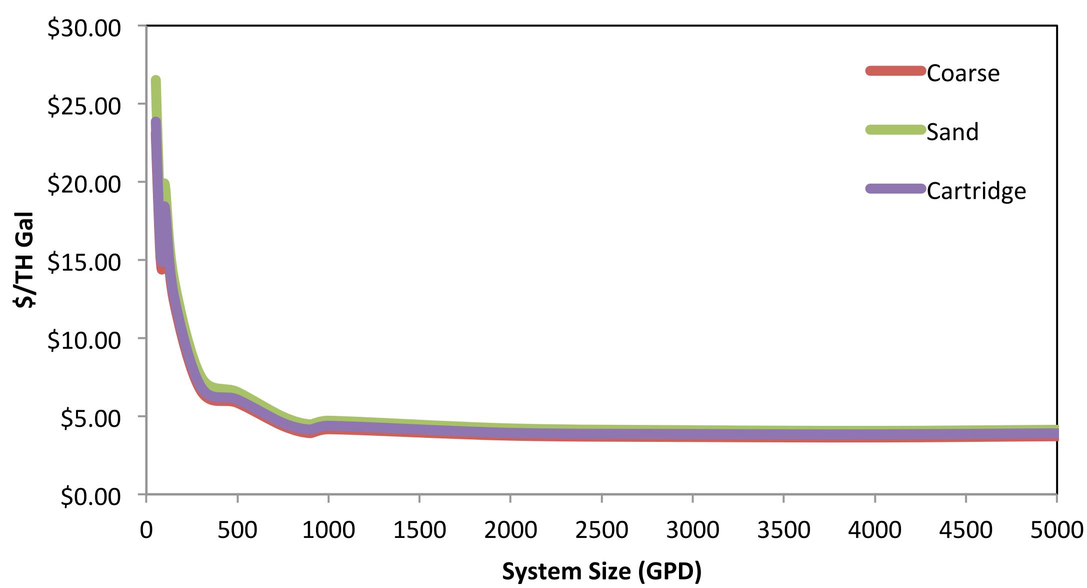

Figure 4.3 Graywater Reuse Cost as a Function of Filtration and System Size

Table 4.5 shows at low system size (≤100 gpd) it is hard for a graywater reuse system to be cost effective and results in treated water cost ≥$14.41 per TH gallon. System sizes between 100-1,000 gpd result in a treated water cost of $3.92-$12.43 per TH gallon, and the cost effectiveness at this scale will be highly dependent on local utility water rates which ranged $2.82-$15.32 per TH gallon. For larger systems, >1,000 GPD, the treatment water cost began to level out and had a range of \$3.72-\$4.17 per TH gallon. At this scale, graywater reuse can be cost effective at many different locations. This trend is outline in Figure 4.3 which shows a steep change in water treatment cost on scales <1000 GPD but a flattening out effect on system sizes >1,000 GPD. Graywater reuse becomes more economically beneficial in areas that have high municipality water rates. A more thorough discussion on the regional effects on the implementation of graywater reuse is provided in the next section (4.3.3).

One of the most difficult things to estimate is the maintenance cost associated with graywater reuse systems. This is because there are not many graywater reuse projects that have been installed to reference. An estimate was determined by calculating the average hours of maintenance that may be required in a month relative to the system size. A well-manufactured system should not require the frequent maintenance that was allotted in this calculation, while other systems may require more than what was selected in this analysis. The maintenance estimates used here are probably less conservative for small systems but overly conservative for large systems with an annual cost of \$240 and \$4,800 respectively (Table 4.5). It is important to understand that the resulting system maintenance will have a large impact on the cost effectiveness of a graywater reuse project. This cost is hard to estimate with the limited number of multi-residential graywater reuse systems in practice.

4.3.3 Utility Rates and System Payback Analysis

The regional cost effectiveness of graywater reuse was determined by looking at eight different cities municipal rates compared to the cost to reuse graywater. Calculations included the cost to reuse water, annual savings and simple payback (Table 4.6). To understand this graphically, Figure 4.4 outlines regional water rates relative to the calculated simple payback of a 1,000 gpd system. A 5.5% escalation rate was applied to the current municipal rate to account for the expected increase in water rates over the next ten years.

Table 4.6 Annual Savings and System Payback at a System Size of 1,000 GPD

City	Current Rate $/TH gallon	Escalated Rate $/TH gallon	Graywater Reuse $/TH gallon	Average Annual Savings $/year	Simple Payback years
Fort Collins	$5.18	$5.99	$4.17	$1,066	3.8
San Diego	$11.96	$13.83	$4.17	$3,927	1.0
Phoenix	$7.29	$8.43	$4.17	$1,956	2.0
Portland	$15.32	$17.71	$4.17	$5,345	0.7
Boston	$13.14	$15.19	$4.17	$4,425	0.9
Orlando	$5.64	$6.52	$4.17	$1,260	3.4
Denver	$6.63	$7.67	$4.17	$1,678	2.4
Chicago 2008	$2.82	$3.26	$4.17	$70	57.6
Chicago 2012	$4.74	$5.48	$4.17	$880	4.6
Chicago 2015	$7.64	$8.83	$4.17	$2,104	1.9

