ON-SITE BIOREMEDIATION: A SOLUTION TO TREATMENT OF GREYWATER

A Thesis
by
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Abstract

ON-SITE BIOREMEDIATION:
A SOLUTION TO TREATMENT OF GREYWATER

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Treating wastewater on site via bioremediation and mechanical methods can save energy by reducing the stress on a large central water treatment facility to process greywater. This greywater can instead be used for various purposes on site. Development of such systems will depend on characterization of this wastewater in order to properly design the system and test its performance. The purpose of this research was to develop and test a greywater system to be used for cleaning greywater from a hair salon.

The system that was tested uses bioremediation, the process of using organisms to consume and break down pollutants. The experimental apparatus is a constructed greywater system using readily available parts. It is unique in that it is exclusively gravity fed with exception of the sump pump to provide the initial input. It is a three-trough system that flows from a top-center trough, then down to two adjacent troughs via aeration siphons. An additional innovation from previous designs was using these siphon outlets from the top to the lower trough, which passively aerates the system.

The study included two phases, a short-term study consisting of four variations, and a 16-day "batch" study. These four variations included (1) a baseline assessment, (2) no plants with only a biofilter, (3) no biofilter with plants only, and (4) a complete system incorporating both plants and biofilter. The baseline assessment provided data on system performance using only the mechanical aspects of the system (siphoning/aeration). The latter trials assessed performance of the system with biological components that included the biofilter and plants. The results showed the system has potential for successful implementation, but that a 48 hour cycle time was not sufficient to bring turbidity and TSS of the greywater (the parameters of primary concern for lavatory reuse) to acceptable reuse standards based on NSF/ANSI 350 and 350-1 onsite water reuse guidelines.

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I would like to extend a special thanks to all who have helped me through this process. Dr. James B. Houser has helped tremendously as both a mentor and a friend throughout this study and it simply could not have been done without him. A special thanks is also extended to Travis Bethmann and Emil DeJong for assistance and much needed company during the course of this study. Additionally, I would like to thank Dr. Marie Hoepfl and Dr. Michael Hambourger for their contributions. The support I received throughout this project has been immeasurable and will never be forgotten.

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CHAPTER 1: INTRODUCTION

Further development of systems to treat and reuse greywater in residential and commercial settings must be pursued and their effectiveness must be evaluated in order to develop a more sustainable pattern of water use. The policy environment regarding greywater reuse is not yet up to date with the technological developments. Because of this lack of policy implementation in the US, technological advances towards greywater systems are mostly found in laboratory settings. If greywater systems can be used to appropriately treat wastewater on site, then the economic and social benefits of using wastewater and of reducing the amount of fresh water consumed can be reaped. Treating wastewater on site via bioremediation and mechanical methods can save energy by reducing the stress on a large central water treatment facility to process greywater. This greywater can instead be used for various purposes on site, also reducing transportation of wastewater. Development of such systems will depend on characterization of this wastewater in order to properly design the system and test its performance. For example, through designing a greywater system for a hair salon, the performance of that system can then be evaluated and transferred to other locations. This study focused on one such designed system and its associated performance.

Statement of the Problem

In many areas of the world clean water is a resource in limited supply. It is the lifeline for nearly every organism on the planet. Because freshwater supplies are limited, conserving and using this resource in a responsible manner will help to ensure water is available for future generations. Most water used in the home or business, except water from toilets, results in discharge of wastewater known as greywater. In developed nations, this greywater is a form of “waste” that is typically discharged directly back into the water treatment system. This historic way of using and discarding fresh water compromises the amount of potable water available to communities. Greywater can be used for many things, such as toilet flushing and irrigation. By using greywater for appropriate purposes, strain on the potable water supply can be relieved. Using greywater for lawns is especially beneficial because the soil is often a better means of purifying water than sending it through a water treatment plant. In addition, this type of greywater reuse requires no chemicals and very little energy to process. The plants remove nutrients that are otherwise wasted. Utilizing greywater is simply a more practical and sustainable method of dealing with used water.

Many businesses, such as dry cleaners, hair salons, and restaurants, have heavy water demands that result in dirty water. This water can be re-purposed and implemented for other purposes without giving a water treatment plant more water to clean. On-site bioremediation is far less energy intensive and can effectively treat greywater for further use. However, there are not enough examples of greywater reuse to help inform policy decisions regarding future implementation of such systems.

Greywater can be characterized by business types based on their water use and outputs. Limited testing has been done to demonstrate potential benefits and expose potential drawbacks involved with on-site greywater treatment. Feasibility of on-site bioremediation technologies must be determined through implementation and testing of systems in order to promote positive greywater policies and to help decrease irresponsible use of drinking water.

Purpose of the Study

The purpose of this research was to develop and test a greywater system to be used for cleaning greywater from a hair salon. The system uses bioremediation, the process of using organisms to consume and break down pollutants. Plants naturally clean water because it is a part of their metabolic pathway. Nutrients, including “waste,” are taken into the roots and the water remaining is then cleaner and less harmful to humans and the environment. In addition the system implements a biofilter which uses beneficial bacteria to further treat the greywater and help break down organic material in the system. By designing a system that can be installed in a business such as a hair salon, the greywater can be treated on site for toilet use and in turn reduce or eliminate the need to use drinking water for this purpose.

Research Hypothesis

Following an established bioremediation strategy for treating wastewater from sinks at a hair salon in Boone, North Carolina, the resulting treated greywater will be acceptable for use as reclaimed water for toilet flushing in North Carolina as measured by:

1. Chemical Oxygen Demand (COD)
2. Dissolved Oxygen (DO)
3. Temperature
4. TSS (total suspended solids)
5. Turbidity
6. pH

Limitations of the Study

This study was limited to treatment of wastewater from one hair salon in the town of Boone, NC. The NSF 350 and 350-1 standards (NSF International, 2016) served as the baseline water quality standard, and this may vary from other standards used in various locations, such as USEPA (United States Environmental Protection Agency [USEPA], 2012) suggested guidelines for reuse. In addition, the system designed was only tested under the conditions of one specific hair salon; therefore, data collected were only representative of similar facilities with similar greywater characteristics.

