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THESIS

GRAYWATER RESEARCH FINDINGS AT THE RESIDENTIAL LEVEL

Submitted by

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ABSTRACT

GRAYWATER RESEARCH FINDINGS AT THE RESIDENTIAL LEVEL

As populations continue to grow and water supply sources become more stressed, innovative means for reducing our reliance on municipal water are becoming more prevalent. Graywater reuse is one water conservation practice which has the potential of reducing household water demands by 30% indoors and outdoors, depending upon irrigation demands. In areas where water scarcity is an ongoing challenge, implementation of graywater reuse practices is becoming more widely accepted. However, constituents commonly found in graywater may pose a threat to the environment or human health.

The objective of this thesis is to present graywater research findings from 2003 to the present which have occurred as part of a graywater research program at Colorado State University. The research findings address issues and concerns raised regarding graywater and present the case for graywater reuse being a viable safe, simple and economical technology. In order for graywater reuse applications to continue to expand, the concerns regarding public health risks raised by regulating agencies and public health officials need to be fully addressed.

Early research on a residential pilot graywater system for outdoor irrigation formed the foundation for more recent research targeting effects on soil quality (chemistry and microbiology), plant health, groundwater contamination, graywater quality and potential human health risks (Sharvelle, 2009, Shogbon, 2010, Neghaban-Azar, 2012).

An optimal residential graywater system prototype for drip irrigation has been developed (Alkhatib, 2008) which includes two tanks, one for collection, coarse filtration and settling and the other for usable storage. The WERF study (Sharvelle et al., 2012) showed no need for disinfection of graywater being used for irrigation. The presence and levels of pathogens on

field sites whether being irrigated with either municipal water or graywater were the same. The WERF research (Sharvelle et al., 2012) coupled with the prototype configuration supports no need for inclusion of disinfection as part of the treatment train when graywater is being applied for irrigation.

The most recent research is a multi-residential graywater reuse demonstration project for toilet flushing completed on Colorado State University campus, Aspen Hall (Hodgson, 2012). Graywater used for toilet flushing will require a higher level of treatment due to the increased potential for exposure. Hodgson studied and selected Chlorine as the disinfectant for the residence hall. The resulting water quality with storage, filtration and disinfection determined by Hodgson achieves similar results as found in the 2003 residential pilot graywater system research which used UV rather than chlorine.

The difficulty of navigating the varying graywater regulations between states drove Glenn's research (2012) into the graywater requirements for each state and who developed a tool for use by regulators to homeowners for finding an appropriate graywater technology to meet their local requirements. Also, a need was identified for providing a comprehensive guidance manual for separating graywater from blackwater for graywater reuse (Bergdolt, 2011). The manual provides design guidance and maintenance best management practices to ensure safe and appropriate graywater installation and operation.

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always knew when I could use some encouragement, needed a good laugh and kept it real, really real.

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I came to CSU for a graduate degree in engineering and came out with a life enriched with stories, friends and memories to last a life time as well as a degree. I did not plan on that and would not trade it for anything.

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DEDICATION

To all my family and friends, here and passed, who never stopped believing in me. Thank you.

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CHAPTER 1 INTRODUCTION

The challenge of ensuring a sustainable water supply within the United States, particularly in the arid south-west, has led to dedicated research on a variety of water conservation efforts. As population growth drives urban sprawl, innovative techniques for abating negative watershed wide impacts from development and for sustaining the urban water supply are inevitably merging into integrated watershed management plans. One water conservation focus area of particular interest is household graywater reuse. The potential for reducing household water demand and therefore protecting the fresh water supply by reusing graywater is rapidly becoming more widely accepted.

1.1 Graywater Reuse Makes Sense

By the strictest definition, graywater is any wastewater not generated from toilet flushing, otherwise referred to as blackwater. The definition of graywater which is being used here is taken directly from the 2000 edition Universal Plumbing Code (UPC) which states graywater is "untreated household wastewater which has not come into contact with toilet wastes. Graywater includes used water from bathtubs, showers, bathroom, wash basins, and water from clothes washing machines and laundry tubs. It shall not include waste water from kitchen sinks or dishwashers". The most frequent use of graywater is for landscape drip and sub-surface irrigation. Toilet flushing is another application for graywater reuse seen more commonly outside of the United States.

1.1.1 Household Water Budget Analysis

The first part in determining the potential value of graywater reuse is evaluating household water use. Residential water budgets can vary for many reasons such as a particularly dry year, installation of water conserving devices and changes to landscape features. Research into residential end uses in 12 North American cities by Mayer et al (1999) determined that indoor and outdoor use is generally equal. Figure 1-1 graphically compares the indoor and outdoor water usages as a ratio where a value greater than one indicates that indoor water use exceeds outdoor water use.

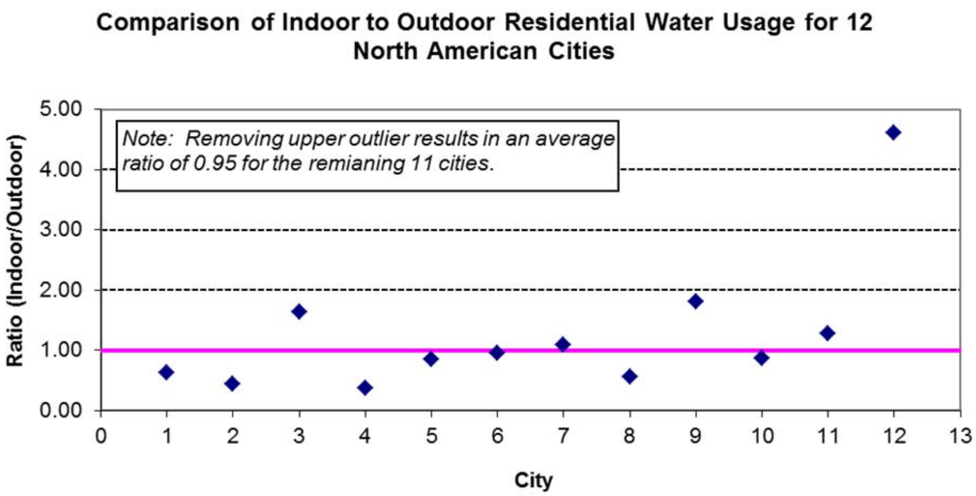

Figure 1-1: Ratio of Indoor to Outdoor Water Usage

(City Key: 1 – Phoenix, AZ; 2 - Scottsdale/Tempe, AZ; 3 – Lampoc, CA; 4 – Las Virgenes, CA; 5 – San Diego, CA; 6 – Walnut Valley, CA; 7 – Boulder, CO; 8 – Denver, CO; 9 – Tampa, FL; 10 – Eugene, OR; 11 – Seattle, WA; 12 – Waterloo, Ontario Canada)

City number 12 (Waterloo, Ontario) has over four times the amount of indoor water use compared to outdoor use. City 12 water usage ratio is removed from the analysis due to the Cities northern location and the great variance in residential water usage. By removing the City 12 result from the data set, the remaining 11 cities have an average ratio of 0.95:1 indoor to outdoor residential water usage.

The Residential End Uses study (Mayer et al., 1999) also collected detailed indoor use data from 1,200 households in the 12 cities. The average indoor water use across all 12 cities was 63.2 gallons per capita day (gpcd) which is distributed between showers, baths, clothes washers, faucets, dish washers, leaks, toilets and other domestic uses as shown in percentage of indoor water use in Figure 1-2.

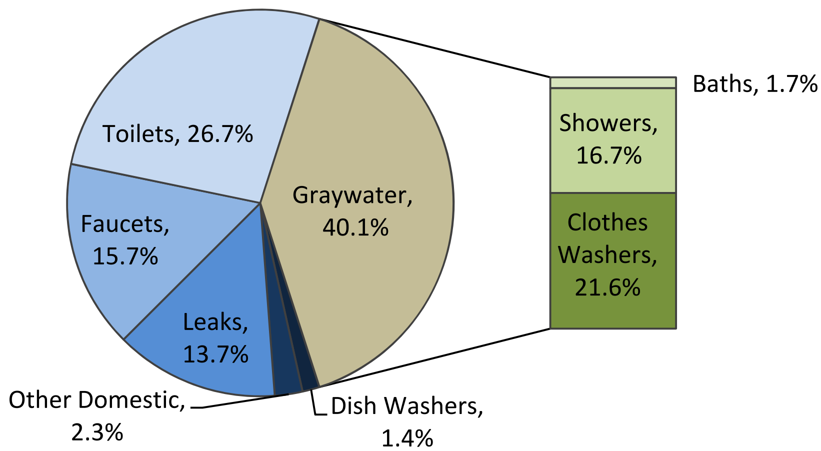

Figure 1-2: Average Indoor Water Use for 12 North American Cities

These graywater generating fixtures conservatively represent 40% of the indoor water use and therefore 20% of total residential water use (Mayer et al., 1999). The end use values reported by Mayer are comparable to those reported by City of Fort Collins Water Conservation 2012 Annual Report. Fort Collins reported a water demand range of 144 to 161 gpcd and an estimated outdoor water use of 36% resulting in a ratio of 1.77 indoor to outdoor water use, almost double the average ratio from the 11 cities of 0.95 (Figure 1-A). However, outdoor water use at the residential graywater reuse pilot project was found to be 50% of the total water use.

Outdoor irrigation is a seasonal activity which does not have a year round demand for graywater. In addition, not all outdoor water uses are appropriate for irrigation with graywater. Graywater should not be used on edible plants for example. If toilet flushing were another application for graywater reuse it would provide a year round graywater demand. According to Figure 1-2, toilet flushing demand could be covered completely by the graywater generated by the average household.

The potential to reduce fresh water use by reusing graywater is significant on a regional scale. For example, a City with a population of 100,000 generating and reusing 25 gpcd of graywater would decrease City water supply demand by 2.5 MGD or 912 MG per year. Safe and reliable graywater reuse makes sense.

1.1.2 Graywater Constituents

The potential to reuse graywater needs to be balanced with the intended end use and the graywater composition. Constituents commonly found in graywater may pose a threat to the environment or human health. Graywater constituents include salts, pathogens, household pharmaceutical and personal care products and organics/nutrients (detergents are main source). When graywater is compared to domestic wastewater, graywater has lower contaminant concentrations of organics, solids, nutrients and pathogens (Bergdolt, 2011).

A number of studies have identified levels of pathogens in graywater that exceed regulatory limits for reclaimed wastewater and recreational water (Casanova et al., 2001; Christova-Boal et al., 1996; Rose et al., 1991). The presence of indicator organisms is generally taken as confirmation of fecal contamination and subsequently the presence of pathogens and viruses which pose a threat to human health. However, the presence of indicator bacteria does not always indicate the presence of pathogens (Chistova-Boal, 1996).

Dixon et al (1999) suggests instituting guidelines for graywater reuse which assesses the range of risk associated with exposure to graywater accompanied with the level of microbial contamination and targeted population. It is important to safely handle and reuse graywater to limit exposure to pathogens.

1.1.3 Graywater Regulations

Currently, there are no federal regulations for graywater reuse systems. Instead, the choice to develop and adopt graywater reuse regulations is left up to individual states. What is often found is the individual states will apply wastewater reclamation requirements to graywater reuse systems even though both the composition of and end use for graywater is considerable different. The Universal Plumbing Code (2000 edition) includes graywater system plumbing design requirements. A reference to the regulatory agencies responsible for administration of graywater reuse regulations and criteria for each state is provided in the Guidance Manual for Separation of Graywater from Blackwater for Graywater Reuse, Appendix B (Bergdolt, 2011).

1.2 Household Graywater Research Program

The potential value of reusing graywater is evident from the average household water budget analysis and residential graywater systems are gaining wider acceptance in the United States. Although acceptance of graywater practices is increasing, there are some concerns which need to be addressed and studied before larger implementation can be realized. One concern is the potential threat to human health and the other is the long term impacts of graywater on landscape plants, soil chemistry and microbiology, and groundwater quality. The focus of the graywater research program at Colorado State University works to address these concerns through comprehensive experimental research.

In 2003, Colorado State University researchers initiated a residential pilot graywater reuse project to investigate system treatment configurations and to collect baseline data on household graywater. The residential pilot study research served as a key source of information for confirming the feasibility of designing an economical and simple to maintain graywater reuse system for homeowners. Positive results and findings from the 2003 pilot graywater treatment pilot project informed the development of more extensive research and experimental design of a graywater landscape irrigation study plan. The study goals were 1) household graywater – water quality, collection, treatment and storage 2) soil chemistry changes due to graywater application 3) graywater effects on soil microbiology 4) presence of indicator organisms for human health considerations and 5) impacts on various classes of residential landscape plants (Criswell, 2005).

The WERF study, Long-Term Effects of Landscape Irrigation Using Household Graywater, was conducted in two phases: a literature review and research needs identification phase (Phase I) and an experimental study phase (Phase II). The objectives of Phase 1 of the WERF study (Roesner et al., 2006) was to bring together the current state of knowledge on potential long term impacts of landscape irrigation with household graywater and to identify knowledge gaps that need to be addressed in future research. The resulting recommendations propose a targeted household graywater research program to answer three broad questions related to household graywater on landscape plant health, human health risks, soil chemistry, soil microbiology and groundwater:

1. Over the long term, will a residential landscape that is irrigated with graywater remain healthy and vibrant? If not, are there steps that can be taken to minimize or mitigate the impact?

2. Over the long term, does irrigation of a residential landscape with graywater pose a threat to the quality of groundwater? If so, can these threats be minimized or eliminated?

3. Over the long term, does graywater irrigation of a residential landscape with graywater pose a health risk to humans? Can the risk be minimized?

Phase II carried out a large number of the experiments recommended in Phase I through a three part Experimental Study (Sharvelle et al., 2012). First, soil samples irrigated for five years or more were collected from existing graywater households. Second, soil samples were collected from residences with new household graywater system installations. The field experiments are subject to high variability which was addressed in the third set of controlled greenhouse experiments.

By answering these three questions the research team expects to produce comprehensive guidance to homeowners on the proper type of collection and distribution system to install, the appropriate type of plants that can be irrigated with graywater and the appropriate application rates for the selected landscape. When all of these research components are completed the regulating community will have confidence that household graywater systems will be adequate, safe and pose little or no threat to the quality of the environment while reducing household water demands from 30 to 50%.

1.3 Thesis Objective

Researchers have been working on household graywater experiments at Colorado State University since 2003 when the residential graywater reuse pilot study was initiated. Over the following years many of the recommended experiments associated with long term effects of household graywater have been conducted in response to the research program questions. In this thesis, household graywater research findings from 2003 to present were reviewed and determine 1) whether the key research questions identified in the WERF Literature Review and Synthesis

(Roesner et al., 2006) have been answered? 2) Is the regulating community confident in the safety of household graywater systems?

1.4 Thesis Organization

The thesis structure is focused on providing a presentation of graywater research findings. Chapter 1 introduces background information and an overview of graywater research at Colorado State University. Chapter 2 provides specific household graywater research findings in a two-part format separating the early graywater pilot study research (system prototype and turf growth experiments) from later experiments conducted to investigate long term effects of graywater on landscape irrigation. Chapter 2 has been written as a journal article for submission to Water Practice & Technology. In Chapter 3, graywater findings to date, current research underway and the future vision for graywater reuse are presented. Two appendices are included at the end of the thesis containing details from the 2003 graywater residential pilot study Literature Review (Appendix A) and the Residential Graywater Reuse Pilot Study (Appendix B).

CHAPTER 2 GRAYWATER RESEARCH FINDINGS AT THE RESIDENTIAL LEVEL

2.1 Introduction

The challenge of ensuring a sustainable water supply in the arid west within the United States has created dedicated research towards a variety of water conservation efforts. Successful water conservation practices have become more critical as populations continue to grow in already water stressed areas. The City of Fort Collins, Colorado is one example where regional water supply management plans, coupled with local water conservation programs, are striving to meet supply demands today and anticipated water demands for the future. Researchers at Colorado State University in periodic collaboration with other research partners have worked over the past decade or more to investigate and understand the potential for household graywater reuse as a viable, safe and sustainable water conservation practice. Research studies have built steadily upon previous work as they continued to evaluate and assess graywater system prototypes, plumbing configurations, pathogen exposure risk as well as long term effects on plants, soil microbiology and groundwater.

Graywater reuse is a viable water supply source for supplementing household water use, particularly for outdoor irrigation. The City of Fort Collins Annual Water Conservation Report (2012) presented water usage data with an average per capita demand of 150 gpcd. Of the 150 gpcd, outdoor use comprises roughly 50% of the total water usage in a household (Mayer et al., 1999). Indoor water uses which generate graywater include showers, baths, and clothes washers. These graywater-generating fixtures conservatively represent 40% of the indoor water use and therefore 20% of total residential water use (Mayer et al., 1999). The opportunity for residential graywater reuse has the potential to decrease municipal water water demand.

One of the challenges of graywater reuse systems is the need to develop water quality criteria appropriate for the end use. Existing regulations and water quality limits for water reuse systems are based on wastewater characteristics which vary greatly from graywater characteristics. Water tests are performed for Fecal Coliform counts which are used as the indicator organisms for pathogens that may pose a risk to human health. However, evidence has found that while fecal coliform concentrations grow in graywater, true pathogens have not been observed to grow in graywater (Ottoson et al., 2003). For this reason, graywater may not pose the same level of pathogen exposure risk as the same fecal coliform counts found in domestic wastewater.

In the absence of sufficient understanding of both graywater quality and potential risk exposure pathways connected to graywater systems, regulators hold graywater systems to wastewater reuse water quality standards. Graywater systems in Colorado are required to meet Regulation 84 Individual Sewage Disposal Systems (ISDS) with limits established for Fecal Coliforms. Another regulatory source for comparison is Regulation 31 recreational water quality standards which assess risk based upon potential contact with *E. coli* in surface waters. These regulations are not specific to graywater pathogen levels but provide a basis for human health potential exposure risks.

2.2 Graywater Definition

The definition of graywater being used here is taken directly from the 2012 International Plumbing Code (IPC) which states graywater is "waste discharged from lavatories, bathtubs, showers, clothes washers and laundry trays". Graywater includes used water from bathtubs, showers, bathroom, wash basins, and water from clothes washing machines and laundry tubs. It shall not include waste water from kitchen sinks or dishwashers".

2.3 Literature Overview

Over the past decade, several compilations of graywater literature reviews have been produced. A literature review was completed in advance of the 2003 Colorado State University pilot residential graywater reuse study reviewing physical, chemical and microbiological characteristics of graywater (Marjoram, 2014). This literature review research was incorporated as part of future research studies associated with the graywater research program. In particular, a comprehensive literature review on the long-term effects of landscape irrigation using household graywater published by the Water Environment Research Foundation (Roesner et al., 2006) reviews relevant studies conducted to date on graywater quality, health risks, end-uses, system configurations, microbiology, chemistry, soil and landscape plant effects.

2.3.1 Microbiology

Research performed by Rose et al., (1991) identified bacterial differences between graywater sources and household composition. Rose found that Total Coliform and Fecal Coliform counts were consistently higher in shower water than clothes washer water as well as being higher for households with children. Total Coliforms were reported with a 10^7 order of magnitude and Fecal Coliform counts were found to have a 10^5 order of magnitude (Rose, 1991). Research on the presence of pharmaceuticals and personal care products (PPCP) in residential graywater by Eriksson (2003) reported *E. coli* values ranging from 100 to 2,800 CFU/100mL.