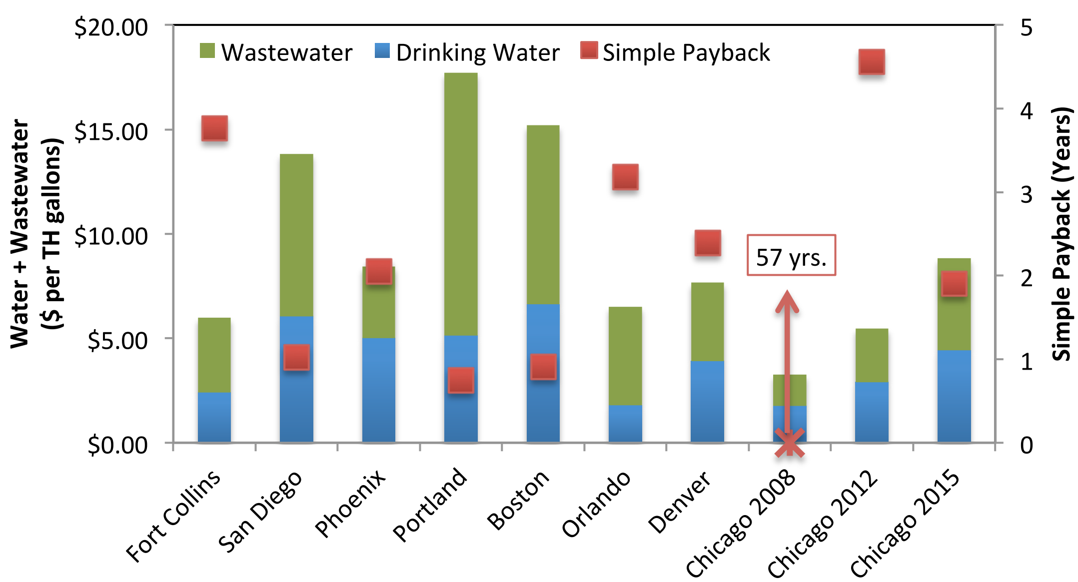

Figure 4.4 System Payback versus Municipal Water Rates at a System Size of 1,000 GPD

Water reuse applications are more beneficial based on regions with higher water and wastewater rates. Regions considered for water reuse are typically areas with a limited water supply like San Diego and Phoenix. While those areas show good potential for water reuse, there are other regions like Portland and Boston that have very high water cost and graywater reuse may be a very economically beneficial alternative. Higher water treatment costs are seen in some cities, like Boston, because they utilize combined sewer systems resulting in higher infrastructure and treatment costs. San Diego, Portland and Boston show the most benefit with paybacks of 0.7-1.0 years based on the high water rates (Figure 4.4). Fort Collins, Phoenix, Orlando and Denver also showed a benefit to implementing graywater reuse with a payback 2.0 to 3.2 years (Table 4.6).

Changing water regulations is proving to have a large impact on the potential benefit of reuse projects. Chicago has had significant rate increases from $2.82 per TH gallon in 2008 to $7.64 per TH gallon in 2015. Based on this substantial rate increase the same reuse project was not cost effective in 2008, marginally beneficial in 2012, and very beneficial in 2015 with a project payback of 57.6, 4.6 and 1.9 years respectively (Figure 4.4). The cost calculations did include an escalation rate of 5.5% based on the consumer price index (Bureau of Labor Statistics, 2012). Regionally the escalation rate may be higher, increasing the potential economic benefit of graywater reuse projects.

This analysis showed that at a scale of >1,000 GPD graywater reuse may be beneficial in many different regions and have reasonable payback periods of <4.6 years (Table 4.6). The city of Guelph reported a system payback of 18-56 years for a residential graywater reuse system with much smaller water use (City of Guelph, 2012). The Guelph report is consistent with the above calculations that show very long payback and therefore low feasibility of graywater reuse at the residential scale. The Pacific Institute stated that firms typically require water conservation projects to have <2-year payback in order to be implemented (Gleick et al., 2003). This is because as the payback period increases there becomes a higher chance that a project does not recover cost and proves to be economically unfavorable. Graywater reuse for toilet flushing at the multi-residential scale can be a beneficial reuse application capable lower payback periods. This is because there is financial benefit from fresh water and wastewater reduction. Other reuse projects either have a high treatment cost or repurpose water for irrigation and therefore do not gain the financial benefit of wastewater reduction.

As mentioned earlier, this analysis focuses on the LCC system cost and neglects the cost of dual-plumbing a residence for separate graywater collection and reuse. This estimate can be highly variable and the largest cost component of a project. The facility manager at CSU, Richard Pott, estimates this cost around $300-$460/person. These estimates will vary depending on if dual plumbing is incorporated with initial design, during a change order or as a retrofit. Based on those estimates the cost for dual plumbing would be the driving cost for implementation and would potentially affect the feasibility of a project. Since the cost of dual-plumbing multi-residential buildings can be high it is important to find the most efficient and cost effective treatment system.

4.3.4 Energy Consumption of Graywater Reuse

Understanding the energy use in water treatment is important for economic and environmental reasons. Treatment processes that have large energy demands will potentially be less feasible to implement. The energy consumption for the treatment and on-site distribution of graywater was calculated in Table 4.7. The treatment process was based on gravity filtration, chlorine disinfection and a pressure boosting distribution pump.

Table 4.7 Energy Consumption of Water Treatment

	System Size: 1,000 gpd	
	kWh/TH gallons	kWh/year
Water Treatment	1.9 - 23.7	694-8,651
Graywater Reuse	3.4	1,223

Like water, energy is a commodity in high demand; therefore, there is much interest in conservation and optimization of energy consumption. The graywater reuse system requires some energy to power the peristaltic pump when disinfecting using chlorine. However, the majority of the energy is consumed in the distribution of the treated graywater back to the toilets. This was estimated based on a refill rate and the manufactures documentation of pump energy consumption. The estimated energy consumption for graywater reuse is 3.4 kWh/TH gallon (Table 4.7). This is on the low end when compared to water treatment that is in the range of 1.9 to 23.7 kWh/TH gallon (Table 4.7;U.S. Department of Energy, 2006). This shows that graywater reuse provides on-site water treatment at low energy consumption. The treatment process analyzed is a passive, low-energy process. If the system used advanced filtration or high-pressure membrane graywater reuse would require more electricity to operate and backwash. Additionally, the electrical consumption would be substantially different if UV or ozone was utilized as shown in the section 4.3.1 (Figure 4.2). Advanced disinfection or filtration options may make the system less desirable from an energy standpoint.