Significance of the Study

This study may help promote the use of greywater systems in the town of Boone and other areas throughout North Carolina. Responsible business owners and city leaders can use the findings from this study as a basis for considering alternative water use policies in order to help create a more sustainable environment for operation. Hair salons, dry cleaners, and other producers of greywater need to feel confident that such measures are both physically effective and cost effective to pursue. Through demonstrating the performance of this system it may be possible to promote investment in greywater technologies to help with water strains and to reduce wastewater created in certain industries. The practice of not reclaiming greywater is a misuse of resources and is an issue that must be addressed. Reduction of potable water use is highly beneficial to municipal water treatment facilities and good business practice as a whole. This study helps to address critical points of these problems and may pave the way for future implementation of greywater systems.

CHAPTER 2: REVIEW OF LITERATURE

Greywater

According to the United States Environmental Protection Agency (USEPA), greywater (or “gray water”) is “reusable wastewater from residential, commercial and industrial bathroom sinks, bath tub shower drains, and clothes washing equipment drains” (USEPA, 2016, para. 3). It is typically reused on site, usually for landscape irrigation. Using greywater is a form of water recycling that is generally accepted as reusing treated wastewater for beneficial purposes such as agricultural and landscape irrigation, toilet flushing, and replenishing groundwater sources (North Carolina Cooperative Extension, n.d.).

Policies and Codes Governing Reuse of Greywater

USEPA standards.

There are many variations of policy depending on the state in which greywater is planned to be reused. About 30 of the 50 states have regulations pertaining to recycling of greywater (USEPA, 2012). Although there are currently no federal regulations concerning greywater use, the USEPA (2012) has general guidelines pertaining to the suggested type of treatment to be implemented based on its strategy for use. These guidelines are based on principles regarding water quality as per national standards. Appendix A shows the use types and identifies what treatments should be undertaken. Appendix A shows the guidelines for urban reuse and agricultural reuse, reuse for impoundments, environmental reuse, groundwater recharge, and indirect potable reuse.

NSF/ANSI Standard 350 and 350-1.

The standard set by NSF International for greywater reuse systems establishes material, design, construction, and performance requirements for residential and commercial water reuse systems. Compliance with these standards is only *recommended* at this point in time. The standards are known as NSF 350 and 350-1. In addition, water quality standards are provided that align with and / or surpass those set by the USEPA suggested requirements. The standards set by this organization are presented in Table 1, Table 2, and Table 3.

Table 1. *Scope of NSF 350 and 350-1* (NSF International, 2016)

NSF/ANSI Standard 350: On-site Residential and Commercial Water Reuse Treatment Systems

Building Types	- Residential, up to 1,500 gallons per day - Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	- Combined black and greywater - Bathing water only - Laundry water only
Effluent Uses	- Non-potable applications, such as surface and subsurface irrigation and toilet and urinal flushing
Ratings	Two classifications that vary slightly in effluent quality: • Class R: single-family residential • Class C: multifamily and commercial Systems are further described based on the type of influent (combined, graywater, bathing only, laundry only).

Table 1. (Continued) *Scope of NSF 350 and 350-1* (NSF International, 2016)

NSF/ANSI Standard 350-1: On-site Residential and Commercial Graywater Treatment Systems for Subsurface Discharge	
Building Types	- Residential, up to 1,500 gallons per day - Commercial, more than 1,500 gallons per day and all capacities of commercial laundry water
Influent Types	- Combined black and graywater - Bathing water only - Laundry water only
Effluent Uses	- Subsurface irrigation only
Ratings	- Single effluent quality with no classifications - Systems are further described based on the type of influent (graywater, bathing only, laundry only).

Table 2. *NSF 350 and 350-1*: *Summary of Influent Greywater Test Water Concentration for Systems Testing Laundry and Bathing Source Waters Combined* (NSF International, 2016, p. 15)

Parameter	Required Range
TSS	80 -160 mg/L
COD	250 - 400 mg/L
Temperature	77 – 95 °F
pH	6.5 – 8.0
Turbidity	50-100 NTU
Total phosphorous	1.0 – 3.0 mg/L
Total nitrogen	3.0 – 5.0 mg/L
Total coliforms	$10^3 – 10^4$ CFU/100mL
E. coli	$10^2 – 10^3$ CFU/100mL

Table 3. *NSF 350 and 350-1*: *Summary of Average Effluent Criteria for Commercial Reuse* (NSF International, 2016, p. 24)

Parameter	Class C requirements
CBOD	10 mg/L
TSS	10 mg/L
Turbidity	2 NTU
E. coli	2.2 MPN/100 mL
pH	6.5 – 8.5

North Carolina Plumbing Code.

North Carolina, like other states, provides individual leeway as to the level of monitoring and types of use permitted for greywater systems. States such as California, New Mexico, Texas, and Arizona have their own state greywater policies that are in some cases more favorable for greywater reuse. According to the *NC Plumbing Code* (International Code Council [ICC], 2012), treated greywater may only be used to flush toilets and urinals, or for subsurface landscape irrigation. These greywater systems must only receive waste discharge from bathtubs, showers, lavatories (bathroom sinks), and clothes washers or laundry trays. Collection reservoirs of such systems must be made of approved durable, nonabsorbent, corrosion-resistant materials and must be closed and gas-tight vessels. Overflow mechanisms must be used, which should be connected to the sanitary drainage system. In addition to these requirements, systems used for urinal flushing and water closets must uphold increased regulations. These include having a collection reservoir that is a minimum of twice the volume of the water required to meet the daily flushing requirements of the fixtures supplied with greywater, and must be no less than 50 gallons in size. Disinfection is required and must be done by an approved method that employs one or more disinfectants such as chlorine, iodine, ozone, or UV light. Because potable water is the source for the greywater system, backflow protection must be implemented. Due to the type of water in the system one must identify and label it clearly as non-potable water. The greywater must be dyed blue or green with food grade vegetable dye before such water is supplied to the fixtures. This is yet another way of identifying and labeling the water type. Finally, in order to implement a greywater system in North Carolina one must acquire a permit and the system must follow in its entirety the *International Plumbing Code* (ICC, 2012).