2.3.2 Graywater System Configurations

The components integrated into residential graywater systems vary depending upon the characterization of graywater sources, the residential application and local regulatory requirements. All of these factors contribute to the graywater reuse system design which can be extremely basic to highly complex. More basic designs include storage and often filtration before application. More complex designs have been seen to replicate domestic wastewater treatment on a small scale with the inclusion of expensive disinfection systems. Alkhatib et al., (2006) presents a comprehensive overview of graywater collection and treatment systems which includes a wide range of proprietary and individual homeowner design configurations. Further work by Glenn (2012) compiled graywater regulations from a total of 41 states, counties and city utilities into a database tool which matched the appropriate proprietary graywater technology for meeting the local regulations.

2.4 Research Objective

The objective of this research is to provide an overview of residential graywater research findings from early research in 2003 up to the present. Early graywater research at Colorado State University began in 2003 with the implementation of a residential graywater system within a pilot household. The pilot project experimented with graywater system prototypes and applied graywater to landscape plants as well as a turf watering test plot. The research determined that residential graywater systems are feasible, affordable and warrant additional research and study. Research studies have built steadily upon previous work as they continued to evaluate and assess graywater system prototypes, plumbing configurations, pathogen exposure risk as well as long term effects on plants, soil microorganisms and groundwater.

2.5 Early Research (2003): Household Graywater Reuse Pilot Treatment System

2.5.1 Introduction

In 2003, research began at Colorado State University to pilo their first system prototype for residential graywater reuse. In the absence of substantial technical guidelines for constructing residential graywater reuse systems, core research focused on experiments with system designs capable of collecting, treating, and distributing residential graywater. Key factors used to evaluate stages of the prototype included economic feasibility, ease of operation, and ability to achieve the desired level of treatment appropriate for the intended use.

The household graywater pilot study included research into prototype treatment configurations and measured indicator bacteria populations throughout the study. Collected graywater was used to drip-irrigate landscape areas already in place on the pilot household property. In addition to studying graywater system prototypes, a turf growth experiment was conducted to investigate any observed differences between irrigating with graywater versus municipal water (Marjoram, 2014).

2.5.2 Methods

The two person pilot household had installed parallel plumbing to allow for graywater collection from household fixtures prior to the start of the research project. At the initiation of the project, graywater plumbing was extended to the collection tank located in the basement.

Pilot Household Water Budget and Graywater Tank Sizing

The size of the storage tank was based upon the pilot households' outdoor watering demands. The outdoor watering demands were calculated using the homeowners water utility bill and the accepted values found in the Uniform Plumbing Code (2000 edition). The previous year water utility bill reported water usage of 75,000 gallons over 245 days which equated to water usage of 75 gallons per capita day (gpcd). Seasonal fluctuations in usage showed that 50% of the water consumption was being used for outside watering of landscape features. Since the landscape features were newly planted during that period additional watering was being conducted in order to properly establish the plants. For this reason, a value of 50 gpcd taken from the Universal Plumbing Code (UPC 2000 edition) was used to size the 300-gallon storage tank with a three day storage volume.

Graywater System Prototype Experiment Phases

A phased approach was used to develop the pilot household graywater system prototypes using readily available components which were affordable and simple to maintain. Each phase and associated component(s) targeted a treatment objective. The treatment objectives included aeration, storage/settling, filtration and disinfection. The experimental system design began with a base system of collection, storage and recirculation. Further pilot project phases were implemented in the order and with specific components as listed in *Table 2-1* below.

Table 2-1: Residential Graywater Research Project Phases

Experimental Phase	**Date**		**Treatment Component(s)**	**# Samples Collected**
	Start	**End**		
Base Configuration	04-05-2003	8-14-2003	Collection, Storage and Recirculation	0
Phase I	08-14-2003	10-07-2003	Aeration	6
Phase II	10-07-2003	12-31-2003	Aeration, Filtration	8
Phase III	12-31-2003	03-01-2004	Aeration, Filtration, UV Disinfection	7
Phase IV	03-01-2004	05-06-2004	Aeration, UV Disinfection	17
Turf Growth	07-16-2003	10-09-2003	n/a	n/a

As part of the base configuration a SeaMetrics flow computer and flow sensor assembly was installed to collect graywater generation data. The pilot household graywater generation rates were found to be 35-gpcd, 15% less than the 50-gpcd value suggested in literature (UPC 2000).

The processes selected for experimentation as part of the pilot research project included aeration to ensure stored graywater remained aerobic, filtration to remove suspended solids which did not settle out in the tank, and disinfection using ultraviolet light to reduce pathogens

Graywater samples were taken during each phase and tested by the Colorado State University Environmental Health Services (EHS) laboratory for the presence of total aerobic bacteria populations, total coliform, fecal coliform and *Escheria coli* (*E. coli*) using membrane filtration methodology described in Standard Methods for the Examination of Water and Wastewater (20^{th} ed., 1998).

In order to prevent stored graywater from turning septic, Phase I established aeration within the pilot graywater system by inserting a handmade venturi into the recycle line and continually running a 330 gph (0.5 HP) recycle pump. An initial aeration pump installed was the submerged Aquarium Pump Penguin 1140 Power Head 300 gph. Within a couple of months the Aquarium Pump Penguin failed and was replaced with a Harbor Freight 0.5 HP recycle pump attached to a Petco 12" air stone and silicone tubing. Challenges with maintaining aeration in the graywater tank continued and a Rio180 pump/powerhead 120 gph air compressor was installed.

A Hach colormetric field testing kit was used during Phase I to perform basic chemical water quality analyses for free and total chlorine, dissolved oxygen, Ammonia-N, Nitrate-N and orthophosphate. The HACH kit included 4 color disks (Ammonia-N, Chlorine, Nitrate-N, Phosphate Phosver), powder pillow packs (free chlorine, total chlorine, ammonia salicylate, ammonia cyanurate, NitraVer5 nitrate, PhosVer3 phosphate, DO1, DO2, DO3), a thermometer, pH reader, 2 1.0 mL droppers, 2 23 mL square glass bottles, 100 mL demineralized-deionized water, 100mL sodium thiosulfate standard solution, glass dissolved oxygen bottle, 4 plastic sample tubes, clippers, color comparator with long wave attachment, dissolved oxygen test solution with sodium azide. The results showed water quality ranges consistent with those found in the literature and comparable residential studies. Since the water quality results were within expected ranges and the primary concern expressed by local health authorities was human health risks, research focused on collecting microbiology data for the duration of the experiment.

Experiment Phase II and III included a Hayward 14 inch sand filter and pump (0.25 HP) assembly purchased from a local pool supply store for providing filtration. Phase III of the experiment also included installation of an Aqua 15 Watt UV disinfection unit (200 to 500 gph). The UV unit was installed after the sand filter to minimize fouling of the UV bulb sleeve. A Phase III schematic along with Phase III photographs are provided in *Figure 2-1* and *Figure 2-2* respectively.

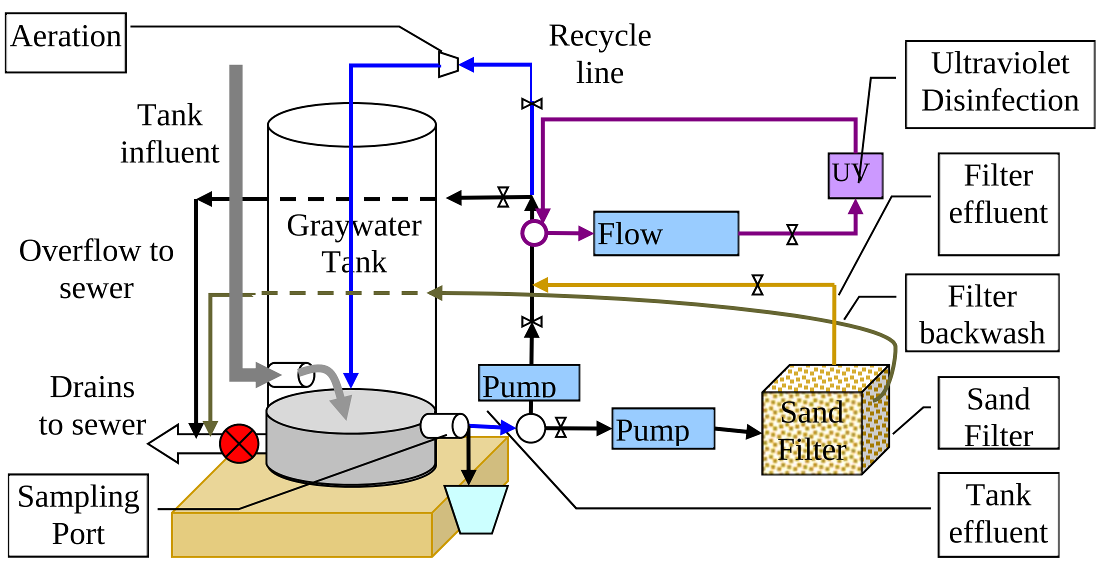

Figure 2-1: Graywater Pilot System Configuration Schematic Phase III

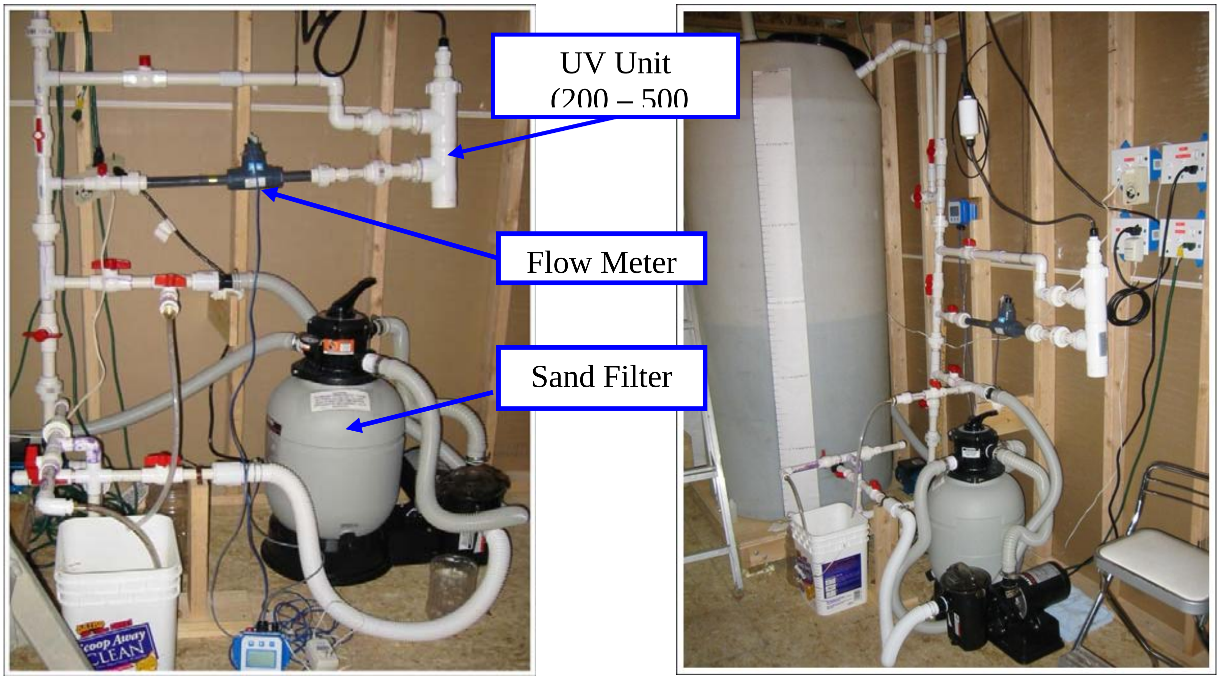

Figure 2-2: Graywater Pilot System Photographs Phase III

Experiment Phase III represented the highest level of pilot system complexity and included all system components. Experiment Phase IV removed the sand filter from the pilot system configuration. Indicator bacteria data was collected to determine if filtration was a necessary component of the graywater prototype.

Turf Growth Experiment

Pilot household graywater was applied to outside landscape features through an existing drip irrigation system to supplement the outdoor potable watering demands. Since graywater typically contains higher levels of nutrients and no chlorine residual compared to municipal water it was expected that plant growth would be greater for vegetation irrigated with graywater. The objective of the turf growth experiment was to collect basic growth data and determine if plant growth was greater when irrigated with graywater.

Beginning in July and continuing into early October of 2003, graywater and municipal water from the pilot household were used to irrigate four (4) turf plot cells contained in a constructed planter box. The planter box was designed to be off the ground, to isolate each turf plot using a plastic liner and to incorporate drainage ports into each of the four plot containers. The media profile included a pea gravel drainage layer on the bottom covered with a top soil mix depth to support turf growth. The turf plots were designated as T1, T2, T3 and T4 from left to right. Plots T1 and T2 were watered with tap water and T3 and T4 were watered with graywater. One gallon of water or graywater was applied to the turf plots on an average of every three days throughout the summer. Figure 3 presents photographs of the turf plots before and after cutting along with a diagram depicting the measurement locations.

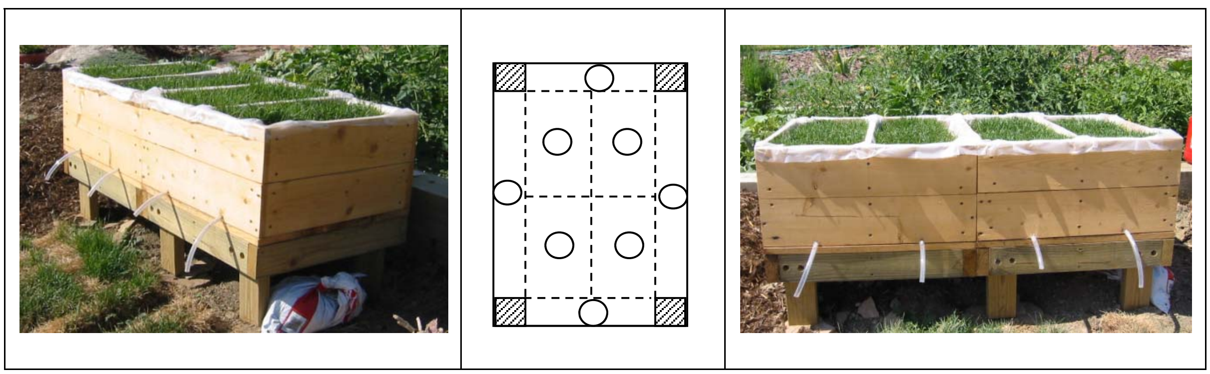

Figure 2-3: Turf Growth Plot Photographs and Turf Height Measurement Location Diagram

The turf was cut a total of five times over the three months growth experiment. Measurements of local turf height were recorded before and after cuts at the eight numbered locations for each turf plot. The average growth for each turf plot was calculated from the 8 individual values. Biomass measurements were not taken as part of the turf growth experiment.

2.5.3 Results and Discussion:

Graywater Microbiology Results

Throughout all phases of the pilot study, graywater samples were collected and analyzed for the presence of indicator bacteria. Indicator organism data for *E. coli* are graphically presented in Figure 2-4 below along with information for the specific experimental phases. The legend values are in the same order as the vertical lines representing experiment components. Reference lines are included representing the Colorado Department of Public Health and Environment (CDPHE), Regulation 31 (March 2001) recreational waters classification numerical values for water quality Class 1a and 1b (primary contact) *E. coli* counts of 126 per 100 mL and 235 per 100 mL respectively.

The microbiology results for the pilot study varied depending upon the prototype phase, contributing graywater flows from the residents and operational interruptions. In early phases, aeration of the graywater system was not consistent due to challenges with the initial method.

As was expected the most simple treatment phase, aeration (Phase I), had the highest observed microbiology values over the course of the experiment. The first *E. coli* sample result of 1,000 #/100 mL reflects the initial establishment of the graywater reuse system whereas subsequent results all exceed 100,000 #/100 mL. The aeration issues coupled with no other treatment practices is reflected in the high *E. coli* counts observed in Phase I.

Phase II, aeration and filtration, shows a general trend of decreasing *E. coli* results by orders of magnitude over the experiment phase. Aeration was a recurring issue in Phase II. Although *E. coli* values are observed to decrease significantly after the sand filter was incorporated into the system, the elevated *E. coli* value on November 20th, 2003 is likely a result of diminished aeration in the tank coupled with a period of no graywater additions preceding the sample. Interruptions to system operations occurred twice during Phase II when the valve directing graywater to the tank was closed and graywater was being sent to the sanitary sewer. The effect of not adding graywater to the storage tank leads to continual treatment without new graywater additions and steadily improves tank water quality over time. Prior to the first stoppage of graywater contributions to the storage tank, *E. coli* results were reported as less than 1. The decrease in microbial populations for the first 5 *E. coli* samples of Phase II appears to be a result of the introduction of sand filtration.

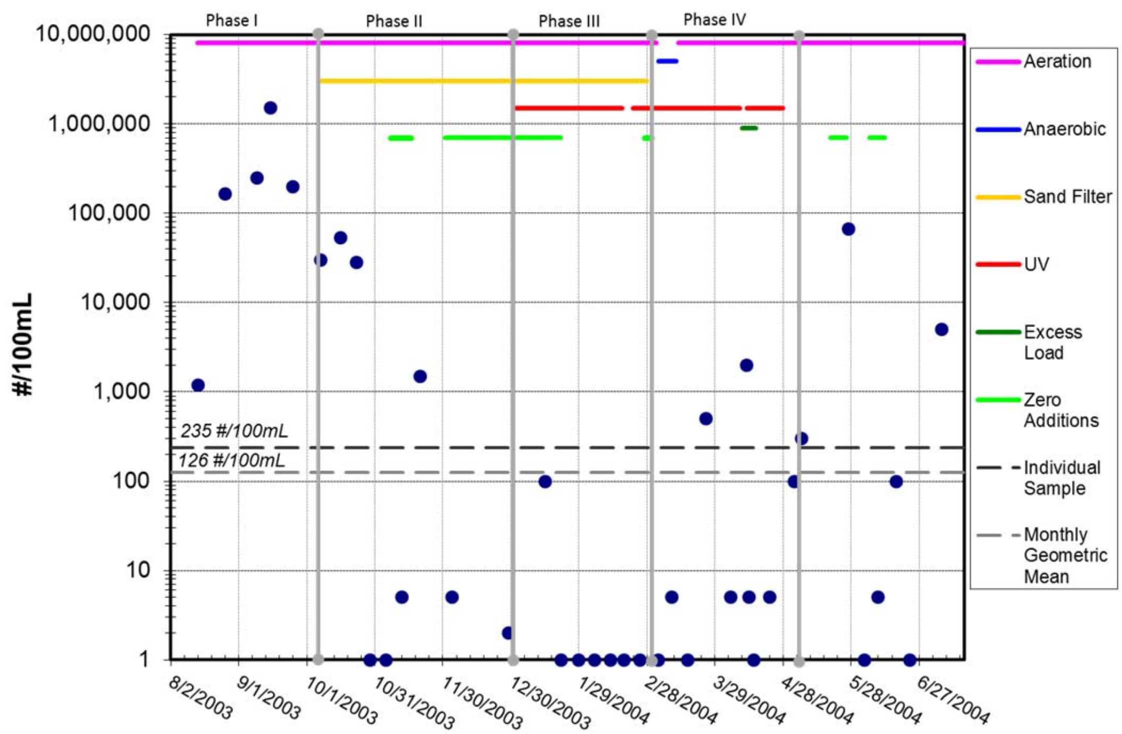

Figure 2-4: Pilot Residential Graywater Tank E. coli Results

The system interruption preventing the addition of new graywater to the storage tank continued into Phase III when UV was added into the treatment train. With the exception of one sample, all *E. coli* results were less than 1 #/100 mL. Low *E. coli* values would be expected to correlate with the zero graywater contributions, however, the results remained below 1 #/ 100 mL for over a month once the system was back into full operation. Also during this phase, the

UV treatment was interrupted for four days due to an operational failure. The microbiology results were not impacted as a result of the UV interruption. The Phase III treatment train including aeration, filtration and UV resulted in the lowest *E. coli* results for the duration of the experiment.