4.4 Summary

Graywater reuse for toilet flushing at the multi-residential scale can provide an economically beneficial way of conserving water. The economic benefit is more favorable on system sizes larger than 1,000 gpd. Potential system maintenance is hard to estimate and can have a large impact on implementation potential. Areas that have high water rates show the most promise for reuse projects. This includes regions like Boston where reuse applications are maybe valued less socially. Graywater reuse at the multi-residential scale can be implemented with a short payback even when the burden of capital and operational cost is on the consumer. Additionally, these treatment systems can provide a more energy efficient treatment process than the alternative of utilizing a municipal water source.

5.0 NEWLY DESIGNED DEMONSTRATION SYSTEM AT THE ASPEN HALL

5.1 Introduction

Colorado State University is interested in water conservation projects including graywater reuse in the student residence halls. This would provide substantial reduction in water use on campus. The filtration and disinfection efficiency study (Chapter 3) provided necessary information to guide system design and operation. The graywater reuse system must provide a safe and aesthetically satisfactory water quality utilizing a treatment process that is low in cost and maintenance.

A new demonstration system was designed and installed at the Aspen Hall that can be implemented for graywater reuse for toilet flushing. This system collects and treats water from the first floor. The system was designed based on literature research, economic considerations and testing of a demonstration unit throughout the spring 2011-spring 2012 semesters. The resulting system is based on settling, coarse filtration and liquid chlorine disinfection (Chapter 3 and Chapter 4). The demonstration unit will be hooked up to a toilet for the fall semester to monitor system performance, chlorine residual and regrowth potential. This is the final step necessary to establish the treatment efficiency and potential for graywater reuse at the multi-residential scale.

5.2 Design of Demonstration Unit

5.2.1 Disinfection and Filtration Selection

The criteria for filtration and disinfection selection was that it must be minimal maintenance, low operating cost and, most importantly, provide safe water quality for use in toilet flushing. The proper disinfection and filtration was determined utilizing the data that was gathered during the testing of the pilot scale unit at the Aspen Hall (Chapter 3). The filter selection was between a coarse, sand and cartridge filter. The disinfectants considered included chlorine, ozone, UV and H_2O_2.

The three different filters tested did not prove to have any substantial effect on chlorine consumption. While the sand filter provided the best water quality, it requires significantly more maintenance and proved to have potentially adverse chlorine effects as a result of biological growth. The coarse Matala filter was selected because of the low operational cost and easy maintenance. A literature review of other filters showed an increase in water quality effects but often at a much larger capital and operational cost (Chapter 2). For that reason, a coarse Matala medium density filter (Matala, Laguna Hills, CA) is best for implementation in the designed demonstration unit.

Chlorine was selected to be the most efficient disinfectant for graywater reuse. This is because it had the highest efficacy against *E. coli* and total coliforms with minimum contact. Chlorine is one of the most common disinfectants, and other graywater treatment processes have also effectively utilized chlorine at the multi-residential scale. Chlorine disinfection using 6% NaOCl was selected over tablet chlorine. Tablet chlorine may have a lower LCC, but there are concerns with proper control of disinfection dose (Chapter 4). Sodium hypochlorite is low in cost, easy to obtain and store, and allows for the precise dosing of chlorine.

The chlorine consumption of the system was determined to be 13.4±2.6 mg/L Cl_2 (Chapter 2). The EPA requires maximum residual of 4 mg/L Cl_2 for free or monochloramine (Weiner, 2008). A minimum residual of 1 mg/L Cl_2 is desired to persist in the distribution lines and prevent regrowth of bacteria. March et al. observed a non-detect of total coliform when a chlorine residual >1mg/L Cl_2 was maintained (March et al., 2004). This results in a 16.4 mg/L Cl_2 in order to achieve a 3 mg/L Cl_2 residual.

The system operates to favor monochloramine formation instead of breakpoint chlorination (Chapter 3). This is different than other applications that require large chlorine doses to overcome organics and ammonia levels in graywater (March et al., 2004). This results in a significantly lower operational cost but is dependent on the ammonia concentration in graywater which ranges from <0.1-15 mg/L-N (Eriksson et al., 2002). Formation of monochloramine is favored with a mass of chlorine to ammonia less than 5:1 (Weiner, 2008). Utilizing monochloramine formation also provides a more persistent residual in the distribution system and a decreased DBP formation potential.

The disadvantage of monochloramine is that it requires longer contact time versus free chlorine. The system was designed for a 1-hour contact time based on literature reviews, batch experiments and operation of the pilot unit. Literature reviews show a Ct of 95-180 mg-min/L is necessary for 2 Log_{10} inactivation of *E. coli* (Siemens, 2009). Therefore, a 3 mg/L Cl_2 residual would require 31-60 minutes contact. The batch experiments showed that *E. coli* and total coliform inactivation occurred at about the same rate in graywater. The batch tests showed a 7 Log_{10} reduction was achieved within the first 15 minutes and a non-detect after 60-minute contact (Chapter 3). The 60-minute contact time also stabilized the monochloramine residual allowing for the initial chlorine consumption reactions to complete. The pilot system operated utilizing chlorine disinfection for part of the fall 2011 and spring 2012 semesters. During that time the system operated with a 110 minute contact time and showed consistent non-detect *E. coli* and total coliform disinfection when a chlorine residual was measured.