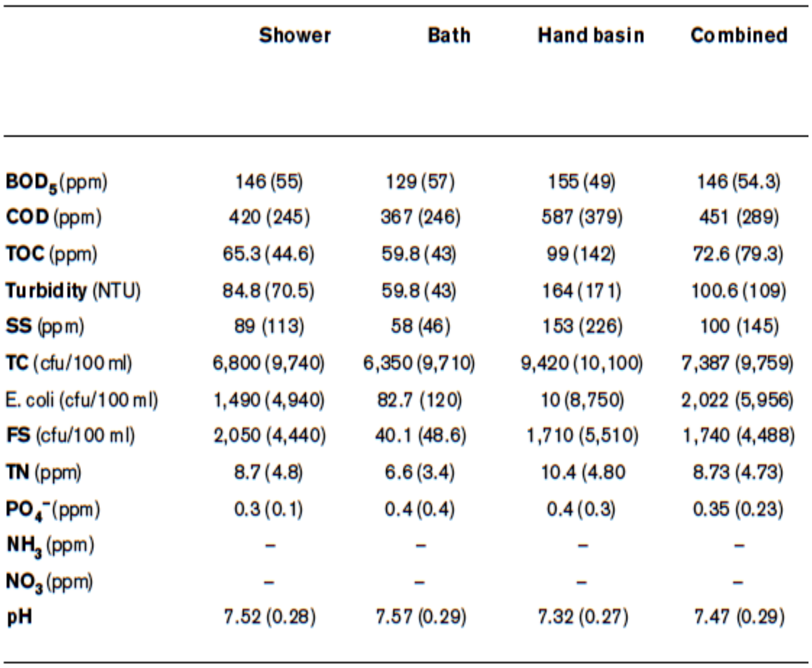
Controversies Surrounding Reuse of Greywater

Greywater reuse has long been a method of conserving water in many countries. Unfortunately, social and economic barriers have risen and have prevented development and integration into current systems. Originally, greywater reuse was a water management technique for areas that face water shortages. Due to public health concerns, energy-intensive centralized treatment facilities overcame the practice of using greywater treatment systems. The emergence of more significant energy and water problems in recent times has forced societies to rethink water management strategies. Reusing greywater is one of the largest savings that could be made to address declining water resources. Areas with arid or semi-arid climates face the tightest water budgets and are being forced to examine potential sources of water available to communities According to Aljayyousi (2003), greywater comprises 50% to 80% of residential wastewater. Reusing greywater saves both water and money. Australia found this amounts to potable water savings to both the consumer and to the state water authority of up to 38% (Water Authority of Western Australia, 1994). As is often true with these types of systems, it is the guidelines and regulations that must catch up with the technology in order to reap full benefits of water reuse systems. The main source of issues lies in the realm of public health. Greywater systems have not been readily deployed because of the risk of human exposure and a general lack of knowledge surrounding greywater quality and acceptable uses. Nations adopt greywater reuse for different reasons, whether it is drought, population, or short-term reactions to water scarcity. Sustainable water use is becoming a priority globally and greywater systems must now be implemented along with the proper regulatory and treatment techniques.

Characterization (Chemical Composition) of Greywater Based on Source

Greywater comes in many varieties. Differences in composition inherently dictate the methods that must be used for treatment. In a study conducted by Aljayyousi (2003), reported mean COD values of greywater varied from 40 to 371 mg/l between sites, with similar variations arising at an individual site (Aljayyousi, 2003). This was attributed to changes in the amounts and variations of inputs from greywater sources. A study by Jefferson, Palmer, Jeffrey, Stuetz, and Judd (2004) described the variations in greywater composition that can be found depending on the type of washing being done, based on data they collected from 102 individuals with varying ages, gender, and washing applications. The results are shown in Table 4.

Table 4. *Comparison of Real Greywater Characteristics* (Jefferson et al., 2004, p. 161)



	Shower	**Bath**	**Hand basin**	**Combined**
BOD_5 (ppm)	146 (55)	129 (57)	155 (49)	146 (54.3)
COD (ppm)	420 (245)	367 (246)	587 (379)	451 (289)
TOC (ppm)	65.3 (44.6)	59.8 (43)	99 (142)	72.6 (79.3)
Turbidity (NTU)	84.8 (70.5)	59.8 (43)	164 (171)	100.6 (109)
SS (ppm)	89 (113)	58 (46)	153 (226)	100 (145)
TC (cfu/100 ml)	6,800 (9,740)	6,350 (9,710)	9,420 (10,100)	7,387 (9,759)
E. coli (cfu/100 ml)	1,490 (4,940)	82.7 (120)	10 (8,750)	2,022 (5,956)
FS (cfu/100 ml)	2,050 (4,440)	40.1 (48.6)	1,710 (5,510)	1,740 (4,488)
TN (ppm)	8.7 (4.8)	6.6 (3.4)	10.4 (4.80	8.73 (4.73)
PO_4^- (ppm)	0.3 (0.1)	0.4 (0.4)	0.4 (0.3)	0.35 (0.23)
NH_3 (ppm)	–	–	–	–
NO_3 (ppm)	–	–	–	–
pH	7.52 (0.28)	7.57 (0.29)	7.32 (0.27)	7.47 (0.29)

(BOD: Biologic Oxygen Demand; COD: Chemical Oxygen Demand; TOC: Total Organic Carbon; SS: Suspended Solids; TC: Total Coliform; FS: Faecal streptococci; TN: Total Nitrogen)

As shown, each source produces its own characteristics, and a greywater system must be designed to accommodate the different chemical composition of the greywater. Greywater qualities vary considerably and the appropriate treatment must be utilized to handle water from each source accordingly. Once treated, greywater has its own use characteristics depending on if it will be used for irrigation or in toilets and urinals. Additionally, characteristics vary by public standard. Public health is a major concern, and greywater is treated accordingly based on its chemical and biological compositions. According to *Characteristics of Grey Wastewater*, a study by Eriksson, Auffarth, Henze, and Ledin (2001), one must conduct a thorough characterization of greywater and source evaluation of the possible sources of pollutants in grey wastewater, before reuse, in order to be able to establish the proper treatment method. Characterization is the foundation on which systems can be developed.