Phase IV removed the sand filter from the treatment train leaving aeration and UV in place. At that time aeration operation was interrupted completely. On March 13th, 2004 an air compressor was introduced into the system to ensure aeration and recirculation of stored graywater was properly met. The graywater system load contributions were greatly increased from April 10th to April 16 2004 due to house guests. At the same time UV was inadvertently shut off from April 9th to April 11th. The tank had rapidly fouled by April 11th with a dense foam layer on the surface, visually the water color had turned gray and a strong septic odor was present. As would be expected, the *E. coli* counts were elevated to 2,000/100mL for the 4/12/2004 sample. However, a sample taken the next day (4/13/2004) reported an *E. coli* count of less than 10 CFU/100 mL. In early May, system recirculation and therefore UV treatment was interrupted and large microbial growths were observed in the tank. The two samples taken after the operational failure reflect *E. coli* counts increasing.

UV was elected to be turned off in order to evaluate the system response with an improved oxygenation process. Comparing the results at the end of the experiment with those in Phase I, the base system is observed to have improved aeration operations as reflected in the overall lower *E. coli* results.

A summary of the microbiology results for each experiment phase is presented as a geometric mean in Table 2-2: Experiment Phase Microbiology Geometric Means below.

Table 2-2: Experiment Phase Microbiology Geometric Means

Experimental Phase	Treatment Component(s)	# Samples Collected	Geometric Mean		
			Total Coliforms (#/100mL)	Fecal Coliforms (#/100mL)	E. coli (#/100mL)
Phase I	Aeration	6	459,399	102,699	87,481
Phase II	Aeration, Filtration	8	2,152	57	57
Phase III	Aeration, Filtration, UV Disinfection	7	3,164	49	2
Phase IV	Aeration, UV Disinfection	17	103,990	1,365	16

Microbiology results in terms of the geometric mean by phase are observed to be lowest for Phase II and Phase III of the experiment. It should be noted that these treatment approaches are more likely relevant to a graywater reuse system for toilet flushing than drip irrigation.

Turf Growth Experiment Results and Discussion

To analyze the turf growth results, median and mean values were computed from the measured growth in each turf plot. Average, or mean, turf growth is plotted for the tap water (T1, T2) and graywater (T3, T4) irrigated turf plots over five sample events in *Figure 2-5*. Each sample event shows greater plant growth for turf irrigated with graywater. Growth was greater during the summer growing season following the first sample event. The last sample event in October marks the end of the typical turf growing season.

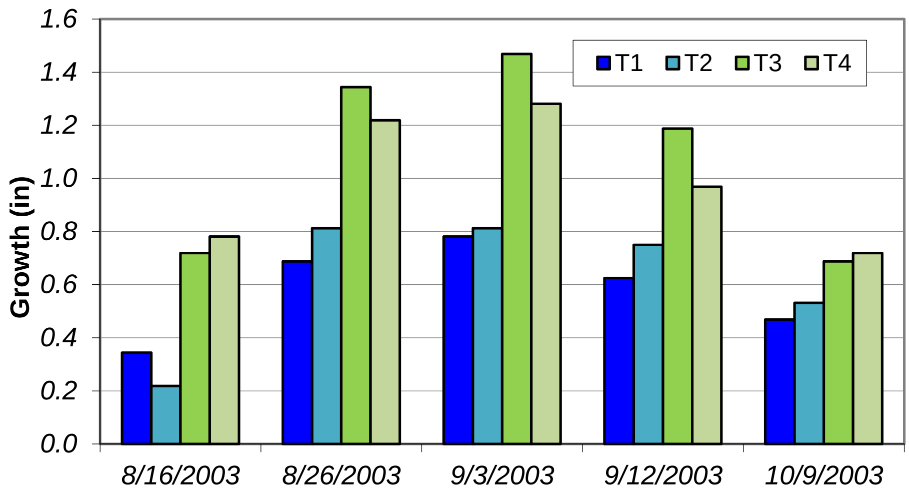

Figure 2-5: Average Turf Growth

A summary of total growth for the duration of the experiment is presented in *Table 2-3* by irrigation water source.

Table 2-3: Summary of Total Turf Growth

Water Source	*Mean (in)*	*Median (in)*
Municipal Water	3.0	2.9
Graywater	5.2	4.9

The total turf growth height for graywater irrigated turf plots is 2 inches more than those irrigated with municipal water.

2.5.4Conclusions

The residential graywater pilot project conducted in 2003 and 2004 provided ground level research for moving toward a cost-effective residential prototype system capable of installation and operation by a homeowner. At the end of the experiment it was clear that additional work was needed on refining the system configuration to allow for graywater system fluctuations. The research results show the feasibility of the system to achieve appropriate water quality levels suitable for intended end-uses. The turf growth experiments provide basic data on the value of irrigating with graywater over tap water. By coupling an improved system with a new approach to assigning water quality standards for graywater the residential graywater reuse system can become a safe a viable option for sustainable water use.

2.6 Recent Graywater Research Findings – 2004 to 2013

Research findings from the early residential graywater reuse pilot study served as the basis for continued research by Alkhatib (2008) on improving the household graywater treatment system design as well as studying the effects of graywater irrigation on landscape plants and soils. Alkhatib determined that the graywater system design needed to include two tanks: one tank for graywater storage that includes coarse filtration, aeration and settling and a second tank for disinfection. Alkhatib's plant tissue analysis showed higher levels of sodium and total nitrogen (TN). Soil results showed elevated levels of sodium (Na) and nitrate nitrogen (NO_3-N) along with a higher sodium adsorption ratio (SAR).

The research on graywater reuse up to this point was instrumental in the identification and development of several key research needs in order for graywater reuse to be established as a safe, reliable and economical practice in the United States. A 2006 WERF study (Criswell, 2005; Roesner et al., 2006) developed recommendations for scientific experiments to address graywater reuse knowledge gaps in the areas of household graywater quality; optimal system design; graywater irrigation effects on soil chemistry, soil microbiology and residential landscape plants; and the presence of indicator organisms for human health considerations.

As work on the long term impacts to landscape irrigated with household graywater continued, research projects were conducted more recently on graywater regulations and graywater treatment technologies which meet them (Glenn, 2012) as well as a demonstration project for multi-residential toilet flushing with graywater.

2.7 Long Term Effects of Landscape Irrigation Using Household Graywater

2.7.1 Introduction

Several of the graywater research areas identified above were addressed in the WERF study Phase 1, Long Term Effects of Landscape Irrigation Using Household Graywater – Literature Review and Synthesis (Roesner, 2006). The study provided a comprehensive literature review and identified data that needed to be addressed in future research a number of which were addressed in Phase 2 of the WERF study (Roesner, 2006). Phase 2 investigated the fate and occurrence of graywater chemical constituents and pathogens and their potential impacts on soil quality, groundwater quality, plant health and human health (Sharvelle, 2012).

Field studies were used to collect scientific data for use by regulatory agencies and homeowners interested in installing a graywater reuse system. Field studies included households with existing graywater irrigation systems in place for 5 years or longer and households with newly installed graywater systems. Greenhouse studies were used to conduct controlled experiments on leachate quality and soil quality.

2.7.2 Plant Health

Field studies were used to assess plant health and found that most plants were healthy under long-term graywater irrigation. Three (Avocado, lemon tree and scotch pine) of the twenty-two species evaluated showed leaf burning or reduced growth or fruit production (Sharvelle et al., 2012). The Arizona household with new graywater system installed also exhibited positive impacts of graywater irrigation.

2.7.3Human health risks

A primary concern for graywater reuse is the potential human health risk since graywater presents an opportunity for exposure to pathogens and viruses. In an effort to address this concern, samples from three homes with established graywater irrigation systems for 5 years or more were analyzed for soil microbiology parameters total coliforms, *E. coli* and Enterococci (Sharvelle, 2009). Pathogen indicators were generally not found to be higher in graywater-irrigated soils compared to the freshwater irrigated control soils and decreased with soil depth. In some cases, results for the control soil were higher than the graywater soil. Pathogen indicators were highest in soils where animals defecated in the area.

The results of this research provide guidance to decision makers, water agencies, regulators, product manufacturers and consumers on how safe graywater irrigation systems can be installed and operated for household irrigation.

2.7.4Groundwater Contamination Potential – Greenhouse Experiments

Shogbon (2010) studied the potential for groundwater contamination from graywater irrigation by performing leachate analyses with synthetic graywater and municipal water (control) irrigated plants and turf in controlled greenhouse experiments. On average, leachate from graywater irrigation had higher concentrations of TOC, TN, nitrate, ammonium, TDS, TSS, VSS, sulfate, conductivity, boron and SAR compared to municipal water leachate. Accumulation of salt and boron was observed, with accumulation increasing over time. For most synthetic graywater constituents, leachate had lower concentrations than the influent. This supports the known biodegradation processes present in the soil matrix.

2.7.5 Physical and Chemical Soil Quality and Groundwater Contamination Potential

Research was conducted on the long term effects of graywater application on the physical and chemical quality of soil, including surfactants, salts and boron accumulation, organic matter (OM) leaching, and soil hydrodynamic properties (Negahban-Azar, 2012). The research study also included investigation of surfactant fate and transport.

- *Salts/Boron*: Field site soils were observed to accumulate sodium, although not at levels that are of concern to plant health and soil quality. Greenhouse studies showed salt concentrations in the leachate which may have the potential to migrate into groundwater. Similar results were found for Boron (B) which accumulated in soil and was found to have the potential to migrate to groundwater. However, there is not a human health risk posed by B in groundwater.
- *Nutrients*: Total Nitrogen (TN) values in soil and leachate were higher in graywater irrigation areas than the control areas irrigated with municipal water. Phosphorous did not accumulate in soils and no difference between leachate concentrations was found.
- *Organic matter*: Increases in soil Organic Matter (OM) are considered beneficial for both soil quality and plant health. Graywater irrigation was found to be beneficial by increasing surface soil OM.
- *Infiltration*: In theory, the presence of surfactants in graywater reduces capillary action resulting in decreased infiltration rates. However, depending upon the mechanism dominating the movement of water within the soil matrix, infiltration may remain the

same or decrease. Gravitational flow in the soil from graywater applied with a hose or bucket tended to maintain infiltration capacity.

- *Antimicrobials:* Antimicrobials were only detected in surface soils where they accumulated after irrigation with graywater. Antimicrobials may have adverse impacts on soil microbiology. Additional investigation into the effects of antimicrobials on soil microbiology was recommended. Soil antimicrobials, triclosan and triclocarban, did not appear to be present in graywater irrigated soils at concentrations of concern.
- *Fate and transport of surfactants:* There is no evidence that accumulated surfactants have a negative impact on plant health or soil quality. As was expected, in this study graywater irrigated soil samples were found to have significantly higher surfactants than municipal water irrigated soils which generally accumulated in surface soil. Any surfactants which were not retained in the column study soils (19%) were observed to leach through with a trend of increased concentrations the duration of the experiment. A mass balance on added surfactants in the greenhouse study showed 92% to 96% biodegradation concluding that the majority absorbs to surface soils and/or is biodegraded.

2.7.6Summary

The results of the WERF Phase 2 study support graywater reuse as safe for human activities provided best management practices are followed. In addition, plant health, soil quality and groundwater are able to remain within reasonable ranges with residential graywater irrigation of landscape areas. The SAR, an indication of salt accumulation, did accumulate in soil. However, values were not at a level which would cause concern. Boron was not observed to accumulate in greenhouse experiments or newly installed graywater systems. There is a potential for salts, B and N to leach into groundwater. The majority of surfactants sorbed to the soil matrix and underwent biodegradation. However, the portion of surfactants that was observed to leach out of the column increased over the 17 month study duration.

2.7.7 Household Graywater for Landscape Irrigation - Future Research

This research was able to fill in a number of data gaps originally identified in the WERF Phase 1 report. Some additional research is recommended to complete this component of graywater research. Antimicrobials were confirmed to be present in graywater irrigated soil. Researchers are working to learn more about the effects of antimicrobials on soil microbiology. In particular, studies on whether antimicrobials have a role in the formation of antibiotic resistant genes. Another area for continued research is studying the long term leaching of surfactants. An increase was observed in the 17-month greenhouse study but it is not clear if this trend will continue. Lastly, there is a research need to assess the risk associated with pathogens and viruses in graywater.

2.8 Graywater Regulations in the United States

Graywater regulations vary between states, depending upon size and end use, and depending upon whether it is part of a residence or not. The differences in graywater regulations have made the administration or creation of graywater rules confusing and challenging. In an effort to help regulatory officials make decisions based upon water quality information, available technologies and standards Glenn (2012) compiled information on available graywater regulations. Data collection included distributing a survey to state agencies, county offices and city utilities of which 41 states responded. The research resulted in a graywater reuse database (Microsoft Access 2010) and guidance document available on WateReuse.org. The research summarizes commercially available systems, summarizes regulations and links graywater regulations with treatment systems that meet requirements.

2.9 Graywater Separation, Dual Plumbing, collection of existing research

One of the knowledge gaps identified by Roesner et al. (2006) was the lack of appropriate and comprehensive design, sizing, maintenance and system selection guidance for homeowners and businesses. This knowledge gap has been addressed in the WERF Guidance Manual for Separation of Graywater from Blackwater for Graywater Reuse (Bergdolt, 2011). A dual plumbing system is required for safe separation of graywater from blackwater in a graywater reuse system. Once graywater is diverted it requires some level of treatment before it can be reused which will vary in complexity depending on the end use. The guidance manual applies a logical and systematic approach in determining whether graywater reuse is reasonable option and if so provides guidance on all the steps to a safe and functioning installation. An important element included with the manual is graywater system maintenance which helps to ensure continued protection of public health.

2.10 Graywater Reuse for Toilet Flushing

Researchers at Colorado State University have recently completed a graywater reuse multi-residential demonstration project at Aspen Hall for toilet flushing (Hodgson, 2012). The demonstration project treats 300 gpd and includes collection, storage (compositing, settling no more than 24-hours), coarse filtration, in-line dosing with sodium hypochlorite (NaOCl) and tank chlorine (Cl_2) disinfection before a booster pump refills flushed toilets.

The researchers established a pilot scale test to investigate multiple filters and disinfection options which would provide adequate water quality while having minimal maintenance needs and low operating costs. With these criteria in mind a coarse medium density filter was selected. The pilot scale test results determined that chlorine was the most efficient disinfectant for graywater reuse due to its effectiveness in *E. coli* and total coliform inactivation. The chlorine concentration analysis compared water demand with water residual and resulted in the conclusion that a concentrations of 16.4 mg/L Cl_2 was needed in order to achieve 3 mg/L Cl_2 chlorine residual for a minimum 60 minute contact time. In comparison, the 2003 residential pilot study confirmed the more rigorous treatment processes necessary to decrease microbial populations as shown in the *E. coli* results during Phase III (Figure 2-4: Pilot Residential Graywater Tank E. coli Results). Rather than the use of chlorine to deactivate potential pathogens and viruses, the 2003 pilot system deployed UV treatment with similar results.

Further testing will continue to monitor potential for pathogen regrowth and to assure public health concerns are addressed. The demonstration project has succeeded in meeting the project objectives of providing a safe, cost-effective and efficient graywater reuse toilet flushing system at a multi-residential scale with the potential for commercialization in the future.

The City of Fort Collins, Larimer County, Colorado State University Facilities, Housing and Environmental Health have all approved initiation of toilet flushing with treated graywater scheduled for Fall 2013. CSU worked with the State Plumbing Board to obtain a variance which was received in June 2013.

2.11 Success: Graywater Control Regulation Number 86

All of the research which has been conducted over the past decade and more has had the goal of filling in data gaps necessary to scientifically show the safe, economical and sustainable application of graywater reuse. Earlier this year lead researchers and industry experts from Colorado State University successfully worked with Colorado State legislators to pass House Bill 13-1044 – Graywater Control Regulation Number 86. The Bill requires local municipalities to adopt an ordinance or resolution allowing the use of graywater.

CHAPTER 3 CONCLUSION

The challenge of ensuring a sustainable water supply within the United States, particularly in the arid south-west, has led to dedicated research on a variety of water conservation efforts. The past decade of research has successfully shown that graywater reuse is a viable technology which requires simple treatment, is easy to operate and is capable of significantly decreasing water use.

Over the past decade, a number of key advances in graywater research have been accomplished. A brief summary of some of the highlights is included below.

- The WERF study (Sharvelle et al., 2012) showed no need for disinfection of graywater being used for irrigation. The presence and levels of pathogens on field sites whether being irrigated with either municipal water or graywater were the same.
- An optimal residential graywater drip irrigation system prototype has been developed (Alkhatib, 2008) which includes two tanks, one for collection, coarse filtration and settling and the other for usable storage. The WERF research (Sharvelle et al., 2012) coupled with the prototype configuration supports no need for inclusion of disinfection as part of the treatment train when graywater is being applied for irrigation.
- A multi-residential graywater reuse demonstration project for toilet flushing was completed on Colorado State University campus, Aspen Hall (Hodgson, 2012). Graywater used for toilet flushing will require a higher level of treatment due to the increased potential for exposure. Hodgson studied and selected Chlorine as the disinfectant for the residence hall. The resulting water quality with storage, filtration and

disinfection determined by Hodgson achieves similar results as found in the 2003 residential pilot graywater system research which used UV rather than chlorine.

- Results from the long term study on landscape irrigation for graywater reuse provided scientific data and filled knowledge gaps related to soil quality (microbiology, chemistry), groundwater contamination, human health risks and plant health when graywater is used for irrigation (Sharvelle, 2009; Shogbon, 2010; Negahban-Azar, 2012,).
    - Plants were not adversely impacted
    - Surfactants were observed to absorb to the soil matrix (>90%) and no negative impacts to soil quality or plants were seen.
    - Salt accumulation was not in ranges that are considered harmful to plants
    - Pathogen indicators were generally no higher in graywater irrigated soils than freshwater irrigated soils.
- A tool for matching state and local specific graywater regulations to appropriate commercial graywater technology providers was developed. (Glenn, 2012).
- A guidance manual for separating graywater from blackwater provides a detailed reference for safe design and maintenance of the proper graywater system for homeowner and business owner needs (Bergdolt, 2011).
- WERF reports have been generated for three projects: Long Term Effects of Landscape Using Household Graywater – WERF 03CTS18CO Literature Review and Synthesis, WERF 06CTS1CO Experimental Study and Report INFR4SG09a Guidance Manual for Separation of Graywater from Blackwater for Graywater Reuse.

- Colorado passed state legislature for Graywater Control Regulation Number 86 allowing the local adoption of graywater reuse ordinances.

Significant progress has been made towards filling knowledge gaps related to graywater reuse. However, further research is needed in some areas such as those identified in the long term effects of landscape irrigation using household graywater study. Anticmicrobials were found to be present in graywater irrigated soils. The effect of antimicrobials on soil microbiology is an area where additional research is continuing. In particular, studies on whether antimicrobials have a role in the formation of antibiotic-resistant genes. Another area for continued research is studying the long-term leaching of surfactants. An increase was observed in the 17-month greenhouse study but it is not clear if this trend will continue. Lastly, there is a research need to assess the risk associated with pathogens and viruses in graywater. A recommendation as part of the conclusion of this research is to develop a model for simulating the fate and transport of graywater constituents.