5.2.2 System Description

The implemented system is composed of collection, compositing, settling, filtration and disinfection. Graywater quality is highly variable and it is necessary to composite the influent graywater to achieve a more uniform water quality. The composited graywater is allowed to settle to remove some of the larger solids that may quickly clog the coarse filter. The graywater storage is controlled to maximum of 24 hours preventing undesirable pathogen growth and odors that may occur from prolonged storage. The settled graywater gravity flows through the coarse filter and is dosed in-line with sodium hypochlorite before entering the disinfection contact tank. The graywater is pumped from the disinfection tank by a booster pump refilling flushed toilets. According to plumbing code, the system also includes necessary overflow lines, tank vents and a fresh water supply to supplement toilet flushing in the absence of graywater.

5.2.3 System Operation

The graywater reuse system is controlled by a pressure booster pump, ultrasonic float switch and electronic valves. The disinfection tank is sized so that a 1-hour contact is achieved during the peak operational periods. The peak operational period is assumed that every individual flushes a toilet once in an hour. This is 28 flushes per hour in the Aspen Hall, which is equivalent to 20% of the daily toilet demand occurring in one hour.

The water distribution is controlled with a Grundfos MQ 3-35 booster pump (Grundfos, Olathe, KS). When a toilet is flushed, there is a change in pressure in the distribution line. This pressure change turns on the pump and water is pulled out of the contact tank refilling the toilets until the pressure is re-established and the pump turns off.

The water level in the disinfection tank is decreasing as water is used to fill toilets. When the level decreases 3.4 gallons (Level 2, Figure 5.1), an EchoPod DL14 ultrasonic level (Flowline, Los Alamitos, CA) triggers a ASCO 8016 solenoid valve (ASCO, Florham Park, NJ) to open and draw in graywater from the collection tank refilling the disinfection tank to the max level (Level 1). In the case that graywater is not present; toilets will continue to flush until Level 3. At this point the ultrasonic level triggers a second solenoid valve to open and bring in fresh water to refill the disinfection tank to the max level (Level 1) so that toilets can still be flushed until graywater is generated. Level 4 is the point at which the pump pulls graywater. This is the level of the tank that is sized to maintain the desired 1-hour retention time.

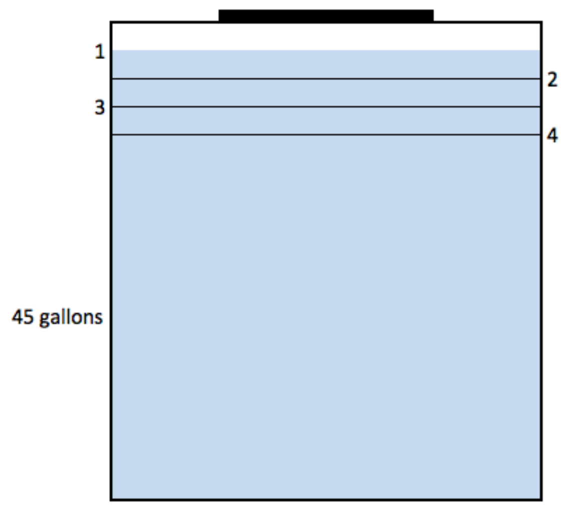

Figure 5.1 Disinfection Contact Tank

The chlorine dose is controlled using a Stenner 85MP1 fixed rate peristaltic pump, Stenner PCM pump control module (Stenner, Jacksonville, FL) and Seametrics MJ 1 gallon pulse water meter (Seametrics, Kent, Washington). When the ultrasonic level triggers the graywater solenoid valve to open, water passes through the Matala filter and then the pulse water meter. The water meter will trigger the pump control module when one gallon passes through the meter. The pump control module operates the constant flow peristaltic pump for a specified amount of time dosing the proper amount of chlorine on a per gallon of graywater basis. This specific chlorine control is important to ensure that proper disinfection is achieved and the graywater is not over chlorinated. High chlorine levels may cause pump and fixture corrosion and potential health issues. A figure of all the treatment components is provided below (Figure 5.2).