Bioremediation

Approaches to Bioremediation

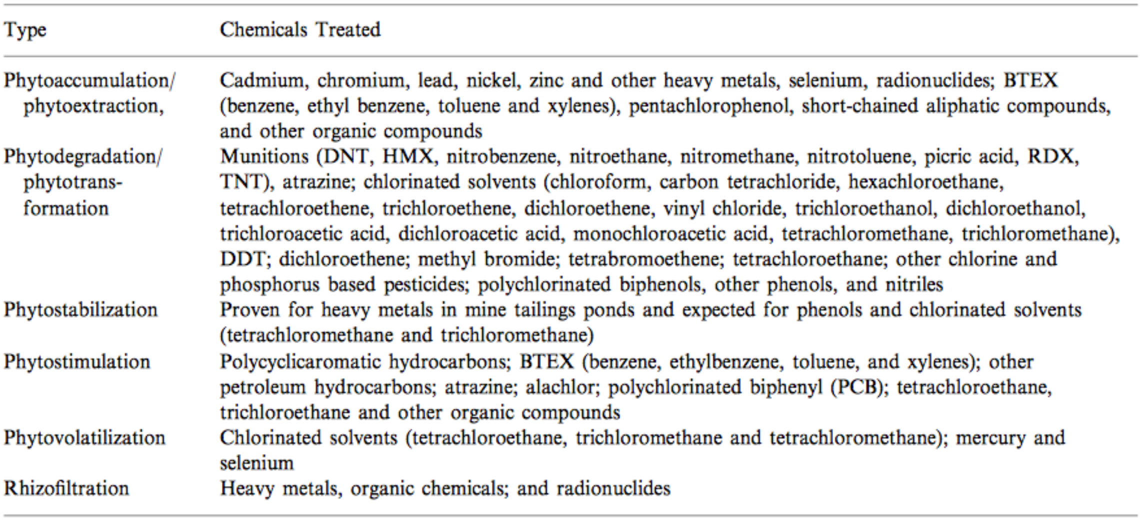
There are many approaches to bioremediation, each having its own advantages depending on the characteristics of the proposed medium to be cleaned. Phytoremediation is a type of bioremediation that depends on plants to degrade, assimilate, metabolize, or detoxify metals, hydrocarbons, pesticides, and chlorinated solvents (Susarla, Medina, & McCutcheon, 2002). There are two basic bioremediation approaches: *ex-situ* and *in-situ*. *Ex-situ* involves extracting and treating a substrate using physical processes such as air stripping and activated carbon adsorption. *In-situ* involves stimulating microbial activity and allowing organisms to perform the remediation process. *In-situ* phytoremediation involves placement of live plants in contaminated surface water, soil, or sediment, or in soil or sediment that is in contact with contaminated groundwater for the purpose of remediation (Susarla et al., 2002). *In-situ* remediation does not require the physical extraction of material and allows a passive approach to be implemented by using plant roots to extract compounds directly from the water to which the roots are exposed.

Types of Plants Used in Phytoremediation

Every plant species has its own range of nutrients/conditions in which it thrives. Because different plant species uptake nutrients in different amounts and in various compositions, one must understand the mechanisms that the plant is undergoing in order to most effectively apply them to a remediation situation. Susarla et al. (2002) differentiated phytoremediation mechanisms with the associated chemicals to be remediated, as seen in

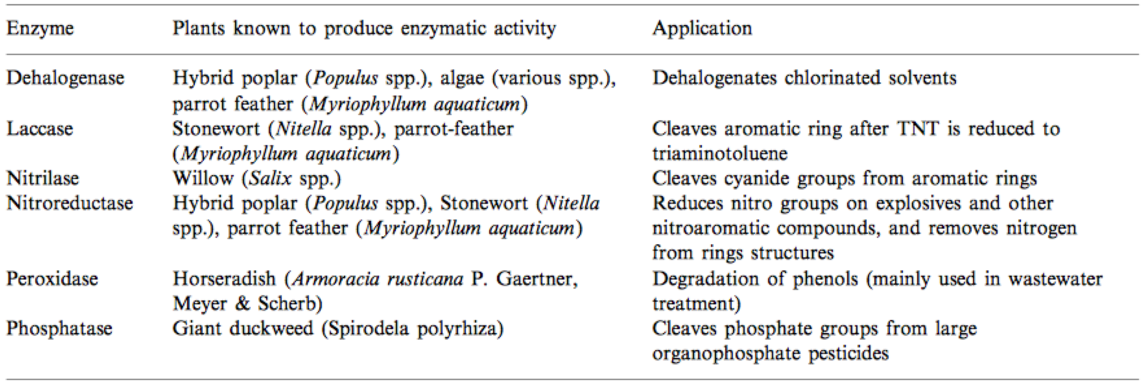
Table 5. In addition to understanding the mechanisms that help to process contaminants, there must be a firm understanding of the enzymes and plant species that will assist in maximizing the desired mechanisms to take place. Using Table 6 and Table 7, one can begin to narrow down the plant species that would most appropriately perform the task at hand. By understanding the characteristics of the greywater, one can then propose an effective plant species to be used for remediation.