Another area for ongoing and future research is the need to monitor indicator bacteria regrowth within the Aspen Hall demonstration project distribution system and toilets to optimize chlorine dosing and ensure exposure to pathogens and viruses is prevented. At the end of the recent research phase, it was noted that the demonstration project would need to be in operation for multiple years in order to properly assess any microbial impacts to the safety and operation of the system.

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APPENDIX A. LITERATURE REVIEW

Before beginning an in-depth development of the 2003 residential graywater pilot project, it was important to understand the scope of research already performed as well as and to identify areas of ongoing study. The drivers for research into water re-use systems often arise from such issues as critical strain on stressed resources, governmental concern for public health, and industrial interests in developing markets or even public demand. Keeping these points in mind the focus of this literature review is on topics related to developing a residential graywater system. More specifically the questions asked of our research are:

- What are the existing barriers for implementing residential graywater reuse?
- Is water quality and system data available to either support or refute the validity of barriers related to stringent graywater effluent water quality standards.
- Can the Colorado State University research provide an alternative perspective to assist in addressing these barriers?

There is no doubt that graywater reuse practices, commercial or residential, are increasing in acceptance and implementation throughout the United States and even more so internationally. Hotels are marketing themselves with green practices of which graywater reuse is a notable part (March et al., 2004). University dormitories are seeing the added benefits of recycling graywater to flush toilets (Surendran et al., 1998). Individual home owners connect hoses to their washing machines to utilize the wash water for landscape features (Prillwitz et al., 1995). Community developments are built with parallel plumbing systems to separate, collect, treat and reuse graywater (Otterpohl et al., 2003). The wide range of graywater reuse applications based on end user and physical location provided diverse literature sources to inform the graywater pilot study research project.

A thorough review of relevant literature was performed to identify areas needing further research and to shape the understanding of graywater systems and their applicability. For the purpose of this study research emphasis was placed on the graywater residential reuse system.

GRAYWATER QUANTITY

By the strictest definition, graywater is any wastewater not generated from toilet flushing, otherwise referred to as blackwater. As taken directly from the Arizona State Legislature, “Graywater" means wastewater that originates from residential clothes washers, bathtubs, showers, and sinks, but does not include wastewater from kitchen sinks, dishwashers and toilets. Kitchen sinks and dishwashers are often not incorporated into graywater flow due to the high organics content leading to oxygen depletion and increased microbial activity of the graywater.

Within a residence, each of the potential graywater sources contributes to the total indoor water use budget. Research has been performed on varying levels to determine the water distribution between uses in a household. A study released by the American Water Works Association (AWWA) Research Foundation titled the *Residential End Uses of Water* (Mayer, 1999) presents usage data collected in twelve North American cities for approximately 1,200 households. Highly detailed data observations were collected at the end point using computer software and data loggers over a total time period of fourteen weeks. Between all twelve cities the average indoor water use was determined to be 63.19 gallons per capita per day (gpcd). Figure A-1 below graphically displays the average distribution for all twelve cities’ indoor residential water use.

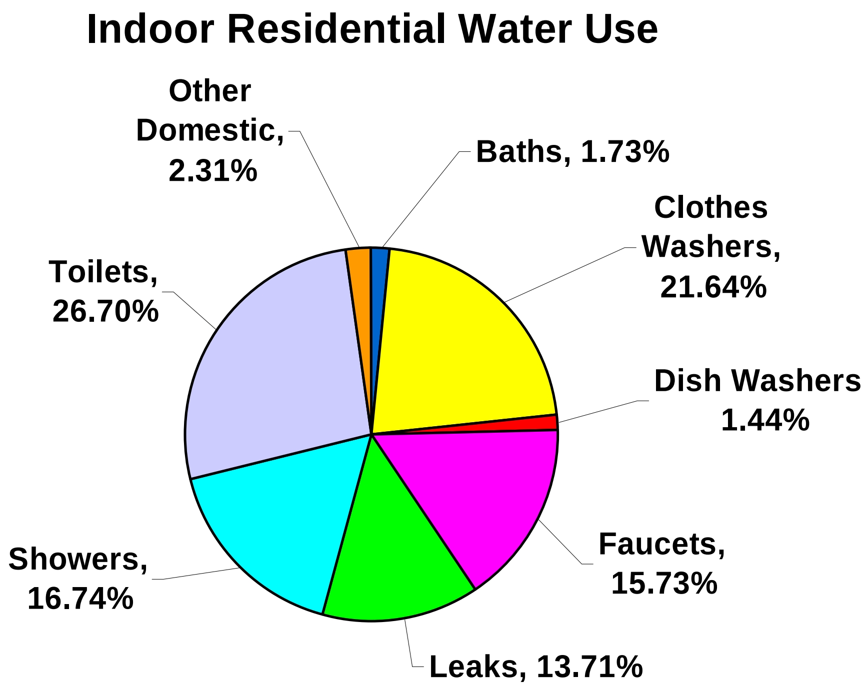


Figure A-1: Average Indoor Residential Water Usage for 12 North American Cities

The sources contributing to graywater are typically baths (1.73%), clothes washers (21.64%), showers (16.74%) and a portion of the faucets (15.73%). Sources of faucet flows are typically bathroom basins, hand dishwashing, drinking water and teeth brushing.

In comparison, the City of Fort Collins distributed a flyer with customers' monthly bills January of 2001 detailing the Monthly Indoor Water Use per person. Table A-1 reproduces the data presented within the January 2001 bill stuffer.

Table A-1: City of Fort Collins Monthly Indoor Water Use (Per Person)

Water Source	**Water Required per Single Use (Gallons)**		**# of Uses per Day**	**Typical Use (Per Month)**		**Conservation Use (Per Month)**	
	Typical Use	**Conserving Use**		**Water (gal.)**	**Cost ($)**	**Water (gal.)**	**Cost ($)**
Shower	32 (4 gpm x 8 min)	8 (2 gpm x 4 min)	1	960	1.19	240	0.30
Bath	40 (full)	15 (min. depth)	1	1200	1.49	450	0.56
Toilet Flushing	6 (pre-1977) 3.5 (after-1977)	1.6 (ultra low flush)	4 4	600 420	0.74 0.52	192	0.24
Washing Machine	50 (max. water level)	27 (min. water level)	0.3	450	0.56	243	0.30
Hand Dishwashing	30 (faucet running)	5 (dishpan or sink)	0.3	270	0.33	45	0.06
Automatic Dishwasher	16 (full cycle)	7 (short cycle)	0.15	72	0.09	32	0.04
Brushing Teeth	6 (faucet running)	0.25 (wet brush, rinse)	2	360	0.45	15	0.02
Drinking Water	1 (faucet running)	0.1 (store in fridge)	3	90	0.11	9	0.01

Notes

1. Indoor water use is approximately half of a household's annual water use. The other half goes to lawn watering.
2. These values are per person. For household use, multiply times the number of residents.
3. These are only averages and individual water use will vary.
4. Costs are based on the 2000 metered rate of $1.24 per 1,000 gallons. For a single family residence, there is also a base charge of $13.86.

Reviewing the City of Fort Collins Typical Use values, indoor water use is distributed between baths (31.4%), showers (25.1%), faucets (18.8%), clothes washing machine (12.0 %), toilet flushing (11.0%) and dishwasher (1.88%). The per person usage is assuming that an individual will use both a bath and a shower in one day. The percentage of use attributed to a bath in Fort Collins (31.4%) is vastly different than the percentage determined with the AWWA

Residential End Uses of Water study (1.73%). The City of Fort Collins bill stuffer did not indicate how the typical use data is determined.

The graywater sources for the Fort Collins residential project intentionally excluded kitchen sink and dishwasher contributions due to the potential for microbial contamination and the high level of organic matter often associated with these sources. A high level of organic matter in graywater adds a level of water treatment complexity for the oxygen demand that is beyond the scope of this project. Therefore, identifying the primary graywater sources from the AWWA research project as showers, baths and clothes washers, contributions to the indoor graywater flow is conservatively represented as 40.11% of the total indoor residential water use budget.

Outdoor usage of municipal water comprises approximately 50% of the typical residential water budget but can vary depending upon region. The research by Mayer et al. (1999) calculated an average of 82.82 gallons per capita per day (gpcd) allocated to outdoor uses, representing roughly 56% of the potable residential water budget. A comparison between indoor to outdoor water use for the individual cities participating in the study determined that the majority have outdoor water use exceeding indoor water use. Figure A-2 graphically compares the indoor and outdoor water usages as a ratio where a value greater than one indicates that indoor water use exceeds outdoor water use. Five of the twelve cities have a ratio greater than one with city number 12, Waterloo Ontario, having over four times the amount of water used inside than outside. The ratio for city number 12 is identified as an outlier and removed from the data set resulting in an average ratio of 0.95 indoor to outdoor residential water usage for the remaining 11 cities. Not surprisingly, other studies show varied results in the percentage of water dedicated to outdoor usage (Surendran, 1998). Residential water budgets can vary for many reasons such as a particularly dry year, installation of water conserving devices and changes to landscape features.

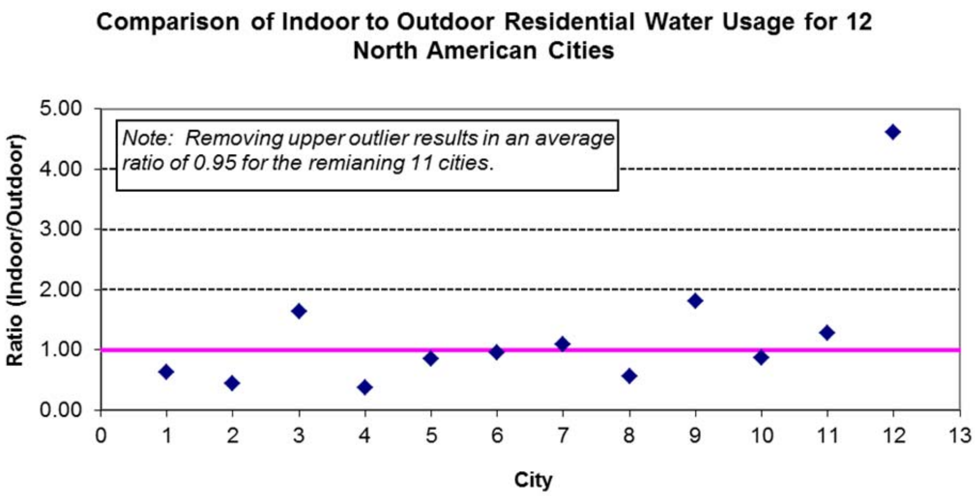


Figure A-2: Ratio of Indoor to Outdoor Water Usage

(City Key: 1 – Phoenix, AZ; 2 - Scottsdale/Tempe, AZ; 3 – Lampoc, CA; 4 – Las Virgenes, CA; 5 – San Diego, CA; 6 – Walnut Valley, CA; 7 – Boulder, CO; 8 – Denver, CO; 9 – Tampa, FL; 10 – Eugene, OR; 11 – Seattle, WA; 12 – Waterloo, Ontario Canada)

Water conservation efforts

Low flush toilets, low flow shower heads, irrigation timers, voluntary watering restrictions, are a few of the options available for conserving water in the home. All of these options reduce the amount of graywater produced and therefore limit the ability to meet intended household demands for reusing graywater. However, as conservation efforts improve the demand for recycled graywater at low flow devices will likely be equally diminished (Leggett, 2002).

GRAYWATER QUALITY

The physical, chemical, and microbial characteristics of graywater vary based upon the sources connected to the collection system. The household composition as well as the cleaning and personal care habits of the residents also impacts characteristics of graywater. In general, the domestic water source has certain water quality characteristics as presented in Table A-2 (adapted from the New Mexico State University, *Safe Use of Household Greywater guide* (Duttle, Rev. 1994)), showing a list of potential constituents for each source.

Table A-2:* Graywater *Characteristics by Source (New Mexico State University* Safe Use of Household Greywater Guide*, 1994)

`	**Characteristics**
Automatic Clothes Washer	Bleach, Foam, High pH, Hot Water, Nitrate, Oil and Grease, Oxygen Demand, Phosphate, Salinity, Soaps, Sodium, Suspended Solids, and Turbidity
Automatic Dish Washer	Bacteria, Foam, Food Particles, High pH, Hot Water, Odor, Oil and Grease, Organic Matter, Oxygen Demand, Salinity, Soaps, Suspended Solids, and Turbidity
Bath tub and shower	Bacteria, Hair, Hot Water, Odor, Oil and Grease, Oxygen Demand, Soaps, Suspended Solids, and Turbidity
Evaporative Cooler	Salinity
Sinks, including kitchen	Bacteria, Food Particles, Hot Water, Odor, Oil and Grease, Organic Matter, Oxygen Demand, Soaps, Suspended Solids, and Turbidity

The kitchen sink and dishwasher water often carry microbial contamination from practices such as rinsing raw meat. Often the raw foods contain enteric organisms that can present a health risk to humans when present in high enough quantities (Casanova, 2001). Due to the potential for increased health risks and additional organic loadings, the kitchen sink and dishwasher water flows should be connected to the sanitary sewer. It should not be included in the graywater collection system.

Graywater quality data is presented in Table A-3 below for three specific studies. Rose et al., (1991) is one of the most frequently referenced research papers with regard to the bacterial differences given particular sources (shower vs. laundry) and household composition (children under 12 present). Households with young children have higher bacterial concentrations according to research performed by Rose (1991). Not only does Rose (1991) find that the presence of children increases bacterial loading but also shower water is found to be higher in total and fecal coliforms than laundry water. The work presented by Casanova et al. (2001) is taken from ongoing research at the Casa Del Agua, an operational graywater demonstration project located in Tucson, Arizona. Eriksson (2003) presents graywater constituent data in the beginning of his research to determine the presence of pharmaceutical and personal care products (PPCP) in graywater.

Table A-3: **Graywater** ***Characterizations from Three Studies***

Reference	**Eriksson (2003)**	**Rose et al., (1991)**				**Casanova (2001)**
Source	**Composite**	**Shower**	**Laundry Wash**	**Laundry Rinse**	**Composite**	**Composite**
Concentration (mg/L)	Range	Range				
Temperature (^oC)	21.6 – 28.2					
pH	7.6 – 8.6				6.54	7.47
COD	77 – 240					
BOD	26 – 130					64.85
TSS	7 – 207					35.09
Turbidity (NTU)		28 – 96	39 – 296	14 – 29	76.3	43
NH4-N	0.02 – 0.42	0.11 – 0.37	0.1 – 3.47	0.06 – 0.33	0.74	
NO3-N	<0.02 – 0.26				0.98	
Total-N	3.6 – 6.4				1.7	
PO4-P					9.3	
Tot-P	0.28 – 0.779					
Sulfate					22.9	59.59
Chloride					9	20.54
Hardness					144	
Alkalinity					158	
Ca	99 – 100					
K	5.9 – 7.4					
Mg	20.8 – 23					
Na	44.7 – 98.5					
Total bacterial pop. (CFU/100mL)	4.0×10^{7} - 1.5×10^{8}	1.0×10^{7} - 1.0×10^{8}	1.0×10^{7} - 1.0×10^{8}	1.0×10^{7} - 1.0×10^{8}	6.1×10^{8}	
Total coliforms (CFU/100 mL)	6.0×10^{3} - 3.2×10^{5}	1.0×10^{5}	199	56	2.8×10^{7}	8.03×10^{7}
Fecal coliforms (CFU/100mL)		6.0×10^{3}	126	25	1.82×10^{4} - 7.94×10^{6}	5.63×10^{5}
Fecal Streptococci (CFU/100mL)						2.38×10^{2}
E. coli (CFU/100 mL)	<100 - 2800					

All of these values are taken before any treatment has taken place. Therefore, they represent a variety of influent graywater qualities. The range in constituent values needs to be considered when designing graywater re-use systems. It is also important to remember the fact that no single graywater system is identical to another.

APPLICATIONS AND END-USES FOR GRAYWATER

The initial applications of residential graywater in the United Stated likely began with homeowners hand-bailing graywater such as shower water and washer water. This was done to help irrigate flowers, shrubs, and other landscape features during times of drought. Another reason for re-using graywater is attributed to homes in remote locations that are unable to connect to municipal sewer systems and need to manage their own wastewater. It is this second option of on-site wastewater treatment systems where the United States Environmental Protection Agency (USEPA, Feb. 2002) addresses the possibility of re-using graywater in an effort to reduce pollutant loading to waste treatment systems. The *Gray Water Pilot Project Final Report* (City of Los Angeles 1992) conducted research on eight voluntary residential sites retro-fitted with graywater systems installed for the purpose of residential sub-surface irrigation. The focus of the data collection was on graywater-irrigated soil characteristics.

Gunther (2000) successfully constructed a “wetpark” in Sweden, essentially a treatment wetland, for a clustered community treating graywater to a level acceptable for re-use within the residences. The design achieved effective treatment while providing a natural area for recreational use. Toilet flushing is another application for graywater re-use currently being practiced in Germany (Thomas, 1997), England (Hills, 2000) and Australia (New South Wales Health, 2000).

Overview

The components integrated into a residential graywater system vary depending on the characterization of the graywater sources, the residential application and regional location of the system. There is an ever-growing market for small scale and large scale graywater reuse systems that is currently supplied by several proprietary manufacturers.

Manufacturers

The literature review revealed several proprietary graywater products already available for individual purchase. Often the manufacturers started with small scale sustainability design concepts which have grown into the field of graywater reuse. Understandably, these manufacturers are found in arid states and countries experiencing droughts, therefore, creating a need for water conservation practices beyond those practiced by the general public.

One manufacturer is Clivus Multrum, Inc. (Figure A-3) who began by designing a composting toilet then developed a means for distributing graywater through an irrigation distribution system. Water is collected from the home and stored in a “dosing tank” where a level float triggers the submersible pump to send graywater to the subsurface irrigation chambers. Irrigation chambers are placed within the root zones of landscape areas. Filtration is not a part of the design since the Clivus Maltrum system relies on the active root zone in nearby soils. It is not apparent that any other kind of treatment has been integrated into the design other than any settling of solids and floating of grease and oil that may occur within the dosing tank. However, the company states that graywater systems are custom designed to suit specific site conditions.