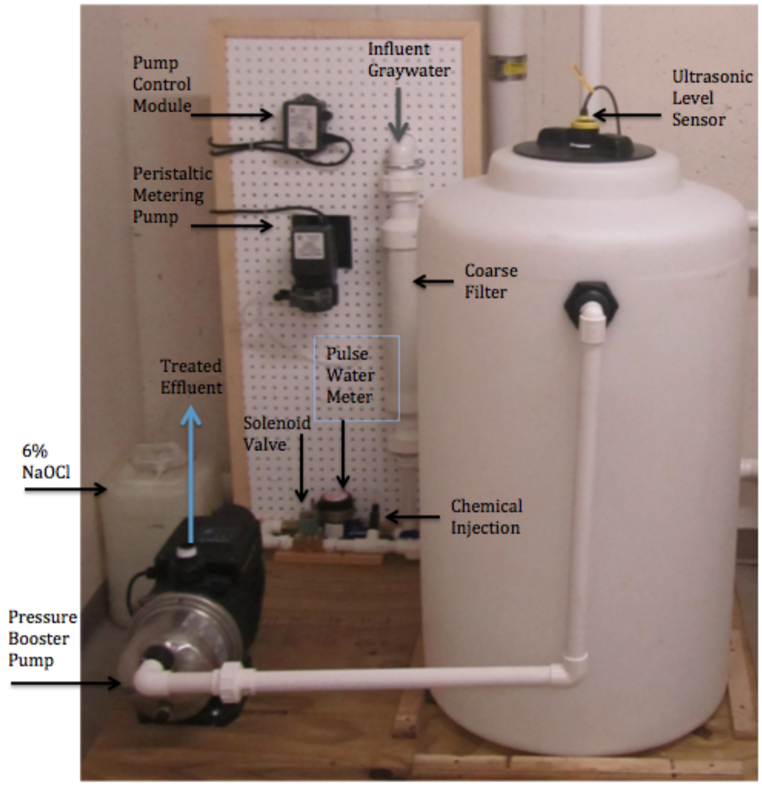

Figure 5.2 Graywater Treatment System

5.2.4 Potential Concerns

It is very important that the system provides a safe and aesthetically pleasing water quality for the intended use. This is especially true when implementing graywater reuse at the multi-residential scale. In this case there is an increased concern with the potential for pathogen transmission. This implemented system will be connected to one toilet to monitor the system performance during the fall 2012 semester. The performance monitoring includes proper disinfection, pathogen regrowth, odor and aesthetic issues, and operational issues.

The most important concern is that the water is properly disinfected. The coarse filtration does not remove the majority of TSS or BOD_5. There are concerns that the residual TSS and BOD_5 may shield the bacteria or prevent proper disinfection. Winward et al. showed that there was a change in chlorine consumption but not disinfection efficiency in the presence of organics in graywater (Winward et al., 2008b). Monitoring of the pilot system suggested that maintaining a proper chlorine residual will ensure sufficient pathogen disinfection (Chapter 3). This was also observed in other graywater treatment systems (March et al., 2004)

Sampling from the installed toilets will allow system monitoring. The chlorine residual will be monitored to ensure that a sufficient residual is maintained. Once implemented there may be a need for an increased chlorine dose as a result of a larger distribution system. This was necessary in other graywater reuse applications once the system went into use (March et al., 2004).

Additionally, regrowth studies should be performed to ensure the storage of the graywater in a toilet tank does not result in unfavorable bacterial growth. Over a weekend, residence may leave and water may sit in the toilets for an extended period of time. Initial experiments suggest that a monochloramine residual may be stable for a couple days and Tal et al. observed no total coliform regrowth after 7 days of graywater disinfected with chlorine (Tal et al., 2011). This suggests that a chlorine residual, prevents bacterial regrowth even in the presence of BOD_5.

5.3 Summary

Graywater reuse for toilet flushing at the multi-residential scale provides an efficient and economically favorable way to reduce water consumption. The demonstration unit at the Aspen Hall provides a way to illustrate the treatment efficiency and implementation potential of these projects. The treatment process must produce a water quality appropriate for the reuse application. Additionally, it needs to be low in maintenance and economically feasible. The demonstration unit was selected based on this criteria and information obtained from the conducted pilot-scale tests. This demonstration unit will be operated throughout the fall 2012 semester to ensure consistent disinfection and stable formation of a residual. Further regrowth testing is necessary to ensure that a residual is maintained in the distribution system and there is no concern on effect to public health.

6.0 CONCLUSION

There is a growing interest and emphasis on ways to conserve water consumption. As population continues to increase, it is increasingly important to find projects that will help decrease water consumption and free up water for a growing demand. Conservation devices have been a large contributor to decreasing water use. They are low in cost, but are also reaching the technological and social acceptance limit of potential for further water reduction. Graywater reuse for toilet flushing provides a way to further decrease water consumption and can be done at a much more cost effective rate than alternative large-scale reuse projects. Graywater reuse can be particularly efficient at the multi-residential scale where systems can be installed onsite with minimal infrastructure and provide water that is safe and aesthetically pleasing to flush toilets.

The pilot-scale unit at Aspen Hall allowed for the investigation of the most efficient filtration and disinfection alternatives. This has been researched at laboratory scales, but there have not been many projects implemented at the multi-residential scale in the United States. The system processed 295 gpd of graywater and samples were taken over the course of three semesters testing three different filtration approaches (Coarse, Sand and Cartridge) and four different disinfectants (H_2O_2+UV, Chlorine, UV and Ozone).

Chlorine proved to be the most efficient disinfectant for graywater reuse with the highest efficacy of *E. coli* and total coliform inactivation. The other disinfectants proved to be less effective and higher economic costs. The pilot-scale unit showed that maintaining a chlorine residual resulted in non-detects for total coliform. Additionally, chlorine provided beneficial odor reduction and was the lowest maintenance of the tested disinfectants. Graywater chlorination is optimized utilizing the influent ammonia to favor chloramine formation. This results in a more stable residual in the distribution system and prevents the need for a large dose. Operating at a lower dose results in a lower operational cost and decreased potential for DBP formation.

Coarse filtration proved to be the best choice providing the lowest maintenance and smallest capital and operational cost. The tested cartridge filter proved to have no water quality or maintenance improvements and did not result in an improvement in potential disinfection efficacy or reduced chlorine demand. The sand filter did prove to achieve some reduction of suspended solids and organic matter. However, the solids and organic removal was not sufficient to meet many states graywater reuse standards. These minor water quality improvements required an increased capital cost and more frequent maintenance. Additionally, sand filtration created biological growth resulting in more reactive organic material increasing the chlorine dose and the potential for DBPs. The installed sand filter was too small to achieve substantial removal or organic content in the processed graywater and installation of a sand filter capable of doing so would be very costly. A literature review showed that advanced filtration of graywater will efficiently remove solids and potentially decrease the organic concentration. However, this can be very costly and make graywater reuse projects economically unfavorable. In applications where organic removal is necessary, a biological treatment process has the potential to appropriately treat the water without the substantial cost and maintenance of advanced filtration processes. Based on this information, coarse filtration was selected as most efficient filtration process adequately treating the water for toilet reuse with the lowest maintenance and most favorable implementation cost.