Table 5. *Phytoremediation Mechanisms (*Susarla et al., 2002, p. 651)



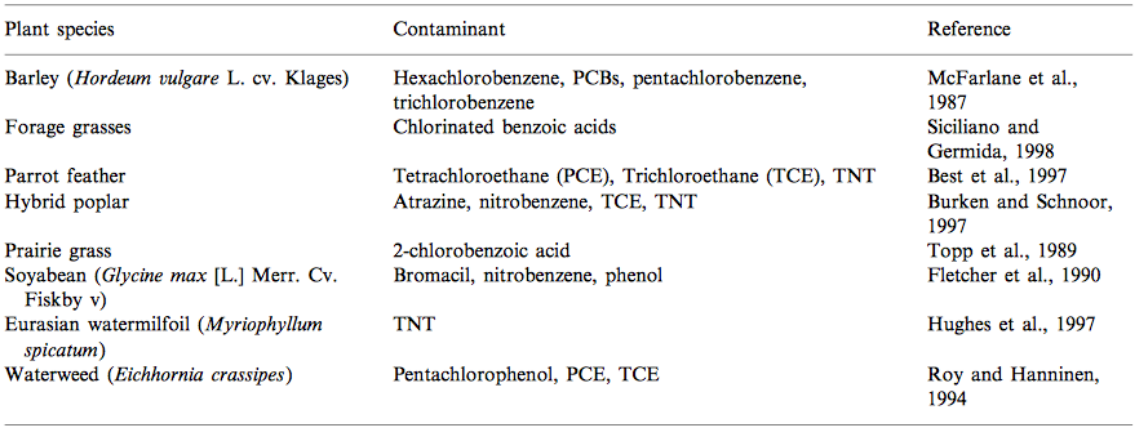
Type	Chemicals Treated
Phytoaccumulation/ phytoextraction,	Cadmium, chromium, lead, nickel, zinc and other heavy metals, selenium, radionuclides; BTEX (benzene, ethyl benzene, toluene and xylenes), pentachlorophenol, short-chained aliphatic compounds, and other organic compounds
Phytodegradation/ phytotransformation	Munitions (DNT, HMX, nitrobenzene, nitroethane, nitromethane, nitrotoluene, picric acid, RDX, TNT), atrazine; chlorinated solvents (chloroform, carbon tetrachloride, hexachloroethane, tetrachloroethene, trichloroethene, dichloroethene, vinyl chloride, trichloroethanol, dichloroethanol, trichloroacetic acid, dichloroacetic acid, monochloroacetic acid, tetrachloromethane, trichloromethane), DDT; dichloroethene; methyl bromide; tetrabromoethene; tetrachloroethane; other chlorine and phosphorus based pesticides; polychlorinated biphenols, other phenols, and nitriles
Phytostabilization	Proven for heavy metals in mine tailings ponds and expected for phenols and chlorinated solvents (tetrachloromethane and trichloromethane)
Phytostimulation	Polycyclicaromatic hydrocarbons; BTEX (benzene, ethylbenzene, toluene, and xylenes); other petroleum hydrocarbons; atrazine; alachlor; polychlorinated biphenyl (PCB); tetrachloroethane, trichloroethane and other organic compounds
Phytovolatilization	Chlorinated solvents (tetrachloroethane, trichloromethane and tetrachloromethane); mercury and selenium
Rhizofiltration	Heavy metals, organic chemicals; and radionuclides

Table 6. *Plant Enzymes That Have a Role in Transforming Organic Compounds (*Susarla et al., 2002, p. 652)



Enzyme	Plants known to produce enzymatic activity	Application
Dehalogenase	Hybrid poplar (*Populus* spp.), algae (various spp.), parrot feather (*Myriophyllum aquaticum*)	Dehalogenates chlorinated solvents
Laccase	Stonewort (*Nitella* spp.), parrot-feather (*Myriophyllum aquaticum*)	Cleaves aromatic ring after TNT is reduced to triaminotoluene
Nitrilase	Willow (*Salix* spp.)	Cleaves cyanide groups from aromatic rings
Nitroreductase	Hybrid poplar (*Populus* spp.), Stonewort (*Nitella* spp.), parrot feather (*Myriophyllum aquaticum*)	Reduces nitro groups on explosives and other nitroaromatic compounds, and removes nitrogen from rings structures
Peroxidase	Horseradish (*Armoracia rusticana* P. Gaertner, Meyer & Scherb)	Degradation of phenols (mainly used in wastewater treatment)
Phosphatase	Giant duckweed (Spirodela polyrhiza)	Cleaves phosphate groups from large organophosphate pesticides

Table 7. *Plant Species Used in Phytoremediation of Organic Compounds (*Susarla et al., 2002, p. 653*)*



Plant species	Contaminant	Reference
Barley (*Hordeum vulgare* L. cv. Klages)	Hexachlorobenzene, PCBs, pentachlorobenzene, trichlorobenzene	McFarlane et al., 1987
Forage grasses	Chlorinated benzoic acids	Siciliano and Germida, 1998
Parrot feather	Tetrachloroethane (PCE), Trichloroethane (TCE), TNT	Best et al., 1997
Hybrid poplar	Atrazine, nitrobenzene, TCE, TNT	Burken and Schnoor, 1997
Prairie grass	2-chlorobenzoic acid	Topp et al., 1989
Soyabean (*Glycine max* [L.] Merr. Cv. Fiskby v)	Bromacil, nitrobenzene, phenol	Fletcher et al., 1990
Eurasian watermilfoil (*Myriophyllum spicatum*)	TNT	Hughes et al., 1997
Waterweed (*Eichhornia crassipes*)	Pentachlorophenol, PCE, TCE	Roy and Hanninen, 1994

Types of Greywater Systems / Components

There are many variations of greywater systems depending on the type of use and the source of greywater being treated. The essential components, however, remain the same, each with a specific purpose and key role in the remediation process (Li, Wichmann, & Otterpohl, 2009). Physical treatments may include a coarse medium to be used as a filtration membrane. This is usually the first step of the treatment process and may involve coarse sand, soil filtration, or a physical filter to help remove sediment and other solids. Chemical treatments, although not as common, can be used in addition to physical treatments in the form of coagulation, photo-catalytic oxidation, and ion exchange. These processes help remove non-organic compounds such as dyes. Perhaps the most important component of a greywater system is the biological treatment process. This is where microbial activity is implemented to reduce organic material as well as to reduce factors such as nitrogen, phosphorus, turbidity and total suspended solids. Regardless of the system type the final step is disinfection, usually via ultraviolet light exposure. The general process is illustrated in Figures 1 through 3. Figure 1 shows the schematic for potential treatment of unrestricted non-potable urban greywater. Figure 2 shows a schematic for a greywater treatment system used for irrigation discharge. Figure 3 shows a schematic for a greywater system that will discharge to water closets and urinals.