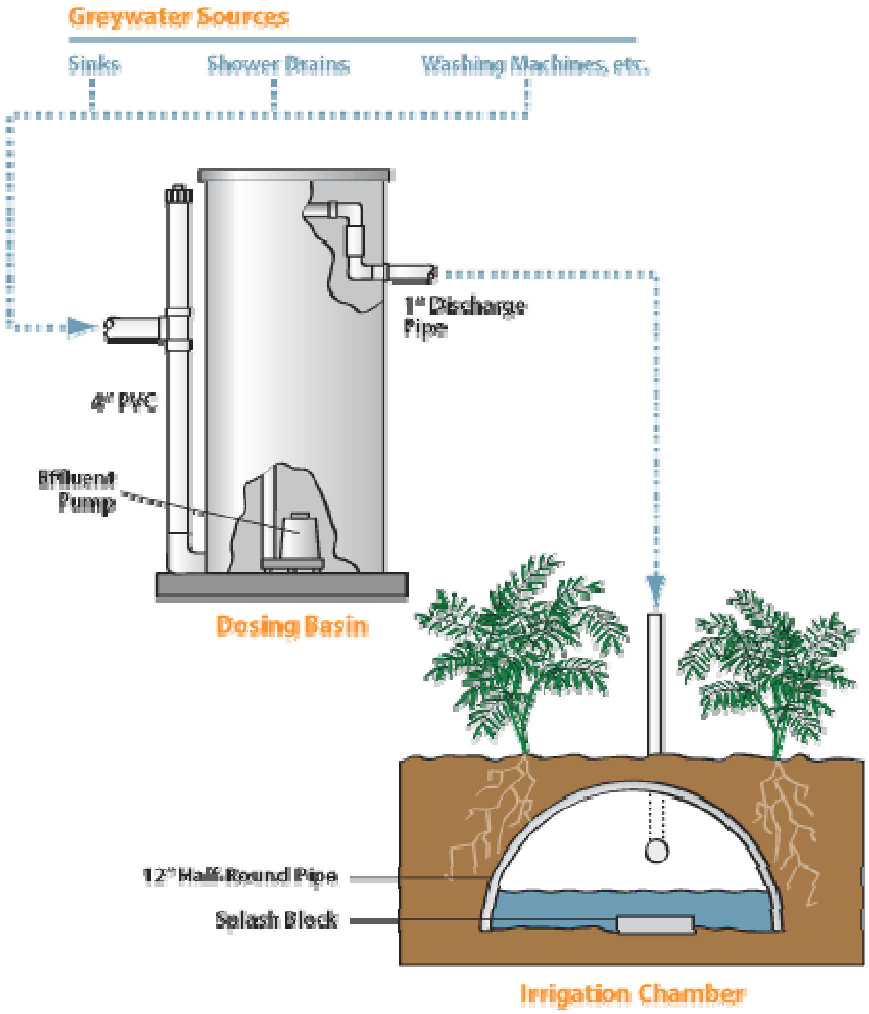


Figure A-3: Clivus Multrum Graywater System

Source: Clivus Multrum, Inc., © 2006-2008 http://www.clivusmultrum.com/products_greywater.shtml, site by: breviloquent
Clivus Multrum, Inc. © 2006-2008
15 Union Street, Lawrence, MA 01840, 1-800-4-Clivus, forinfo@clivusmultrum.com

Architerra Enterprises, Inc. (Figure A-4) is the designer of a passive graywater system stressing the simplicity of not having any moving parts to maintain or replace. Architerra sells a complete self installation package for a residential home consisting of a a filter basin (41 in. H x 26 in. dia.) a graywater irrigation filter, diverter valve, seals, leach field fittings, clean-outs, inspection ports and vents. Graywater is collected from the residence and directed to the subsurface filter basin where solids settle out and fats rise to the surface. Graywater flows through an irrigation filter as it exits the filter basin and heads to the diverter valve and the rest of the irrigation system. Architerra discusses the importance of providing solids removal at the source, particularly for the washing machine.

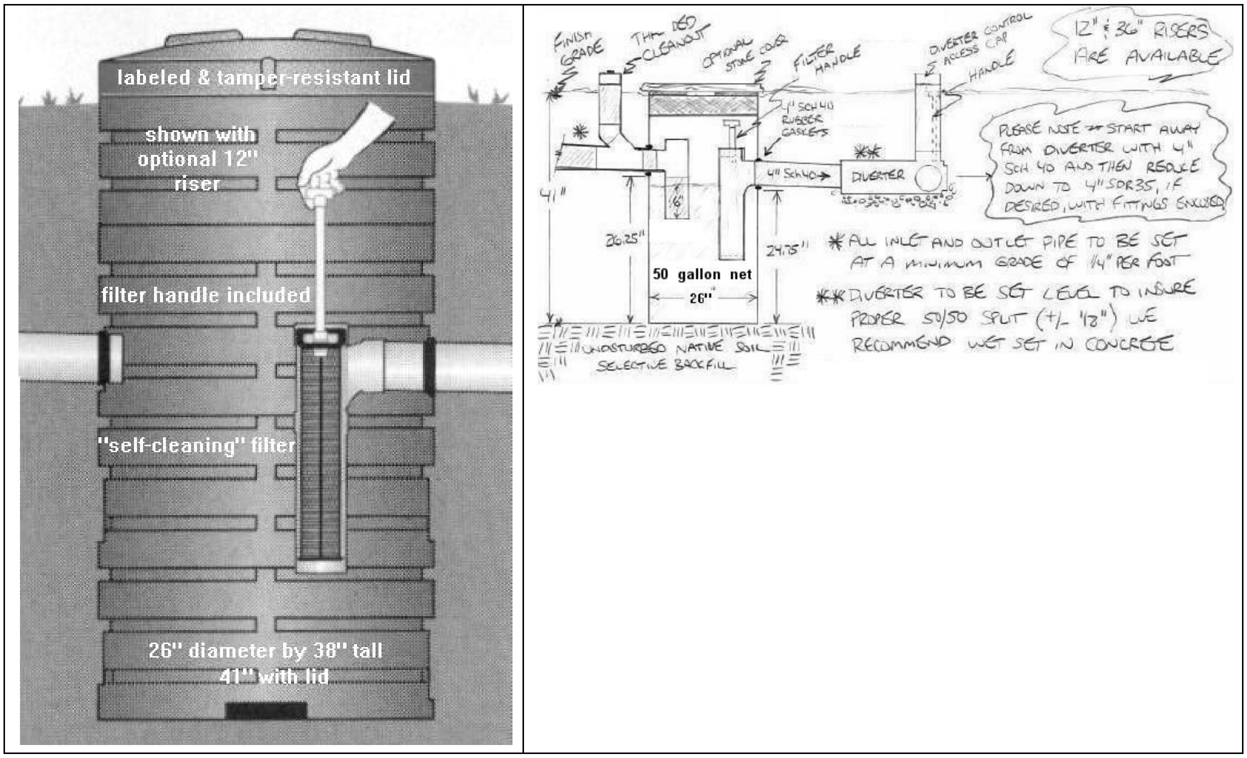
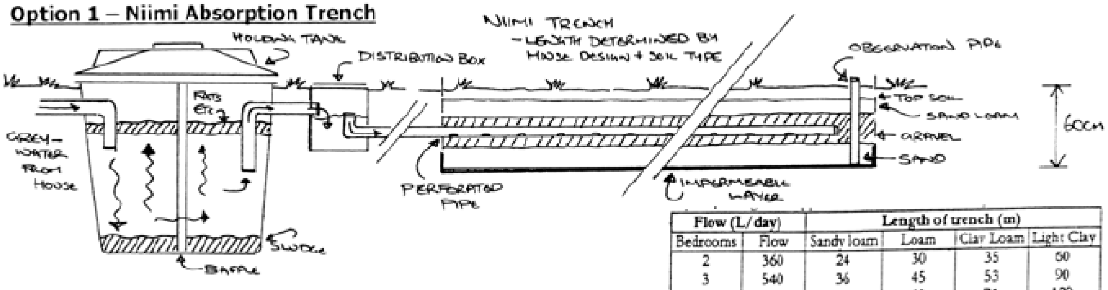


Figure A-4: Architerra Graywater System

source: http://www.thenaturalhome.com/greywater.html, Architerra Enterprises Inc., d.b.a. TheNaturalHome.com, copyright © 1998 – 2009 by Architerra Enterprises Inc.

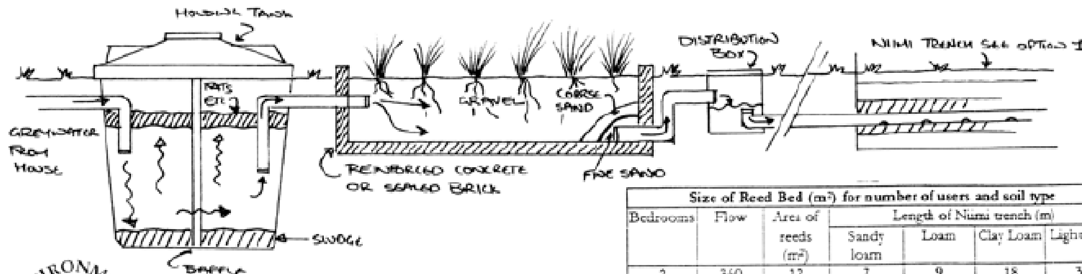
The RotaLoo ® graywater system (Figure A-5) focuses on distribution of collected graywater through either a trench or rock filter system. In both cases, a 2,500 L (660.62 gal.) holding tank provides pre-treatment by acting like a sump before continuing to a distribution box. The effluent flows from the distribution box are directed to the selected treatment system. The irrigation systems are subsurface and run in parallel to allow for alternating use. The landscape areas receiving the graywater contain an impermeable layer.

Option 1 – Niimi Absorption Trench



Flow (L/day)		Length of trench (m)			
Bedrooms	Flow	Sandy loam	Loam	Clay Loam	Light Clay
2	360	24	30	35	60
3	540	36	45	53	90
4	720	48	60	71	120

Option 2 - Reed Bed



Size of Reed Bed (m²) for number of users and soil type						
Bedrooms	Flow	Area of reeds (m²)	Length of Niimi trench (m)			
			Sandy loam	Loam	Clay Loam	Light Clay
2	360	12	7	9	18	36
3	540	19	11	14	27	54
4	720	25	14	18	36	72

ENVIRONMENT EQUIPMENT SINCE 1974

Environment Equipment Pty Ltd 41A Jarrah Drive Braeside, Vic 3195
Tel: (03) 9587 2447 Fax: (03) 9587 5622 Website: www.rotaloo.com

Figure A-5: RotaLoo Graywater System

Source: RotaLoo ®

All three of the manufactured products discussed above rely on subsurface irrigation systems to reuse the collected graywater. This could be limiting for properties graded against the collection system and would require a lift pump to distribute the water through the irrigation network. The Clivus Maltrum system is the only design with the tank above ground which would allow it to be placed within a home or outside at ground level. The placement of the tank may limit the coleection of graywater. The other systems, Architerra and Rotaloo, have submerged collection tanks external to the home which require additiona protection during periods of frost. Only the Architerra system has a dedicated filter for removing solids in addition to the settling of solids and floating of oil and grease that occurs in all three of the products. Other than physical settling and coarse filtration for bulk solids removal, all of these systems do not address pathogen removal since the point of discharge is subsurface and human contact is avoided. The systems that are already on the market are constrained to subsurface irrigation and do not involve any high level of water treatment.

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Health Risks

Indicator bacteria, such as Fecal Coliforms and *Escherichia coli*, are fairly good in representing the presence of bacterial pathogens in water. However, indicator bacteria are not very good at representing the presence of viruses or protozoas in water (Gutteridge, 2001). Dixon et al., (1999) discuss instituting guidelines for graywater re-use. They assess the range of risk associated with exposure to graywater accompanied with the level of microbial contamination and targeted population. The authors pose an interesting question "should the seemingly (and practically) harmless activity of taking a bath be regarded as a health risk comparable in magnitude with that associated with flushing the WC with graywater?" Ottoson et al., (2003) indicate a potential for over-estimation of the fecal load using Coliforms as bacterial indicators for enteric pathogens. The conclusions encourage use of fecal enterococci for a guideline if one must be used.

Is it necessary for graywater to be treated to drinking water treatment plant effluent standards when the exposure pathway and associated risks are vastly different? Currently the United States enforces treatment of graywater to potable standards when it is not applied through sub-surface irrigation systems. The constituents in any given graywater system are typically specific to the site. Therefore, identifying the appropriate level of treatment can be difficult and require reassessment over time depending on the inputs to the system.

No federal regulations exist that set standards for graywater water reuse quality, therefore, the individual states are responsible for establishing their own requirements. This has led to a variety of state regulations across the US. A detailed table of the 50 states positions' on graywater reuse is available in Appendix A of Parker's thesis titled "A Graywater Reuse System for Pikes Peak Colorado". Advocates making the greatest progress not surprisingly come from arid states. These states are making strides towards sustaining their urban water supply.

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APPENDIX B. RESIDENTIAL GRAYWATER REUSE PILOT STUDY

PILOT STUDY RESEARCH OBJECTIVES

In the absence of substantial technical guidelines for constructing residential graywater reuse systems, core research focused on physical design experiments able to collect, treat, and distribute residential graywater. Key factors used to evaluate stages of the physical model included economic feasibility, ease of operation, and ability to achieve the desired level of treatment appropriate for the intended use. Pilot study findings are expected to provide scientific support for re-evaluating the current stringent graywater system guidelines with respect to water treatment levels, system requirements and end uses.

STUDY APPROACH

Overview

The literature review was initiated and key conclusions during the early system design stages were used to elucidate the prime focus of the residential graywater system project. Two elements were derived from this portion of the research: (1) experiment with simple physical model design and (2) measure for microbiological indicators. First, a simplified physical system capable of widespread application needed to be developed. Since development of a prototype system available for mass distribution being the long term goal, there must be a way to integrate existing system designs and the knowledge gained from these experiments, homeowners experiences, and other related projects into a uniform yet flexible design. Second, the water quality bacteriology regulations for graywater applications are unclear and are typically grouped under inappropriate on-site wastewater disposal treatment system effluent limits. It is important and realistic to match water quality with the intended use rather then placing stringent restrictions on effluent waters. The water quality focus of this study is to gather microbiology data for indicator bacteria and assess population responses to system fluctuations and changes.

Research Phases

All research with regard to tank sizing, microbial water quality, and system fluctuations is restricted to a single pilot study site. The study was structured around developing a physical model through phased integration of system components coupled with the collection of water samples for microbial testing. The graywater system configuration phases are as follows:

Base System: Collection, Storage and Recirculation

- Phase I: Aeration
- Phase II: Aeration and Filtration
- Phase III: Aeration, Filtration and Ultraviolet Disinfection
- Phase IV: Aeration and Ultraviolet Disinfection

In addition to the physical model development indicated above, graywater was used for irrigation. The pilot study household applied graywater to landscape features during the growing season. In the summer of 2003 a turf growing experiment was initiated for investigating any observed differences between irrigating with graywater versus potable water. Table B-1 lists each experimental phase, phase duration, and number of microbiological sampling days.

Table B-1: Residential Graywater Research Project Phases

Experimental Phase	Date		Treatment Component(s)	# Samples Collected
	Start	End		
Base Configuration	04-05-2003	8-14-2003	Collection, Storage and Recirculation	0
Phase I	08-14-2003	10-07-2003	Aeration	6
Phase II	10-07-2003	12-31-2003	Aeration, Filtration	8
Phase III	12-31-2003	03-01-2004	Aeration, Filtration, UV Disinfection	7
Phase IV	03-01-2004	05-06-2004	Aeration, UV Disinfection	17
Turf Growth	07-16-2003	10-09-2003	n/a	n/a

Details with regard to system location, sizing, and phase configuration are presented in the following sections. Each phase contains a simplified schematic accompanied by site photographs, narrative discussion, incremental costs of system components, and the associated sampling schedule.

PILOT STUDY SITE DESCRIPTION:

The graywater pilot system was integrated into the residential water cycle of a Fort Collins, Colorado residence. Two residents inhabit the volunteer household and exhibited typical water demand and supply patterns leading to fairly consistent generation of graywater volumes. However, several occasions arose when the graywater system experienced exceptional loading due to house guests and conversely times when the occupants were away and therefore no graywater was added to the collection system. The City of Fort Collins, Colorado is the pilot residences' water supply utility. Situated on a development site this lakeside property of three years old at the time of project initiation and had irrigatable property upward of 0.75 acres. The residents continued to landscape their property for the duration of the project and applied graywater to landscape features requiring drip irrigation. With the exception of disposing of excess system drainage water, the turf areas were irrigated with potable water.

Graywater System Location

As part of a home improvement project in the basement, the homeowners chose to install parallel plumbing specifically for collecting household source graywater. This graywater pilot project location collected effluent water directly from the clothes washing machine, hand basins, showers and baths all located on the main floor. Although the basement was completely refinished to include a full bathroom the plumbing code did not allow nor was it physically possible with a gravity system to collect water generated on the basement level. The function of this part of the residence is to accommodate guests for short periods of time. At the time of research commencement, the plumbing was already in place for collection and only needed to be extended to a collection tank (Figure B-1).

Figure B-1: Residential **graywater** ***system connection point***

The graywater tank footprint was located in an unfinished large storage room in the basement where the system was readily accessible and ample room was available for working with modifications, monitoring water quality, and observing system operations.

Household Water Budget

Integrating a graywater system into a residence will impact the water usage for that household. Before extensive efforts were expended on designing a graywater system, literature was reviewed to gain an understanding of how graywater reuse alters individual water budgets when considering source demand and return to the sewer system. Since a detailed source flow assessment was not performed at the project house, water usage percentages derived from the AWWA *Residential End Uses* (2000) study were applied to the per-capita demand data provided by the City of Fort Collins. They are presented in Figure B-2 below. Excluded from the figure is the loss in water usage attributed to leaks. The study collected detailed measurements within the households. Comparing water meter measurements entering the home to the individual point of use metering measurements resulted in a shortage which is generalized as leakage. The leakage water loss is attributed to leaks occurring after the meter but before the home. The leak value was excluded in order to permit a focus on known uses within the household.

Figure B-2: City of Fort Collins Average Daily Water Use (2000 AWWA REU)indicates that over half the average water use in a Fort Collins household is allocated for use outside the house. Whether this is car washing, pool filling, landscape irrigation or garden watering is undetermined and varies depending upon the season and the household. In the pilot project graywater from the clothes washer, shower, bath and hand basins was collected According to Figure B-2, 21.8% of the pilot study residence waste water will be collected in the graywater storage tank. The potential graywater uses considered for investigation during the pilot study were outdoor watering of landscape features, water distribution through sub-surface drip irrigation and toilet flushing with treated effluent.

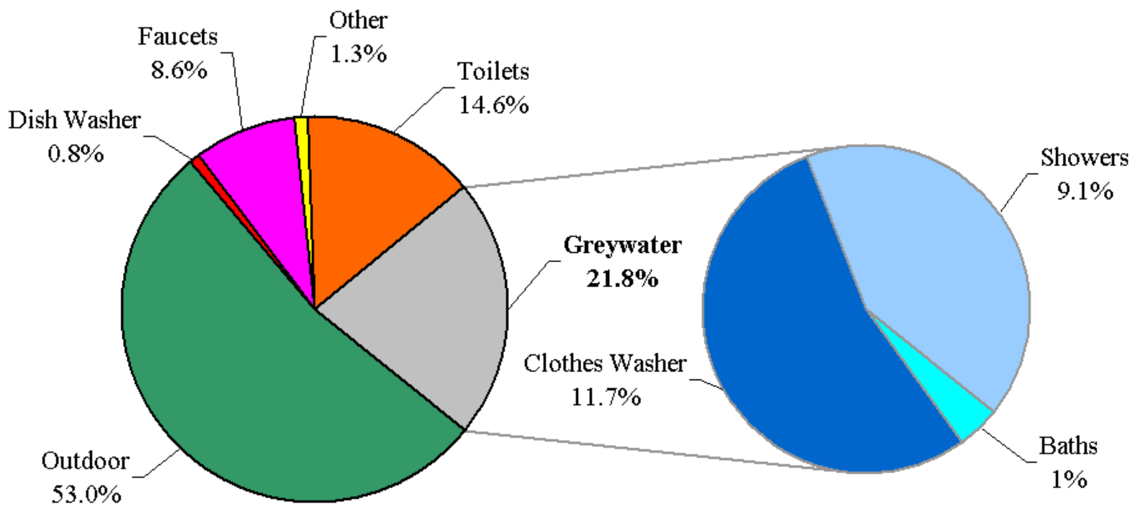

Figure B-2: City of Fort Collins Average Daily Water Use (*2000 AWWA REU*)

Each use inherently implies a reduced demand for potable water. Ultimately, the residential pilot project aimed to reach these goals for water reuse. However, monetary and scheduling constraints limited the extent and depth of project development realistically attainable. During the pilot project, graywater was applied at the surface to areas of landscape vegetation. Other graywater uses were not within the project scope.