When considering graywater reuse at the multi-residential scale it is important that the considered project be financially beneficial for the consumer. Projects that have high capital costs and long payback periods are hard to justify and implement. Graywater reuse at the multi-residential scale can be economically beneficial with short payback periods, less than three years. These projects can prove to have large cost savings over the life of the project and substantially lower LCC compared to the alternative of utilizing fresh water to flush toilets. The economic benefit will be highly dependent on the regional cost of water. As water prices continue to increase, these projects will prove to be more economically beneficial.

There is a growing amount of multi-residential graywater reuse projects internationally. In the United States, there are still few examples investigating the treatment process, benefits and economic significance of these graywater reuse projects. Based on findings from this project, a demonstration until has been designed and installed in Aspen Hall. The system has many advantages over commercially available systems that are currently available, and will likely be commercialized after the demonstration phase. The installed system at Aspen Hall treats 300 gpd utilizing settling, coarse filtration and chlorine disinfection and serves as a demonstration unit for the potential of graywater reuse at the multi-residential scale. This unit provides the ability to analyze treatment efficiency and energy consumption. Further tests will be continued to monitor potential for regrowth of pathogens and assurance of public health. Results to date show promise for the designed demonstration system, which is economic and low maintenance. Success of this project may lead to wide scale adoption of graywater reuse for toilet flushing at the multi-residential scale.

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APPENDIX A: DISINFECTION EFFLUENT GRAYWATER QUALITY (NM MEANS NOT MEASURED)

	Influent	**stdev**	**Coarse**	**stdev**	**Sand**	**stdev**	**Cartridge**	**stdev**
DO (mg/L)	0.33	0.34	0.58	0.56	0.33	0.32	0.42	0.46
Temperature (°C)	24.8	1.9	23.4	1.4	25.6	1.1	25.1	0.4
pH	7.09	0.30	7.10	0.26	6.97	0.25	7.21	0.30
Turbidity (NTU)	31.7	4.2	35.2	8.0	26.7	4.2	27.8	5.3
Conductivity (µS/cm)	255	71	240	72	250	71	283	43
Total Alkalinity (mg/L as $CaCO_3$)	71.3	14.7	66.3	10.5	72.7	16.9	79.0	8.5
Total Hardness (mg/L as $CaCO_3$)	53.9	3.6	51.7	1.5	53.0	3.5	50.5	0.7
%UVT	40%	6%	39%	6%	41%	6%	36%	6%
Adsorption (254nm)	0.40	0.07	0.41	0.07	0.39	0.08	0.45	0.07
Dissolved Adsorption	0.18	0.06	0.19	0.09	0.17	0.04	0.21	0.06
Total Nitrogen (mg/L-N)	12.1	4.0	12.9	3.6	9.2	2.9	13.4	1.9
Ammonia (mg/L-N)	8.4	2.2	8.2	3.0	9.0	1.7	9.1	2.2
Inorganic Carbon (mg/L-C)	13.9	2.1	13.2	2.6	9.0	6.0	15.7	2.4
TOC (mg/L-C)	44.1	12.2	40.9	11.5	37.0	10.9	31.9	5.6
DOC (mg/L-c)	19.9	8.8	19.9	8.1	21.2	8.6	19.0	5.8
BOD_5 (mg/L)	104.8	17.1	102.1	18.0	84.4	19.9	103.6	2.9
Total Solids (mg/L)	167	22	164	12	185	22	146	26
TSS (mg/L)	25	5	29	9	21	5	21	5
TDS (mg/L)	142	22	135	8	164	20	125	27
TVS (mg/L)	77	16	82	15	77	12	73	17
E. coli (Log_{10} CFU/100mL)	4.8	2.4	5.1	1.5	0.9	0.9	3.1	2.6
Total Coliform (Log_{10} CFU/100mL)	8.4	0.6	8.0	0.4	5.4	4.2	8.7	0.6

APPENDIX B: DISINFECTION EFFLUENT GRAYWATER QUALITY (NM MEANS NOT MEASURED)

Main Summary	H_2O_2+UV		Chlorine		UV		Ozone	
	Effluent	Stdev	Effluent	Stdev	Effluent	Stdev	Effluent	Stdev
DO (mg/L)	9.2	0.6	3.5	1.9	3.3	0.3	2.7	0.5
Temperature (°C)	29.6	0.4	25.6	3.3	29.0	3.6	25.4	1.0
pH	6.6	0.6	7.5	0.2	7.2	0.4	6.7	0.2
Total Alkalinity (mg/L as $CaCO_3$)	NM	NM	56	7	54	3	52	2
Total Hardness (mg/L as $CaCO_3$)	NM	NM	73	13	66	10	65	6
Conductivity (µS/cm)	212	57	257	27	240	32	222	41
Turbidity (NTU)	47.4	14.4	54.6	12.3	41.9	8.4	49.2	13.7
TS (mg/L)	187	41	215	23	204	33	172	18
TSS (mg/L)	37	8	30	10	22	4	22	4
TDS (mg/L)	151	39	186	22	181	31	150	16
BOD_5 (mg/L)	156	58	158	22	137	34	150	11
COD (mg/L)	217	100	192	28	194	45	195	33
DCOD (mg/L)	139	60	137	29	128	19	106	17