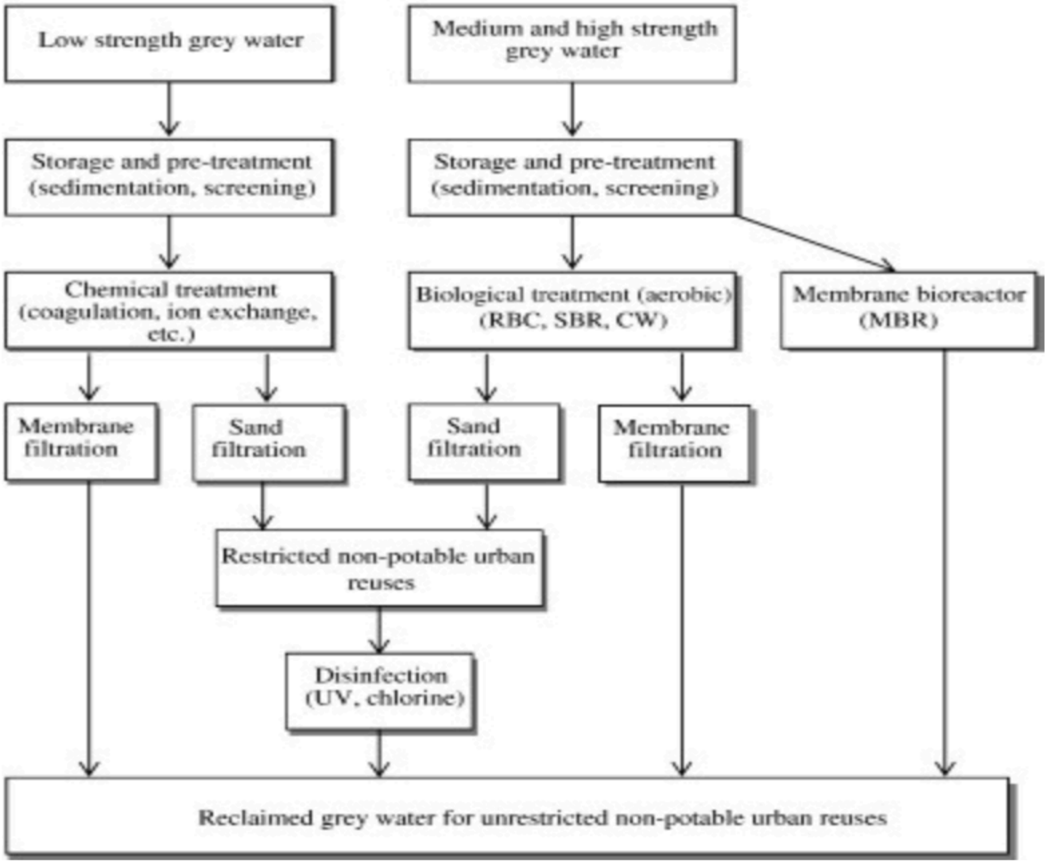


*Figure 1***.** The greywater recycling schemes for non-potable urban reuses. (Li et al., 2009, p. 3447).

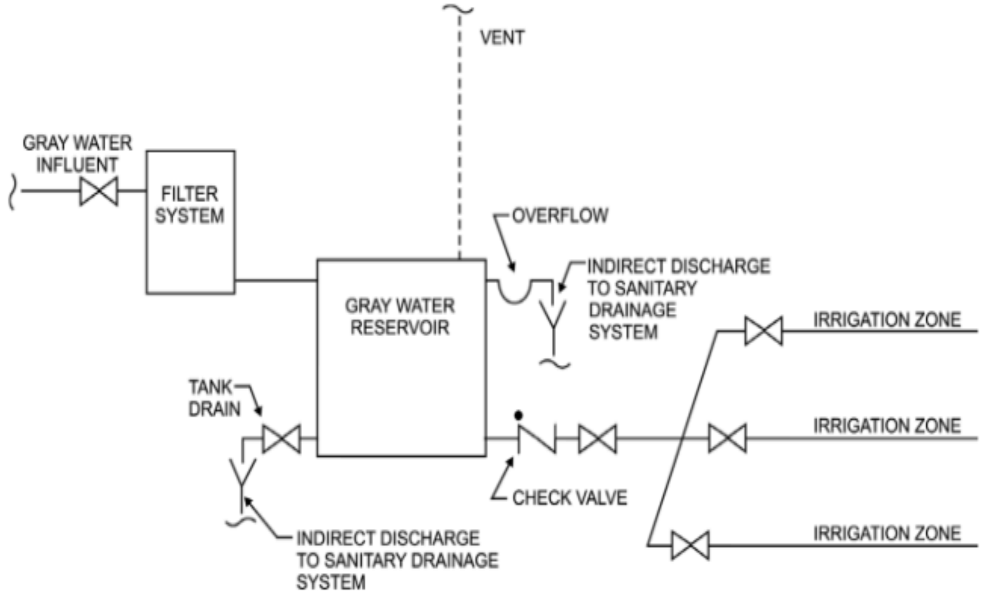


Figure 2. Greywater recycling system for irrigation. (ICC, 2012, p. 107).