Pilot Study Residence Water Usage Analysis for Storage Tank Sizing

An understanding and comparison of literature and actual graywater generation values was necessary for adequate system sizing as well as understanding impacts to the water budget. Two approaches were used to determine the residential water usage in gallons per capita day for the pilot project house. Actual usage values were taken from the previous year's water bill and compared to published values. The most straightforward means of determining gallons per capita day consumption for a household is simply to review the water utility bill. The time period from December 10, 2001 to August 12, 2002 was available for calculating potable water use at the pilot project site. The total number of billed days is divided by the total consumption and a residential usage was found to be 306 gallons per day (153 gpcd). A comparison between summer and winter months indicated an outdoor demand of 29,000 gallons, roughly 50% of the water budget during the growing season. This would also imply that the household had a base indoor usage of 183-gpd. Water use values taken directly from the utility bill are reproduced in Table B-2 below and are used to calculate the indoor/outdoor water budget of which graywater flows were extracted and used to appropriately size the storage tank.

Table B-2: Pilot Study Household Water Use

Date		Usage (1,000's of gallons)			# of Days	Average Daily Usage	Seasonal Usage (Galloms)	
From	**To**	**Current**	**Previous**	**Volume Used**				
12/10/2001	1/14/2002	109	101	8	35	0.229	23,000	Winter
1/14/2002	2/12/2002	115	109	6	29	0.207		
2/12/2002	3/12/2002	119	115	4	28	0.143		
3/12/2002	4/15/2002	124	119	5	34	0.147		
4/15/2002	5/14/2002	139	124	15	29	0.517	52,000	Summer
5/14/2002	6/10/2002	143	139	4	27	0.148		
6/10/2002	7/8/2002	157	143	14	28	0.500		
7/8/2002	8/12/2002	176	157	19	35	0.543		
		Totals:		**75**	**245**			

A total of 75,000 gallons was used over a course of 245 days for the two-person residence. The usage was roughly 150-gpcd. Review of literature values indicated that half the total water demand is attributed to outdoor water use providing a rate of 75-gpcd for indoor consumption. The graywater tank size needed to accommodate a three day residence time for the pilot project site resulted in a 459 gallon storage requirement. In comparison, the 2000 Universal Plumbing Code uses 50-gpcd for sizing a storage system. The higher usage value calculated with the actual utility bills was attributed to an increase in outdoor irrigation from the previous summer during establishment of landscape features. Therefore, the published value of 50-gpcd was selected for sizing the graywater system. A desired residence time of three days was selected for sizing the tank. A three day residence time for a two person household results in a 300 gallon storage tank requirement.

PHYSICAL MODEL DESIGN PHASES:

The pilot project was developed on a physical basis starting with a base system that was built upon throughout the study period. Observations of system performance were one key information source used to assess system efficacy and to adjust the physical design. The other driver for assessing system performance was results from microbiological analysis performed in accordance with Standard Methods. At the project outset four phases of system development were broadly defined allowing a focus on the core designs while facilitating modifications as needed. The physical processes evaluated throughout the phases included aeration, filtration, and ultraviolet disinfection

Base System Configuration

A base system was designed and assembled that remained constant to all phases of the pilot study. Components of the base system included: a collection tank, sized for the household graywater generation rates; a structural support platform, able to bear the weight of a full tank; and inlet, outlet, overflow lines for initial operation of the system. A schematic representation of the base system is included in Figure B-3 below followed by site photographs in Figure B-4.

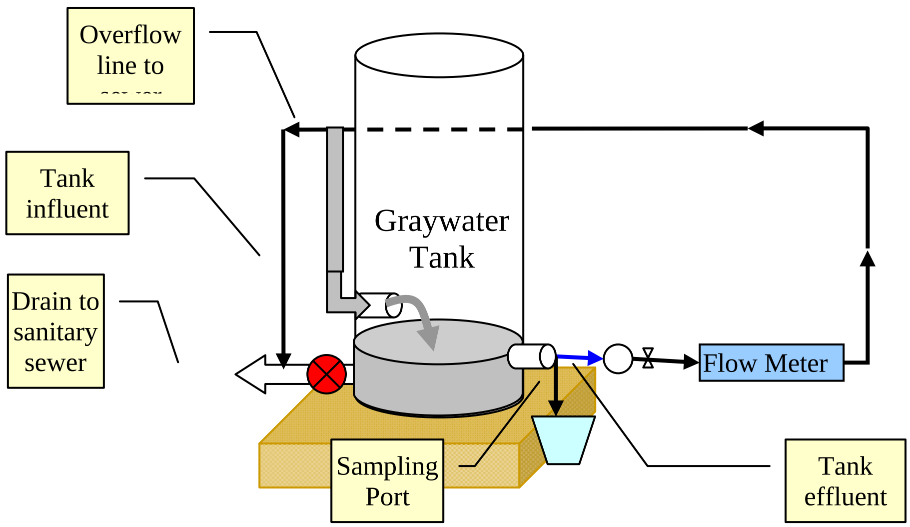

Figure B-3: Base System Schematic

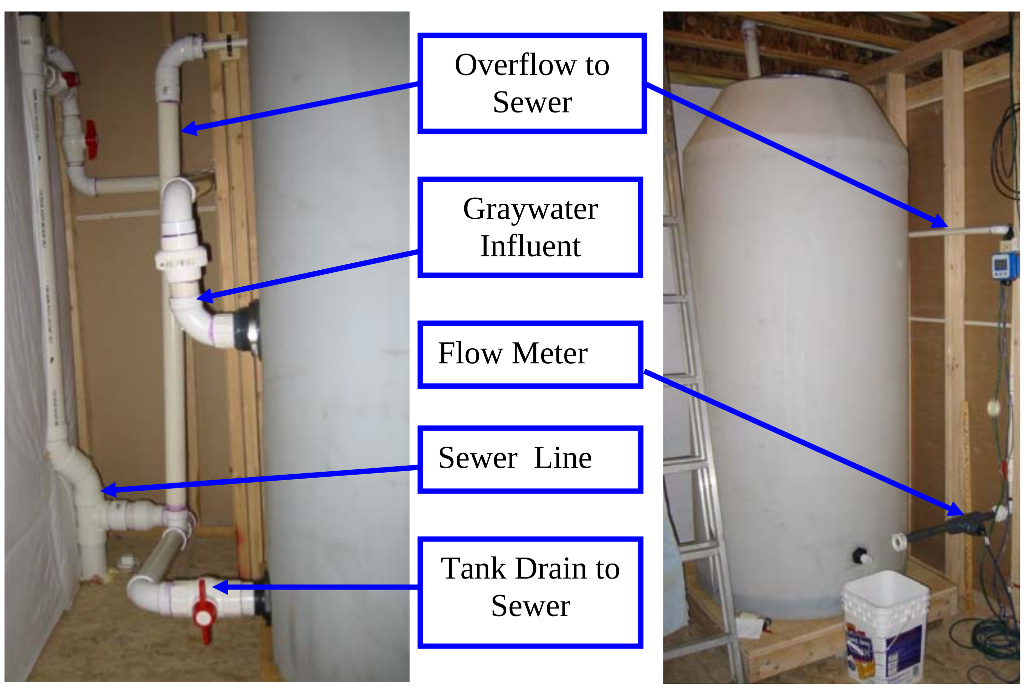

Figure B-4: Base System Configuration Photographs

Graywater was collected through the parallel plumbing system installed by the residents that culminated at a ball valve collection point in the basement storage room. This location was where the storage tank could be placed for long-term usage. PVC pipe, fittings, and valves all readily available at local home repair stores were used to connect the tank fittings to the existing system. Overflow to the sanitary sewer was achieved when the tank capacity reached the graywater influent pipe elevation. A 300-gallon vertical HDPE storage tank was obtained commercially. Its height was 84 inches and its diameter was 36 inches. The density of water is 62 pounds per cubic foot (lb/cf) which equates to 2,490 pounds of water (lbs) with a load of 352 pounds per square foot (lb/sf) for a full 300-gallon tank.   Precautions were made to support the load at full tank capacity including a safety factor. A floating platform was constructed to allow for foundation shifting of the house and consequent load shifting stresses of the storage tank. The platform feet were set in concrete with compressed, treated wood posts supporting a rectangular platform made of the same materials. Construction of the independent platform is shown in Figure B-5 below.

Figure B-5: Tank support platform

The base system was installed on April 5, 2003, and was monitored for overflow rates along with basic water quality data analyzed using a HACH colormetric diagnostic kit. A SeaMetrics flow computer and flow sensor assembly was selected for collecting tank overflow data. Flow meter data was collected and compared with literature values for residential graywater generation. The pilot study household graywater generation rates were monitored and found to be 35-gpcd, 15% less than the 50-gpcd literature values suggested.

Phase I Configuration: Aeration Added to Base System

Graywater aeration as a system treatment component was implemented through all phases of the study. Although, the method of maintaining adequate aeration varied depending on system modifications related to the study Phase. Initially, a small aquarium pump, installed on May 2, 2003, rated at 300 gallons per hour (gph), was used to aerate and recirculate the graywater. At the given rating, tank water should be turned 24 times a day. The pump was suspended from a chain kept at the water surface. A hose extending into the tank allowed for water intake and aeration on outflow. A coarse filter constructed of wire screen mesh was attached to the hose bottom to prevent fouling of the aquarium pump. After a few weeks, the graywater remained septic and an assessment of the pump indicated a larger device was required. The second pump (Harbor Freight) was installed on July 4, 2003, and provided a maximum pumping rate of 330 gph (0.5 HP). With the installation of this pump a recycle pipe was fitted into the system for circulating graywater from the bottom of the tank and returning it to the tank water surface. By maintaining a constant recycle the water was anticipated to remain sufficiently oxygenated preventing septic conditions. Additional ball valves allowed control of sample extraction and the retrieval of graywater for irrigation. Although the flow meter was not a critical component during Phase I, the meter remained within the system configuration. The schematic presented in Figure B-6 depicts the aeration device along with the external recycle pump. In association with the schematic, Figure B-7 presents site photographs of the Phase I configuration.

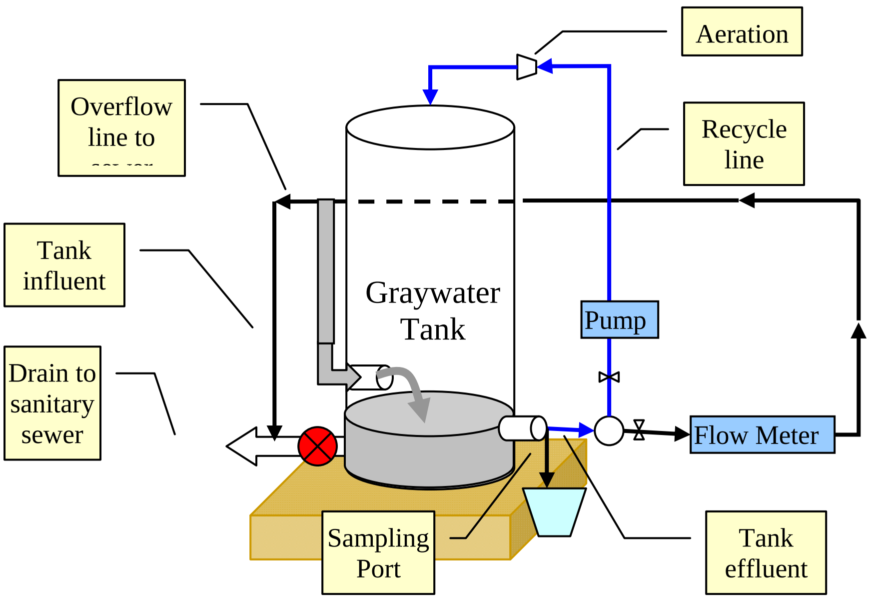

Figure B-6: Phase I* Graywater *System Schematic

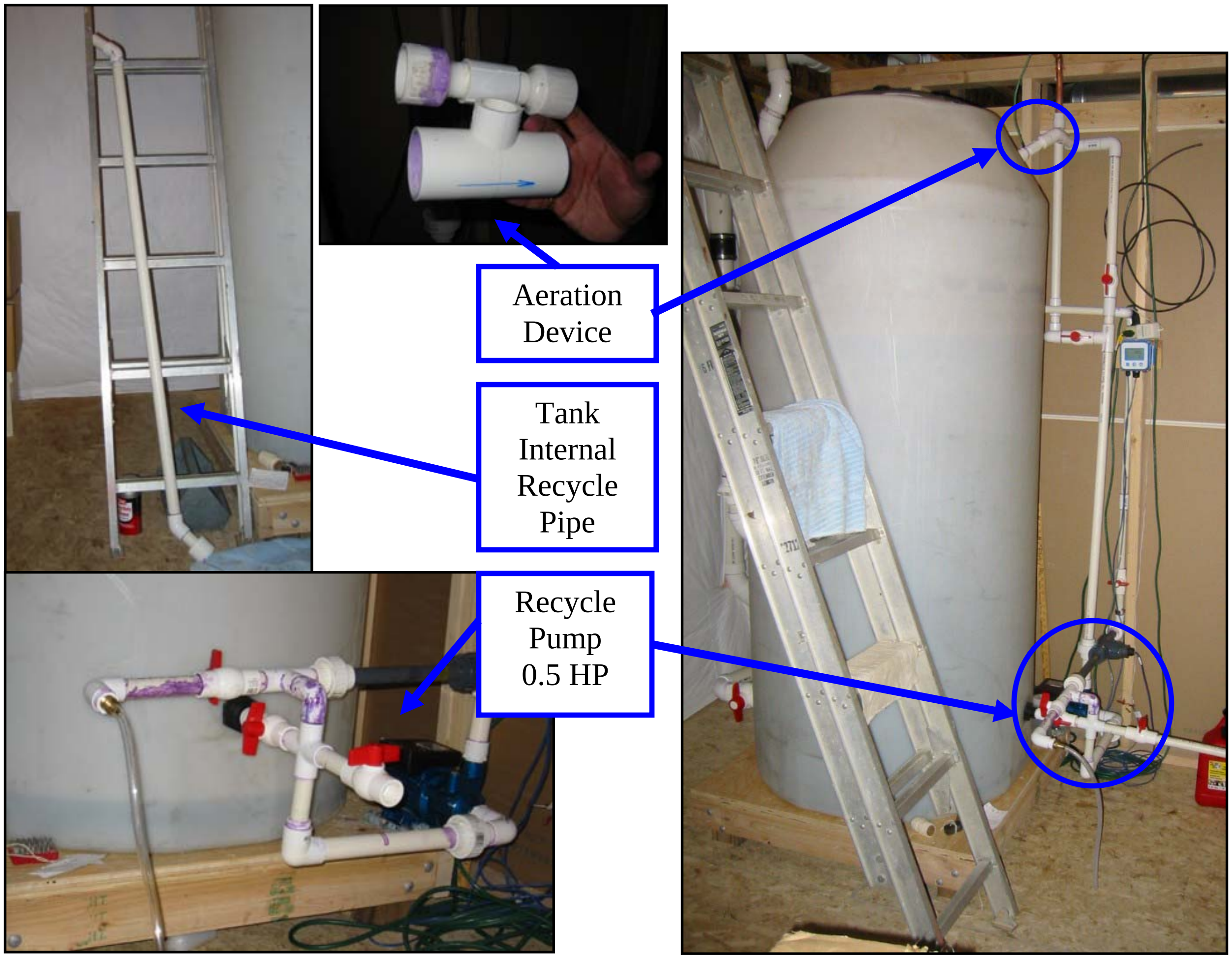

Figure B-7: Phase I Configuration Photographs

A Hach colormetric field testing kit was used during Phase I to perform basic chemical water quality analyses for free and total chlorine, dissolved oxygen, Ammonia-N, Nitrate-N and orthophosphate. The HACH kit included 4 color disks (Ammonia-N, Chlorine, Nitrate-N, Phosphate Phosver), powder pillow packs (free chlorine, total chlorine, ammonia salicylate, ammonia cyanurate, NitraVer5 nitrate, PhosVer3 phosphate, DO1, DO2, DO3), a thermometer, pH reader, 2 1.0 mL droppers, 2 23 mL square glass bottles, 100 mL demineralized-deionized water, 100mL sodium thiosulfate standard solution, glass dissolved oxygen bottle, 4 plastic sample tubes, clippers, color comparator with long wave attachment, dissolved oxygen test solution with sodium azide. Seven grab samples were taken over a course of six weeks and analyzed offsite with the exception of dissolved oxygen.   The results showed water quality ranges consistent with those found in the literature and comparable residential studies.

HACH colormetric test kit results

Parameter	**Range**
pH	6.5 – 7.8 (Units)
Free Chlorine	0.0 mg/L
Nitrate	0.5 – 4 mg/L
Ammonia-N	0.28 – 1.64 mg/L
Phosphate	0.08 – 1.67 mg/L
Dissolved Oxygen	0.0 – 0.8 mg/L

A comparison of the water quality ranges to those found in the literature review shows values consistent with other comparable residential studies. Since the water quality results were within expected ranges and the primary concern expressed by local health authorities was human health risks, research focused on collecting microbiology data for the duration of the experiment.

Phase II Configuration: Aeration and Filtration

Additional treatment of the graywater was achieved by adding a filtration component to the pilot system on August 18, 2003. A Hayward sand filter and pump assembly were purchased from a local pool supply store and integrated into the system. However, continual filtration did not commence until October 7, 2003. Before this time, the sand filter was only operated during watering of the turf plots and outdoor landscape features. A comprehensive discussion of the turf experiment is included within the appendices. Installation of the sand filter and pump (pump

2) required reconfiguration of the system. The sampling port remained at the tank outlet where samples were representative of ambient tank graywater quality. In order to properly install the sand filter and allow for manual backwashing of the filter media, the recirculation line was modified as shown in Figure B-8. Maintenance of the sand filter required back flushing of the filter media as head pressure was observed to drop over time. Site visits of three or more times per week ensured adequate filter backwashing. Photographs of the system configuration in Phase II are provided in Figure B-9 below.