APPENDIX C: INFLUENT GRAYWATER ANOVA ANALYSIS

Analysis of Variance (One-Way): Influent TOC

Summary

Groups	Sample size	Sum	Mean	Variance
Variable #1	6	289.29	48.215	160.59291
Variable #2	7	322.36	46.05143	125.25271
Variable #3	4	137.46	34.365	103.5883

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	507.31629	2	253.65814	1.90389	0.18562
Within Grou	##########	14	133.23184		F crit
					5.24075
Total	##########	16			

Analysis of Variance (One-Way): Influent BOD

Summary

Groups	Sample size	Sum	Mean	Variance
Coarse	3	316.12	105.37	630.22
Sand	4	421.52	105.38	203.64
Cartridge	3	310.	103.33	373.18

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	8.76	2	4.38	0.01	0.99
Within Grou	2,617.7	7	373.96		F crit
					7.2
Total	2,626.47	9			

Analysis of Variance (One-Way): Coarse vs. Sand Chlorine Consumption

Summary

Groups	Sample size	Sum	Mean	Variance
Coarse	6	80.17	13.36	6.69
Sand	7	170.85	24.41	7.96

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	394.16	1	394.16	53.38	0.00002
Within Grou	81.23	11	7.38		F crit
					7.39
Total	475.39	12			

Analysis of Variance (One-Way): Influent TSS

Summary

Groups	Sample size	Sum	Mean	Variance
Coarse	5	136.4	27.28	24.24
Sand	7	184.27	26.32	20.3
Cartridge	5	110.8	22.16	13.16

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	76.13	2	38.06	1.96	0.18
Within Grou	271.35	14	19.38		F crit
					5.24
Total	347.48	16			

Analysis of Variance (One-Way): Coarse vs. Cartridge Chlorine consumption

Summary

Groups	Sample size	Sum	Mean	Variance
Coarse	6	80.17	13.36	6.69
Cartridge	8	136.51	17.06	1.73

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	46.99	1	46.99	12.37	0.0042
Within Grou	45.57	12	3.8		F crit
					7.19
Total	92.56	13			

Analysis of Variance (One-Way): Sand vs. Cartridge Chlorine consumption

Summary

Groups	Sample size	Sum	Mean	Variance
Sand	7	170.85	24.41	7.96
Cartridge	8	136.51	17.06	1.73

ANOVA

urce of Variati	SS	df	MS	F	p-level
Between Grc	201.32	1	201.32	43.72	0.
Within Grou	59.87	13	4.61		F crit
					7.02
Total	261.19	14			

APPENDIX D: DISINFECTION COMPONENT COST ANALYSIS

Initial Components	Tablet Chlorine(1)	Liquid Chlorine(2)	Hydrogen Peroxide(2)	UV(5)	Ozone (Spa Scale)(6,7)	Ozone (Lab scale)(8)	Ozone (Industry Scale)(8)
Model Examined	Hayward Tablet Feeder	Stenner	Stenner	Sterilight	Del Ozone/Petco Air Pump	Enaly Lab Generator/Concentrator	Generator, Ozygen Concentrator, Ozone destruction unit
Common Application	Spa	Water Treatment	AOP	Water Treatment	Spa	Lab production	Water Treatment
Generator	$84	-	-	$259	$195	$644	$6,000
Dosing Pump	-	$399	$399	-	$35	$35	
Timer	-	$188	$188	-	-	-	
Initial Component Cost	$84	$587	$587	$259	$230	$679	$6,000
Chemicals				-			
Dose Form	TriChlor 90% Cl tablet	6% NaClO	35% H_2O_2	UV	O_3 (gas)	O_3 (gas)	O_3 (gas)
Desired Dose	12 mg/L Cl_2	12 mg/L Cl_2	140 mg/L H_2O_2	40 mJ/cm2 @ 95%UVT	1.3 ppm	16 ppm	215 ppm
Chemical Use/year	24.0 (tablets/year)	26.9 (gallons/year)	39.8 (gallons/year)	-	-	-	-
Chemical Cost	$1.00/Tablet	$4 / 1.4 gallons(3)	$70 / 5 gallons(4)	-	-	-	-
Annual Chemical Cost	$24	$77	$557				
Annual Maintenance							
Electrode or Lamp	-	-	-	$85	$60	$68	$600
Warranty	1 year	1 year	1 year	1 year bulb/7 year rest	3 year	3 year	3 year
Frequent Maintenance	Tablet Refill	Liquid Refill	Liquid Refill	Bulb Replacment	Electric Replace	Electric Replace	Electric Replace
Annual Maintenance Cost				$85	$20	$23	$200

Electrical Use							
Generator Electrical Use	-	-	-	262.80	52.60	219.00	5475.00
Pump Electrical Use	-	68.25	68.25	-	43.80	43.80	-
Average Electrical Use	0.08	0.08	0.08	0.08	0.08	0.08	0.08
Annual Electrical Cost	$-	$5	$5	$21	$8	$21	$438
Initial Investment	$84	$587	$587	$259	$230	$679	$6,000
Annual Cost	$24	$82	$563	$106	$28	$44	$638
Uniform Present Value (UPV)	8.5	8.5	8.5	8.5	8.5	8.5	8.5
Life-Cycle Cost Analysis (10-yr life)	$289	$1,289	$5,386	$1,162	$466	$1,051	$11,442
*Cost Derived from Market Cost from (1)Pool Supply World, (2)Cannon Water Technology, (3)Home Depot, (4)TreatmentTechBlue Book, (5)freshwatersystems, (6)Hot Tub Warehouse, (7)Local Spa, (8)ozonesolutions							