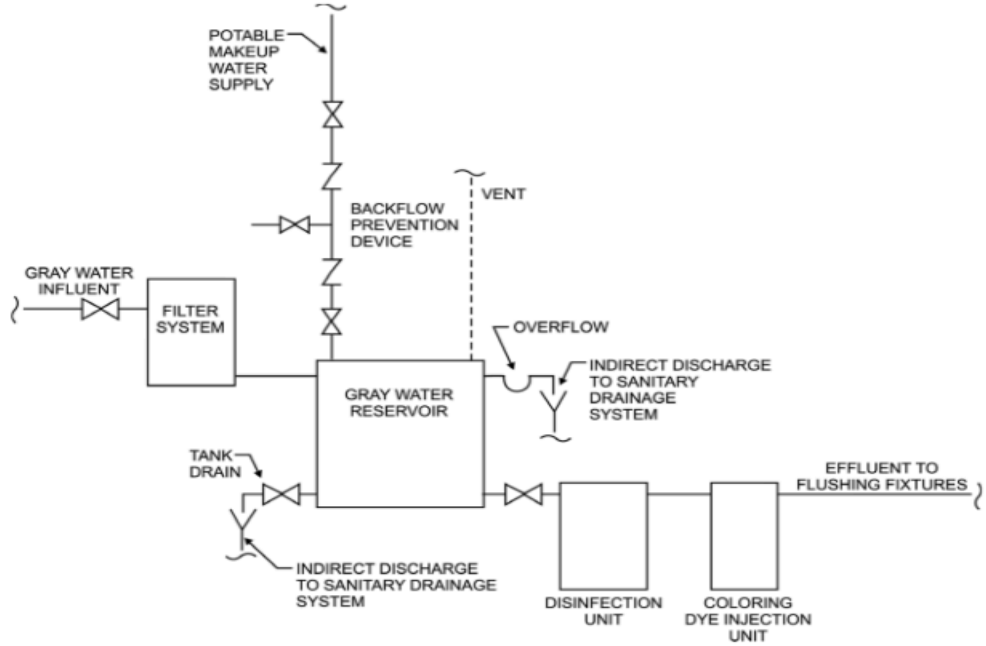


Figure 3. Greywater recycling system for water closets and urinals. (ICC, 2012, p. 108).

Methods for Testing Water Quality

Instruments / equipment.

The methodology used for water quality assessment varies depending on the level of precision that is acceptable for the analysis. In the US one of the most widely accepted procedures is documented by the United States Geological Survey (USGS), which has a published field manual for collection of water quality data (United States Geological Survey [USGS], 2015; see also USGS, 1998.). Each chapter has in-depth resources for the specific component of the study or stage of data collection being performed. Using this methodology insures that proper collection techniques were followed and that samples were not contaminated in the process. This study focused on the collection of water samples from this document. Instrumentation for water quality assessment can vary depending on resources available, but there is a generally accepted set of instruments used that is described by the USEPA (2012). For other standardized procedures, the World Health Organization (WHO) outlines the instruments necessary to measure specific components of water quality (Bartram & Ballance, 1996). Brief descriptions of the instrumentation guidelines are provided as follows.

Temperature.

According to Bartram and Ballance (1996), the temperature must be measured *in-situ* because water temperature will change almost immediately if a sample is taken. It is suggested that the temperature be recorded using a glass thermometer, either alcohol/toluene-filled or mercury filled. An alternative is to use an electronic thermometer of the type that is usually an integral part of a dissolved oxygen or a conductivity meter (Bartram & Ballance, 1996).

pH.

Determination of pH should be done i*n-situ*. Three standard instrument types may be used to measure the pH of a water sample: pH indicator paper, liquid colorimetric indicators, or electronic meters. pH indicator paper is the simplest and least expensive method but is subjective to the user's assessment. Liquid colorimetric indicators change color in accordance with the pH of the water being tested, but again are subjective to the user's assessment. According to Bartram and Ballance (1996), the most accurate and least likely to be altered by chemical properties is the electronic meter, which minimizes interferences such as contamination during collection.

Dissolved oxygen.

There are two accepted methods for determining the dissolved oxygen content of a water sample: the electrometric method using a meter and the Winkler method (Bartram & Ballance, 1996). The electrometric method is suitable for field determination and involves a dissolved oxygen meter and an electrode. The Winkler method uses chemical reagents and titration with sodium thiosulfate solution. The electronic method is more accurate and requires fewer resources to perform the measurement.

Turbidity.

According to the USEPA (2012), the historical method of measuring turbidity has roots based on the Jackson candle turbidimeter. The Jackson candle turbidimeter consists of a special candle and a flat-bottomed glass tube, and was calibrated by Jackson in graduations equivalent to ppm of suspended silica turbidity. A water sample is poured into the tube until the visual image of the candle flame, as viewed from the top of the tube, is diffused to a uniform glow. When the intensity of the scattered light equals that of the transmitted light, the image disappears; the depth of the sample in the tube is read against the ppm-silica scale, and turbidity is measured in Jackson turbidity units (JTU) (USEPA, 2012). However, this method can only measure values down to 25 JTUs. Lower measurements require an updated method. The USEPA (1993) acknowledges electronic nephelometers as the best instrument to be used for low turbidity measurements. The units of turbidity from a calibrated nephelometer are called Nephelometric Turbidity Units (NTU). As with other measurements it is suggested that these measurements be taken *in-situ* to prevent contamination and / or other changes that may vary the turbidity from its true value.

COD.

The accepted method for determining COD is the dichromate method. Bartram and Ballance (1996) describe the chemical oxygen demand using this method as the amount of oxygen consumed by organic matter from boiling acid potassium dichromate solution. It provides a measure of the equivalent of that proportion of the organic matter in a water sample that is susceptible to oxidation under the conditions of the test. The dichromate method has been selected as a reference method for COD determination because of its applicability to wide variety of samples and ease of manipulation (Bartram & Ballance, 1996).

TSS.

Total suspended solids refer to the dry weight of the material that is removed from a measured volume of water sample by filtration through a standard filter **(**Bartram & Balance, 1996**)**. The method described is based on the following conditions: filtering by glass fiber filter (Whatman GF/C grade or equivalent) and drying at a temperature of 103-105 °C for two hours to a constant weight (i.e., a variability of not more than 0.5 mg, according to Bartram and Balance (1996)).