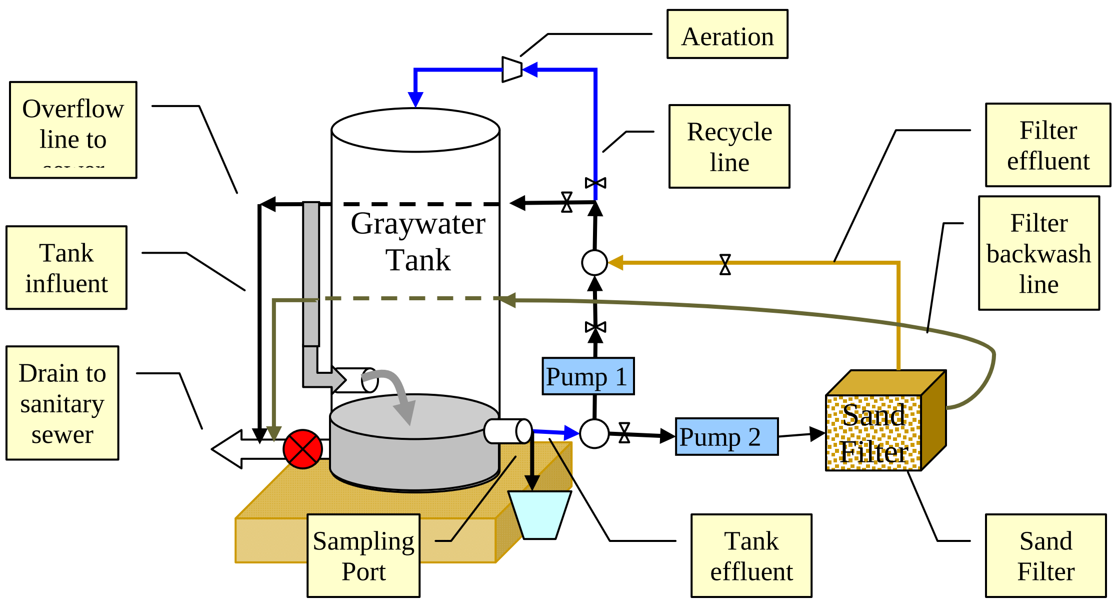

Figure B-8: Phase II Aeration and Filtration System Schematic

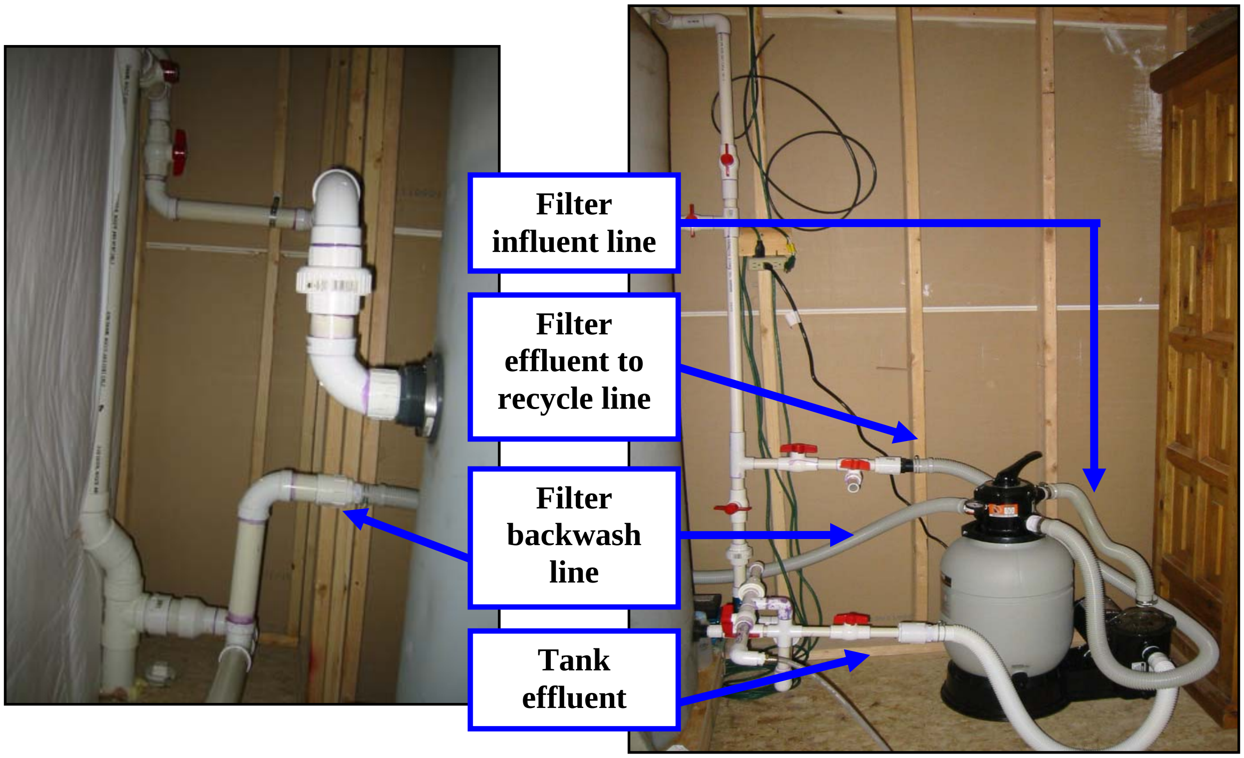

Figure B-9: Phase II Configuration Photographs

Samples collected during the sand filter portion of the experiment once again focused on microbiology. It was anticipated that filtration of the graywater would decrease the microbial populations residing in the graywater tank. Filtration was also expected to improve graywater aesthetics by removing particulates.

Phase III Configuration: Aeration, Filtration and UV Disinfection

Phase III represents the highest level of system complexity since it incorporated an ultraviolet (UV) disinfection unit on December 21, 2003. A UV disinfection system capable of treating the entire 300 gallon tank was acquired. Extensive reconfiguration of the plumbing occurred to incorporate the UV unit into the tank circulation flow path. UV disinfection is placed after the filter in an effort to minimize solids accumulation while maximizing the depth of UV penetration. Critical to the appropriate level of UV treatment was maintaining a flow rate consistent with the desired level of bacteria kill. The flow sensor was incorporated before the UV unit to ensure the flow rates were within desired treatment ranges. Figure B-10 and Figure B-11 presented below provide a schematic representation of the system configuration along with site photographs.

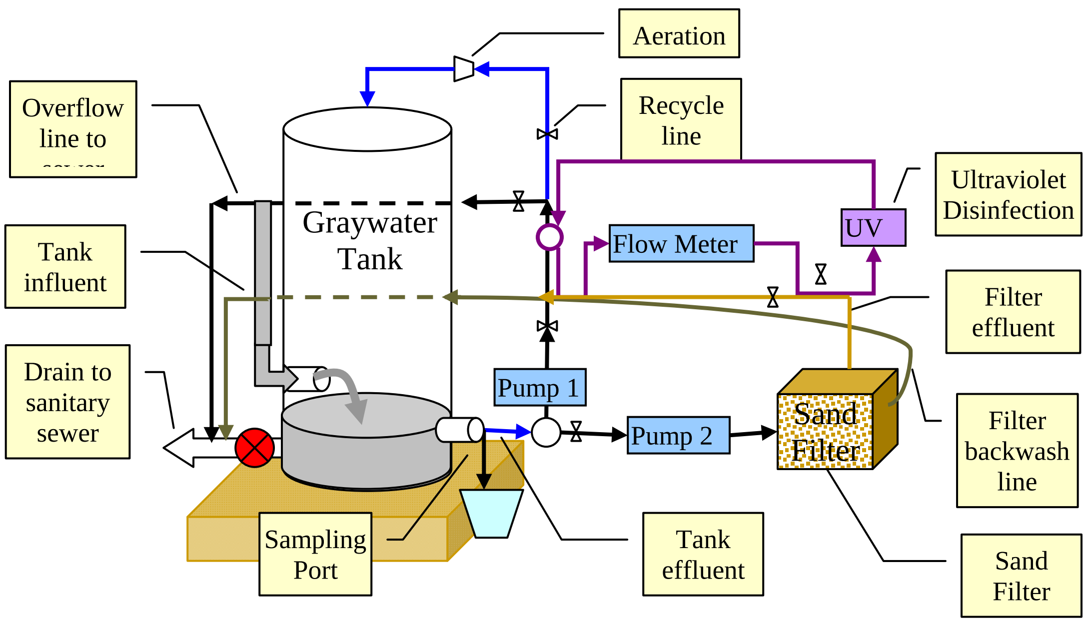

Figure B-10: Phase III Aeration, Filtration and UV Treatment System Configuration Schematic

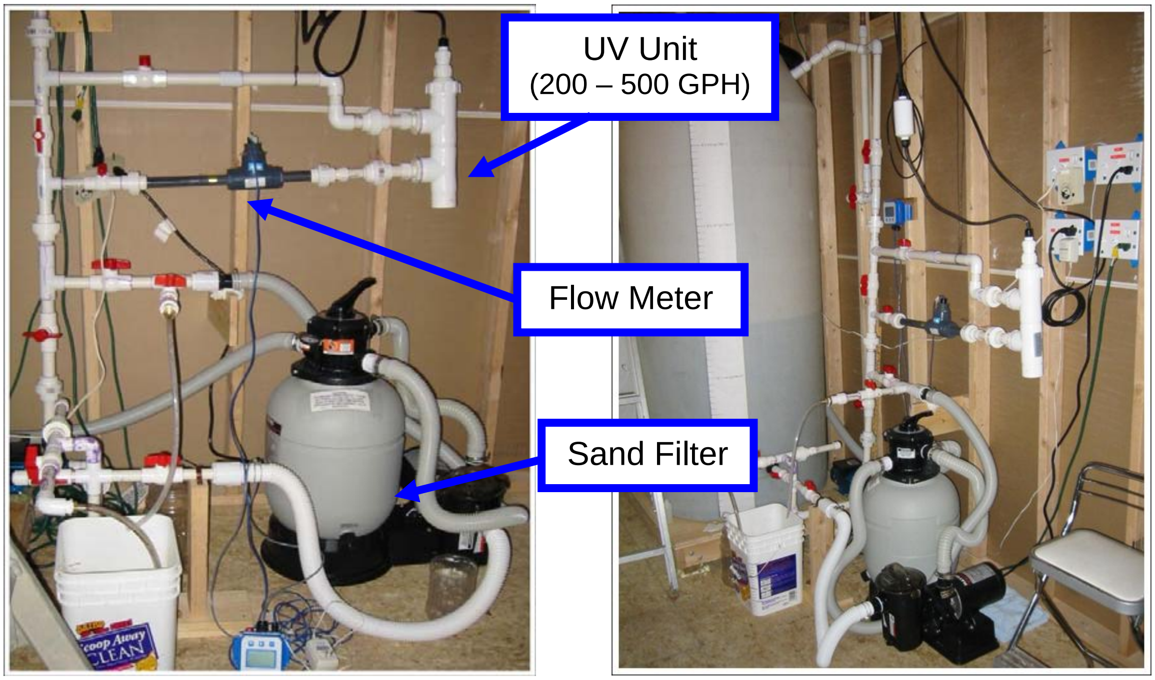

Figure B-11: Phase III System Configuration Photographs

Phase IV Configuration: Aeration and UV Disinfection

Phase IV involved removing the sand filter from the treatment train leaving the UV unit as the primary means of graywater treatment. The sand filter was taken off line on March 1, 2004. The objective was to investigate whether UV treatment alone was capable of providing substantial water quality treatment.

The system piping was modified once more to accommodate UV treatment into the process train. Figure B-12 depicts a schematic representation of Phase IV configuration.

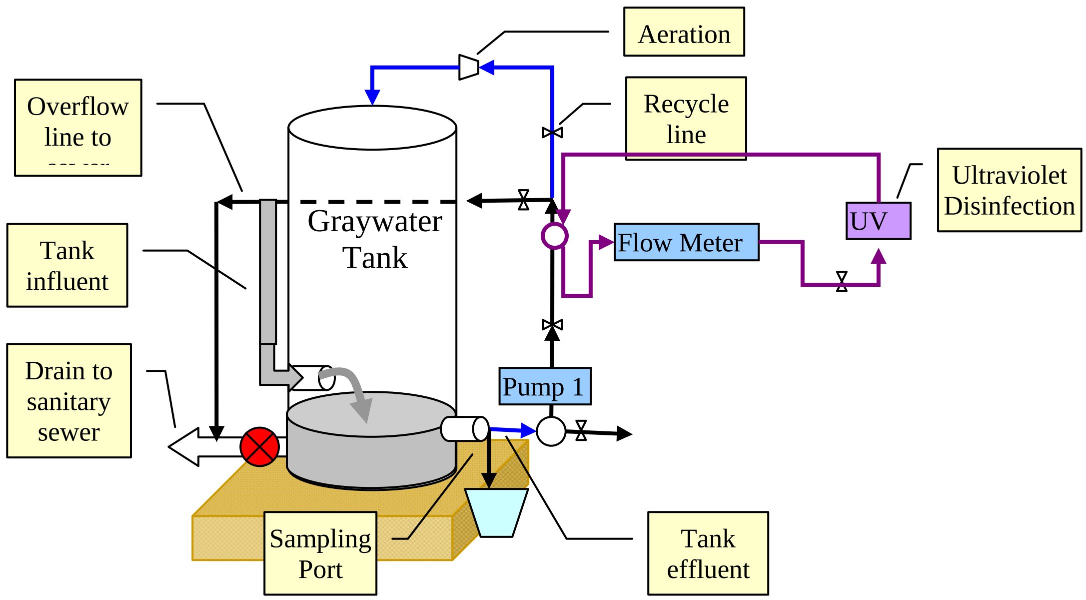

Figure B-12: Phase IV System Configuration Schematic

An air compressor and 12-inch air stone were incorporated into the system on March 13, 2004, to assist with a persistent oxygenation issue. The air compressor remained as a system component until the end of the pilot study.

OBSERVATIONS

With each site visit, notes were taken documenting changes in demand and potential stresses on the graywater system. The notes included tank level, visual inspection of water quality, and presence of noticeable odors. System responses to changes in demand were noted particularly during temporary increases in the number of residents and conversely during times when the homeowners were not home for longer than several days. Additional impacts to system functionality included inadvertent interruptions in operations, for example, a valve was not opened after performing routine system maintenance.

General Observations

Overall the graywater visual quality fluctuated between slightly cloudy and a graywater depth of vision for several feet to large flocculant conglomerates suspended in graywater with close to zero visibility. Periodic pictures were taken to document visual changes in the water quality with the intent of pairing pictures with microbiology and an understanding of the physical system status.

Another subjective qualitative observation was collected based upon odors off-gassing from the tanks water surface. During times of high visual quality, the odors were also minimal and not offensive as would be expected. When a system problem arose the graywater odor increased within a very short time frame most frequently when a recirculation or aeration process failed.

Microbial films were observed throughout the system and during all phases. The storage tank developed varying degrees of film thickness throughout the study. Systems failures in recirculation allowed the build up of microbial films. Twice the tank was completely drained down as part of a system phase change as well as due to a system failure that caused excessive tank fouling. Incorporating process elements into the system required physically connecting into the pipes. Whenever a connection or reconfiguration was needed film was always observed on interior pipe surfaces. Also, the port used to extract graywater samples for microbiology testing formed black mottling after the course of several weeks.

Observations were also made regarding contributing graywater flows related to household use fluctuations. In particular, when the residents were away for time periods extending more than two days and also when house guests were present, there were increasing flow loads to the system. A total of five times over the course of the pilot study the residents were not contributing to the system. On one of these occasions, the tank was emptied completely and the treatment processes were shut down temporarily. In addition to observing system changes related to low graywater production, there was an opportunity to observe changes during a large variation of flow loads due to an influx in house guests over a seven day period.

Individual System Phase Observations

Phase I Observations (August 14, 2003 – October 7, 2003)

Throughout this phase of the pilot study there was a consistent issue with aeration addressed by introducing a recycle pump and modifying the recycle line to extend several feet into the tank. Extending the recycle line was needed to improve the rate of water circulation in the tank and to introduce dissolved oxygen at lower depths. Oxygenation of water passing through the recycle line was accomplished through insertion of a constructed venturi constriction into the pipe. The water surface is turbid when the recirculation line is operating properly.

Phase II Observations (October 7, 2003 – December 31, 2003)

Introduction of the sand filter into the treatment train caused significant modifications to the system configuration. The system complexity was expanded to incorporate shut off valves for directing flows and providing a means for removing system elements. The filter was incorporated into the project on August 20, 2003, before continual operation began in order to support turf irrigation with both filtered and unfiltered graywater. Graywater was actively used for irrigation during the initial month of Phase II. However, once the growing season ended the tank was manually drawn down on a bi-weekly basis to simulate graywater re-use.

- The residents were away from November 7, 2003, to November 16, 2003, during which the tank was monitored for qualitative fluctuations and one microbiology sample was taken.
- The tank reached overflow capacity on November 20, 2003, and therefore any new flow was being directed to the sewer. The graywater quality was not changing in response to household contributions for two weeks.
- Also, at this point in time aeration and recirculation through the venturi constriction was not providing sufficient graywater circulation at full tank depth as indicated by the lack of water bubbling at the surface. The sand filter Hayward Pump was used to backwash the filter as well as backwash the recycle line to dislodge any significant microbial biofilm build up.

Phase III Observations (December 31, 2003 – March 1, 2004)

Addition of the UV disinfection unit into the pilot system involved extensive system modifications for ensuring flows through the unit were adjustable and isolation of the unit was possible. The following observations were noted during this phase of the pilot study:

- Tank is not circulating adequately between the end of January and into Phase IV. Installation of the UV disinfection unit may be compromising the effectiveness of recirculation. The tank water level is to be maintained at 36 inches rather than 48 inches to assist in circulation. Phase III had issues with recirculation and aeration requiring varied means of backwashing and air sparging.
- Tank is manually drained down on January 20, 2004.
- The resident backwashed and flushed the system on February 17, 2004 in response to dissolved oxygen and recirculation concerns. The recirculation pump was used to

backwash the recirculation line with the valve to the sand filter left open. As a result a large amount of debris and dendritic growths were introduced to the tank that may have settled out of the water. Air sparging of the sand filter may have helped to loosen the filter media and decrease clogging also providing improved filtration. A site visit the following day shows bubble profusion at the water surface greatly improved, visibility to two feet with large flocculated masses two to three inches in diameter on the surface. By February 21, 2004 the water is much clearer with reduced particulates and surface foam.

- UV is inadvertently turned off from February 18, 2004, until February 21, 2004.
- Electric junction box constructed for appropriate management of treatment process equipment.
- No graywater contributions from February 27, 2004 until March 1, 2004.

Phase IV Observations (March 1, 2004 – May 16, 2004)

The next system phase removed the sand filter from the treatment process train and monitored the efficacy of UV treatment on the graywater. The UV bulb was inspected on several occasions with the expectation that increase maintenance would be required since the graywater was no longer pre-treated through the sand filter. The following observations were noted during this phase of the pilot study:

- Removal of the sand filter revealed completely anaerobic conditions within the media and associated odors were consistent with anaerobic microbial communities. A microbial film was observed throughout the sand filter pipe network.
- The introduction of an air compressor and air stone on March 13, 2004, improved visual water quality by March 15, /2004, observations indicated a decrease in surface film build up.

- The system load was greatly increased from April 10, 2004, to April 16, 2004, due to a rapid increase of residential inputs from house guests. Concurrently, UV was unintentionally turned off from April 9, 2004, to April 11, 2004. The tank had rapidly fouled by April 11, 2004, with a dense foam layer on the surface, grey colored water, and a strong septic odor.
- On May 3, 2004, sample retrieval was impeded and the tank effluent valve was left in the closed position. Difficulty in extracting sample from the effluent pipe may have been due to the high level of large solids residing in the tank which may have settled into the tank outflow port. By inadvertently leaving the tank effluent valve in the closed position flow was neither recirculated nor treated through the UV disinfection system. Qualitative inspection of the tank water quality revealed excessive microbial growth on tank sides. The large dark clumps of solids are residing at lower water depths, and visual depth is less than twelve inches with musty odors. Inspection of the UV bulb did not show any significant build up as a result of stagnant water conditions. On May 16, 2004, the tank lines were back flushed with potable water to induce scouring and declogging of distribution pipes. Within two days, the water quality was vastly improved, visual depths had increased to two feet, solids were decreased and odors were minimal.
- May 16, 2004, UV treatment was elected to remain off and recirculation using pump two was stopped for the duration of the pilot study. Although, the air compressor remained operational during this time frame, and the system was returned to the Phase I treatment scenario with an improved oxygenation source. At this point in time sufficient data have been collected on all phases of the prototype system and analysis of the data was needed before refining the experiment.