APPENDIX E: COMPLETE SYSTEM COST ANALYSIS

	Units	System Size (GPD)						
		50	75	85	100	150	300	500
Individuals	#	5	7.5	8.5	10	15	30	50
Toilet Demand (100% GRAYWATER)	GPD	50	75	85	100	150	300	500
Floors[(1)]	#	1	1	1	1	1	1	1
Maintenance								
Estimated Hours/Month		0.5	0.5	0.5	1	1	1	1.5
Billing Rate	=	40	40	40	40	40	40	40
Maintenance $/year		240	240	240	480	480	480	720
Model		Grundfos /MQ-35	Grundfos /MQ-35	Grundfos /MQ-35	Grundfos /MQ-35	Grundfos /MQ-45	Grundfos /MQ-45	Grundfos /MQ-45
Quantity	#	1	1	1	1	1	1	2
Energy	Watts	800	800	800	800	1000	1000	1000
Cost	$	448	448	448	448	448.47	448.47	896.94
Tank Selection								
Design Disinfection	Gallons	8	12	13.6	16	24	48	80
Design Collection	Gallons	42	63	71.4	84	126	252	420
Disinfection Tank	Gallons	40	40	40	40	40	65	105
	Price	$70	$70	$70	$70	$70	$100	$236
Collection Tank	Gallons	65	65	105	105	165	300	500
	Price	$100	$100	$236	$236	$306	$270	$390
Total Tank Cost	Price	$170	$170	$306	$306	$376	$370	$626
Disinfection Selection								
Chemical Dosing Pump	13.13 ml/min or 0.79 L/hr	$211.28	$211.28	$211.280 0	$211.28	$211.28	$211.28	$211.28
Pump Control Module		$187.65	$187.65	$187.65	$187.65	$187.65	$187.65	$187.65
Dose Water Meter	1 tick/gallon	$187.80	$187.80	$187.80	$187.80	$187.80	$187.80	$187.80
Chemical Storage	Gallons	7	7	7	7	7	7	7
	Price	$30	$30	$30	$30	$30	$30	$30
Energy	Watts	204	204	204	204	204	204	204

Energy	kWh/ml NaOCl	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04
Total Disinfection Cost		$617	$617	$617	$617	$617	$617	$617
Miscellaneous Components								
Solenoid Valves	Quantity	2	2	2	2	2	2	2
	Price	$250	$250	$250	$250	$250	$250	$250
Ultrasonic Float Switch	Quantity	1	1	1	1	1	1	1
	Price	$350	$350	$350	$350	$350	$350	$350
Switch Control Unit	Quantity	1	1	1	1	1	1	1
	Price	$25	$25	$25	$25	$25	$25	$25
Misc. Piping	(10% Capital)	$124	$124	$138	$138	$145	$144	$215
Total Component Capital		$1,984	$1,984	$2,134	$2,134	$2,211	$2,205	$2,979
Energy w/o dis or fil		800	800	800	800	1000	1000	1000

	System Size (GPD)						
	750	900	1000	2000	3000	4000	5000
Individuals	75	90	100	200	300	400	500
Toilet Demand (100% GRAYWATER)	750	900	1000	2000	3000	4000	5000
Floors(1)	2	2	2	4	6	8	10
Maintenance							
Estimated Hours/Month	1.5	1.5	2	4	6	8	10
Billing Rate	40	40	40	40	40	40	40
Maintenance $/year	720	720	960	1920	2880	3840	4800
Model	Grundfos/MQ-45	Grundfos/MQ-45	Grundfos/MQ-45	Grundfos/MQ-45	Grundfos/MQ-45	Grundfos/MQ-45	Grundfos/MQ-45
Quantity	3	3	3	4	6	8	10
Energy	1000	1000	1000	1000	1000	1000	1000
Cost	1345.41	1345.41	1345.41	1793.88	2690.82	3587.76	4484.7
Tank Selection							
Design Disinfection	120	144	160	320	480	640	800
Design Collection	630	756	840	1680	2520	3360	4200
Disinfection Tank	165	165	165	500	500	1000	1000
	$306	$306	$306	$390	$390	$740	$740
Collection Tank	625	1000	1000	2000	1500+1500	2000+1500	2000+2000
	$350	$740	$740	$1,050	$1,500	$1,800	$4,000
Total Tank Cost	$656	$1,046	$1,046	$1,440	$1,890	$2,540	$4,740
Disinfection Selection							
Chemical Dosing Pump	$211.28	$211.28	$211.28	$211.28	$211.28	$211.28	$211.28
Pump Control Module	$187.65	$187.65	$187.65	$187.65	$187.65	$187.65	$187.65
Dose Water Meter	$187.80	$187.80	$187.80	$187.80	$187.80	$187.80	$187.80
Chemical Storage	7	7	7	7	7	7	7
	$30	$30	$30	$30	$30	$30	$30
Energy	204	204	204	204	204	204	204
Energy	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04	2.58E-04
Total Disinfection Cost	$617	$617	$617	$617	$617	$617	$617
Miscellaneous Components							
0	2	2	2	2	2	2	2

0	$250	$250	$250	$250	$250	$250	$250
	1	1	1	1	1	1	1
0	$350	$350	$350	$350	$350	$350	$350
	1	1	1	1	1	1	1
	$25	$25	$25	$25	$25	$25	$25
0	$263	$302	$302	$386	$521	$675	$985
Total Component Capital	$3,506	$3,935	$3,935	$4,861	$6,343	$8,045	$11,451
Energy w/o dis or fil	1000	1000	1000	1000	1000	1000	1000