- The residents were not generating any graywater for the following time periods during this phase:

  May 19, 2004, to May 26, 2004
  June 5, 2004, to June 12, 2004
  June 25, 2004, to July 2, 2004
  July 7, 2004, to July 11, 2004

- The tank is emptied and the air compressor is turned off from June 25, 2004, until July 2, 2004 because both the residents and researchers were not available to conduct sampling, observations and maintenance of the graywater system. Collection of data was completed as of June 25, 2004 for this phase of the research project.

METHODOLOGY

Throughout all phases of the pilot study, graywater samples were collected and analyzed for the presence of indicator bacteria. Levels of Eschericia coli (*E. coli*) and fecal coliforms contamination in the graywater effluent were selected as the indicator bacteria in order to compare results to public health and safety criteria associated with potential human exposure.

Sampling Plan

Samples were collected from the graywater tank on a weekly basis. The tank effluent line prior to entering any of the physical processes was the main collection point. A few samples were extracted directly from the waters surface simultaneously as the sampling port to provide greater insight into whether the water had distributed microbial populations.   Samples beyond those regularly scheduled were taken when qualitative water quality observations indicated a microbiological change.

Sample Collection and Processing

Graywater samples were collected in plastic bottles that had been washed in high heat water and labeled with magic marker. Two samples were taken on each collection day. The cap was removed, effluent sampling port opened and allowed to run for several seconds before placing the mouth of the bottle into the effluent stream. The bottle was filled to the top, and the cap replaced immediately. Once the bottle was secured, the samples were taken to the CSU Environmental Health and Safety (EHS) microbiology lab, for analysis within six hours of collection. During April redundant sampling was performed and eight samples were tested by both EHS and the CSU Engineering Research Center (ERC). The samples were processed in accordance with American Society for Testing Methods (ASTM) testing procedures for Fecal Coliform and *E. coli*. Plating techniques result in four separate counts for indicator bacteria: Total Heterogeneous Plate Count (THPC), Total Coliforms, Fecal Coliforms and *E.coli*. Total Coliforms are comprised of various species that can be used to broadly assess pathogens of concern for human contact. Under the total coliform group bacterial species are *Escherichia*, *Enterobacter*, *Klebsiella* and *Citobacter*. Fecal coliforms are represented by *Escherichia*, *Klebsiella* and *Citobacter* and comprise 60 to 90% of the total coliforms. *Escherichia*, predominantly *E. coli*, comprises 90% of the fecal coliform category.

RESULTS AND FINDINGS

Two distinct areas of interest for the pilot study included the investigation of bacteria levels present in residential graywater as well as the assessment of system implementation ease in relation to the average homeowner.

Microbiological Data Interpretation

The microbiology data collected for all phases of the pilot study are presented in Table B-3 below. Each graywater sample was measured for THPC, Total Coliforms, Fecal Coliforms and *E. coli* bacteria counts. The measurement of these classes of indicator bacteria was used to quantify the health risk associated with potential human contact. Since the bacteria counts for Fecal coliforms and *E. coli* are considered indicator bacteria, collecting the THPC and Total Coliform counts can be used to compare to Fecal Coliform and *E.coli* counts and determine if other bacterial populations may be dominating the microbiological community. Typically, there is a decrease in bacteria counts from THPC, to Total Coliforms, to Fecal Coliforms to *E. coli*.

The Colorado State Board of Health standards for Individual Sewage Disposal Systems (ISDS) that protect against direct human contact are measured based upon Fecal Coliform counts per 100 mL. The Fecal Coliform column has been highlighted in Table B-3 since the graywater system is currently categorized as an ISDS in Colorado which mandates an effluent standards for Fecal Coliform of a geometric mean of any five consecutive samples not to exceed 25 per 100/ mL and any single sample may not exceed 200 per mL. Columns have been added to the data table clearly showing the system phase and associated treatment processes along with notations when system failures occurred and graywater loading changed.

The Tank Full note indicates that the tank was operating at capacity with contributing graywater overflowing directly to the sewer. The Zero Addition note flags dates when the residents were not home for periods of more than two days. During the residents' absence, graywater was removed from the tank according to either the plant watering schedule or a simulation of this activity; however, there were no new graywater contributions.

Table B-3: Graywater Microbiology Data

Sample Date	Total Plate Count *(#/mL)*	Total Coliforms *(#/100mL)*	**Fecal Coliforms *(#/100mL)***	*E. coli* *(#/100mL)*	Phase	Process Failures/Tank Load Changes	
8/14/2003	9,100,000	4,000	**2,000**	1,200	Phase I Aeration		
8/26/2003	162,000	1,800,000	**166,000**	166,000			
9/9/2003	210,000	1,700,000	**310,000**	250,000			
9/15/2003	1,600,000	1,200,000	**1,900,000**	1,500,000			
9/25/2003	260,000	200,000	**200,000**	200,000			
10/7/2003	2,300,000	3,200,000	**30,000**	30,000			
10/16/2003	2,500,000	3,000	**53,000**	53,000	Phase II – Filtration, Aeration		
10/23/2003	5,800,000	1,600	**28,000**	28,000			
10/29/2003	1,400,000	1,970	**<1**	<1			
11/5/2003	940,000	490	**<1**	<1			
11/12/2003	67,000	770	**<10**	<10			
11/20/2003	10,000	110,000	**1,600**	1,500		Tank Full	
12/4/2003	100	180	**<10**	<10			
12/29/2003	11,200	6,500	**2**	2			Zero Addition
1/14/2004	7,000	5,000	**100**	100	Phase III – UV, Filtration, Aeration		
1/21/2004	34,000	14,000	**<1**	<1			
1/29/2004	29,000	90	**90**	<1			
2/5/2004	78,000	>30,000	**970**	<1			
2/12/2004	250,000	34,000	**1,000**	<1			
2/18/2004	860,000	2,600	**<1**	<1		UV	
2/25/2004	670,000	1,800	**75**	<1			
3/4/2004	320,000	3,500	**10,000**	1	Phase IV – UV, Aeration (air compressor)	Aeration	
3/10/2004	170,000	100,000	**12,000**	<10			
3/17/2004	210,000	800,000	**<1**	<1			
3/25/2004	530,000	480,000	**1,000**	<1,000		UV	
4/5/2004	195,000	150,000	**260**	<10			
4/12/2004	350,000	79,000	**24,000**	2000		UV	
4/13/2004	57,000	6,000	**460**	<10			Excess Load
4/15/2004	67,000	38,000	**8,200**	<1			
4/22/2004	193,000	110,000	**400**	<10			
5/3/2004	2,700,000	3,500,000	**8,200**	100			
5/6/2004	1,700,000	110,000	**3,300**	300			
5/27/2004	1,700,000	1,400,000	**79,000**	67,000	Aeration (Air Compressor)		
6/3/2004	95,000	3,700	**300**	<1			Zero Addition
6/9/2004	210,000	25,000	**130**	<10			
6/17/2004	670,000	110,000	**3,800**	100			
6/23/2004	540,000	100,000	**7,900**	1			Zero Addition
7/7/2004	3,900,000	1,000,000	**21,000**	5,000			

One clear instance of an excess load to the system is identified in the Table which occurred from April 10, 2004, to April 16, 2004, when the home was occupied with four to eight people.

A number of microbiology data points are reported as having less than (<) values. Under these circumstances, the dilution and plating technique performed in the laboratory produced microbial population growth, but were unable to be counted. Values reported with this notation are assigned the associated numerical value. Three dates are highlighted in Table B-3 when the microbiology testing results was counter intuitive to bacteria classification. On 10/16/2004 and 10/23/2004 the Fecal Coliform count exceeded the Total Coliform count. The sample taken on 3/17/2004 resulted in Fecal Coliform values greater than one although the Total Coliform counts were 8.0×10^5 Discussions with EHS laboratory staff determined that these values should have been quantified rather than assigning a greater than one value.

Phase I had the highest Fecal Coliform count on 9/15/2003 of 1.9×10^6, which was an order of magnitude greater than the next largest value. It should be noted that this Fecal Coliform bacteria constituent value is larger than the THPC and Total Coliform counts. Overall, the data collected in Phase I which utilized aeration for the primary treatment process, returned the largest microbial counts. Other system phases had Fecal Coliform values ranging over four orders of magnitude from 10^5 to 10^1.

Isolating the Fecal Coliform data column, the graywater bacteria quality was significantly improved between Phase I and Phase II. Comparing Phase II and Phase III, there was not a noticeable difference in Fecal Coliform counts. Conversely, Phase IV had microbial values consistently greater than those in both Phase II and Phase III. During Phase IV, the sand filter was removed leaving UV and aeration to provide graywater treatment. Phase IV also represented a time period in the system operations with the greatest challenges. The system was subjected to excessive graywater contributions up to three times beyond the design capacity; UV disinfection had two separate failures, and aeration problems continued to persist. Throughout Phase IV, the visual water quality was poor.

Once the UV component was removed from the system, aeration with the air compressor remained as the primary means for treating the graywater. Microbiology samples were taken during the end of the study to monitor any notable response to a time period of low graywater generation coupled with basic treatment. The 5/27/2004 sample was taken the day after the residents returned from an extended absence when the Fecal Coliform count was observed to elevate from 3.3×10^3 per 100 mL to 7.9×10^5 per 100mL.

Graphical presentation of microbial data for *E. coli* and Fecal Coliform are presented below in Figure B-13 and Figure B-14 respectively. Both figures plot bacteria counts per 100 mL for each sample date, indicate the system Phase, and track the treatment processes in operation. Figure B-13 includes a reference line delineating the Colorado Department of Public Health and Environment (Regulation 31, March 2001) recreational classification numerical value for water quality Class 1a and 1b (primary contact) *E. coli* counts of 126 per 100 mL and 205 per 100 mL respectively. Under this classification the exposure assumes that ingestion of small quantities is likely to occur. The Class 2 numerical standard of 630 per 100 mL is not included as part of the graphic and represents a classification where there is no primary contact.

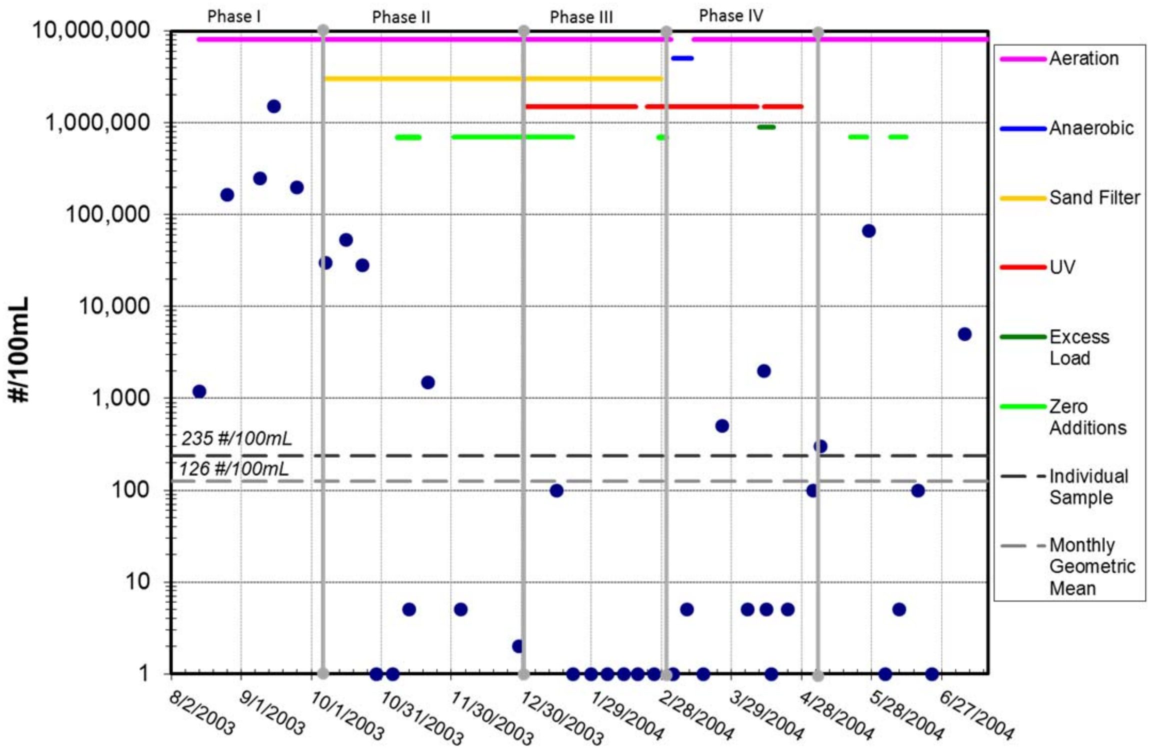

Figure B-13: Pilot Residential Graywater Tank E. coli Results

Figure B-13 shows 24 samples taken during Phases II, III and IV that were tested for *E. coli* would meet the Class 1 recreational water use standards: Five of eight samples in Phase II; all seven samples in Phase III; eight of eleven in Phase IV. Phase III has consistently low *E. coli* results. Looking at the other data points there is a trend of the results increasing in Phase IV compared to Phase III. Following anaerobic conditions at the beginning of Phase IV, the *E. coli* count is elevated by two orders of magnitude before returning to pre-anaerobic condition levels.

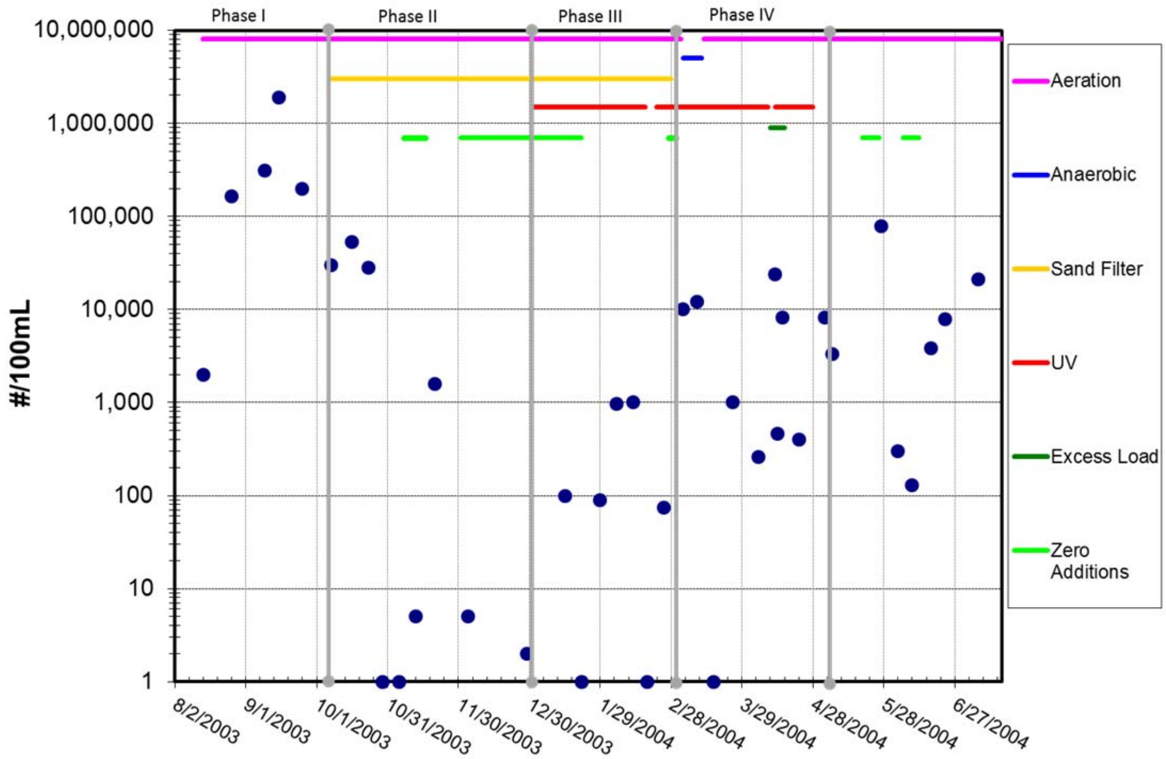

Figure B-14: Pilot Study Fecal Coliform Microbiology

Figure B-14 depicts the Fecal Coliform data measured throughout all system phases. A visual comparison of Figure B-14 to Figure B-13 generally shows a wider range of data scatter for all of the project phases. Phases III and IV have the greatest variance between data plots.

Economic Analysis

Energy usage for the fully implemented system is based upon the City of Fort Collins residential energy rate of $0.056816 per kWh. Each instrument requiring an electric supply is assessed for its energy demand over the installation time period. The total energy costs for all instrumentation used during the residential reuse project is $206.57 for 14 months; an average monthly cost of $14.76. Offsets to this household budget increase are primarily seen as a decrease in water usage.

In addition to energy usage costs, the total materials cost for system construction was assessed as $1,860.34 for the fully implemented system incorporating storage, recirculation, aeration, filtration and UV treatment. Part of these costs included PVC pipes, ball valves and fittings along with electrical junction box installation for managing the power demand from the instrumentation and are estimated to be $150.47. Each time either another phase was incorporated into the pilot project or a system adjustment was needed the tank required plumbing modifications at an average cost of $39. Another significant portion of the costs was the flow monitoring equipment that represents $733.99 of the total project cost. The flow monitoring equipment was used to assess if system recirculation was impeded as well as monitor flow through the UV disinfection unit. During the third phase of the graywater pilot project a new circuit board was added along with switches dedicated to each system component. Costs for installing the circuit breaker and all associated wiring totaled $50.80 and are represented in the total costs. Table B-4 summarizes the materials costs for the pilot project.

Table B-4: Residential* Graywater *Pilot Project Materials Costs

Component	**Cost ($)**	**Description**
Storage	$232.00	300-gallon HDPE Tank
Aeration	$101.90	Air compressor, air stone,pumps
Filtration	$458.15	Sand filter and installation fittings
Disinfection	$144.97	UV system and installation fittings.
Tank modifications	$138.53	Pipe, fittings, valves etc.
Electrical Improvements	$50.80	Circuit breaker, wiring and outlets.
Monitoring	$733.99	Flow Monitoring
TOTAL	**$1,860.34**	

Replication of this residential graywater system could avoid some of the instrumentation and materials costs and realistically be capable of installing a system for $1000 or less excluding the dual plumbing required for graywater collection. The cost of installing a dedicated circuit breaker for the pilot study will likely not be a component of a residential system. Also, the pilot study switched recirculation pumps once the original pump was found to be insufficient for the project. Finally, the monitoring costs of over $700 will not be a component of a residential prototype system. Table B-5 removes these costs and identifies the remaining areas contributing to materials costs.

Table B-5: Adjusted Residential **Graywater** ***System Materials Costs***

Component	**Cost ($)**	**Description**
Storage	$232.00	300-gallon HDPE Tank
Aeration	$66.91	Air compressor, air stone,pumps
Filtration	$458.15	Sand filter and installation fittings
Disinfection	$144.97	UV system and installation fittings.
Tank modifications	$99.67	Pipe, fittings, valves etc.
TOTAL	**$1,001.70**	

By removing these pilot project specific costs a residential graywater system becomes more affordable while providing treatment through aeration, filtration and disinfection processes.

The economic aspect of operating a graywater system is a key component for gaining homeowner acceptance. One of the research objectives of the study was to assess which elements are critical to the system for providing sufficient water treatment while minimizing start up and operating costs. Future work on modifying and optimizing the graywater reuse system will incorporate treatment processes that are cost effective, utilize minimal energy while providing the desired level of water quality treatment.