Quality Control

There are many steps to ensure that data quality is acceptable. The *Water Quality Monitoring Technical Guide Book* provided by the state of Oregon Plan for Salmon and Watersheds (1999) lists the components necessary to provide quality data for further processing. The *Standard Methods for the Examination of Water and Wastewater* (Clesceri, Greenberg, & Eaton, 1998) also depicts quality control methods.

Quantification / Assessment

Statistical analysis guidelines and procedures vary between organizations and nations. For this study, the *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al., 1998) was utilized. Parts 1000-3000 cover the portion known as the Standard Methods for the Examination of Water and Wastewater and fully cover the scope of research performed in this study. Instrument calibration recommendations were followed (according to instrument manuals). Percent difference for values and expression of results were also followed in accordance to this document.

Basis for Research Study

This study was based on previous research conducted by Gross, Shmueli, Ronen, and Raveh (2007). In their research, a recycled vertical flow constructed wetland (RVFCW) was constructed and tested for performance attributes to be implemented in small communities and households. The methodology used was the basis for the methodology in this study. In their research methodologies, a short-term and a “batch” study were implemented. Gross et al. (2007) conducted both studies after three months of a continuous working period. This procedure ensured the development of bio-film in the system and stabilization of the system performance in terms of removal efficiency and flow.

In the short-term study Gross et al. (2007) emptied the pore volume of the filter section and the treated greywater (GW) was introduced into the RVFCW. A subsample of raw GW was collected for analysis (time zero). The GW was then continuously recycled between the reservoir and the RVFCW at rate of 390 L h^{-1}, determined by a water meter attached to the system. Samples of the treated GW were taken immediately after it initially passed the bed and then after 2, 4, 8, 12, 24, and 48 h. Samples were analyzed for total suspended solids (TSS), total phosphorous (TP), total nitrogen (TN), dissolved oxygen (DO), electrical conductivity (EC), pH, 5-day biological oxygen demand (BOD), chemical oxygen demand (COD), and total boron (TB).

The “batch” study GW was meant to evaluate the environmental effects of treated GW on plants and soils in comparison with untreated GW and freshwater (Gross et al., 2007). Greywater was prepared artificially to resemble GW quality of a nearby farm. Every other day at 08:00, 150 L of treated GW was removed from the reservoir and replaced with the artificial GW that was introduced into the root filter zone. They collected water samples three times a month and analyzed for TSS, TP, TN, total ammonia nitrogen (TAN), nitrite (NO_2-N), nitrate (NO_3-N) EC, pH, anionic surfactants as methylene blue active substances assay (MBAS), BOD, COD, TB, total coliforms, and fecal coliforms (FC).

Short-term Study Performance

Gross et al. (2007) reported that the RVFCW efficiently removed virtually all of the suspended solids and about 80% of the COD after eight hours. The EC and pH values were similar to their initial values and within acceptable ranges for irrigation. The results suggested that 8-12 hours of GW recycling was sufficient to produce high-quality water for landscape irrigation. Other relevant data parameters were not shown.

"Batch" Greenhouse Study

The batch study was meant to demonstrate the performance of the RVFCW over a longer period of time. In this study the average TSS was 158 mg L^{-1} – much higher than the standards for "very high quality" treated wastewater that can be used for irrigation in cities (Gross et al., 2007). The treated GW had an average pH of 8.5. Other relevant parameters were not shown. Results were similar to those in the short-term study.

Performance Comparison

A study by Friedler and Hadari (2005) tested the performance of a greywater system installed in an eight-story building within the Technion campus located in Israel. In this study a pilot plant was built in the basement that was gravitationally fed raw greywater to be processed.

Apparatus.

The system itself included biological treatment as well as physiochemical treatment. The biological portion consisted of a rotating biological contactor (RBC). The RBC was used in conjunction with physiochemical treatment that consisted of sand and disinfection. The sand filtration was a compartment 10cm in diameter and 70 cm in depth, filled with quartz (sand size) along with gravel to support it. Disinfection was performed via chlorination (hypochlorite 0.2-0.25%).

Sampling and analysis.

Friedler and Hadari (2005) collected samples twice a week for seven months. Each sample was analyzed for 15 parameters. The parameters of interest for comparison are TSS,

COD_t (total), and turbidity. Unfortunately, pH and dissolved oxygen measurements were not reported. Upon totaling the removal for each parameter, the following removal efficiencies were calculated: TSS, Turbidity, and COD had removals of 82%, 98%, and 75%, respectively (Friedler & Hadari, 2005).

CHAPTER 3: RESEARCH METHODS

General Overview of the Research Design

A greywater system was designed for a hair salon in Boone, NC. The system was tested using produced greywater which mimicked typical wastewater in such a facility. The system included a biological filtration system, which sends the water into bioremediation compartments for further cleansing via plant-based processes. The greywater was composed of different types of inputs that included hair-cleaning products, hair dye products, and other products commonly used in the hair salon. The hair dyes used included 10mL Davines Mask colors 12A and 33NI. Additionally, 10mL Davines Finest Pigments Copper/Rame hair dye was used. Finally, 45mL Davines Activation Source 40Vol was used to activate the hair colors. The shampoo and conditioner used were Bumble and Bumble Straight products; 30 mL of each was used. These products were combined with 20 gallons of tap water to create the greywater concentrate. It was then mixed into 40 gallons of tap water to create the final test greywater. These batches consisting of 60 gallons of greywater each were processed by the system and then tested for water quality after an established time period. Input and output data provided performance data and was then documented for an overall system performance review. The constructed onsite bioremediation apparatus was assessed for removal efficiency.

Experimental Apparatus

The experimental apparatus is a constructed greywater system using readily available parts. It is the third iteration of its kind; two were designed previously by students at Appalachian State University in the Department of Sustainable Technology and the Built Environment but had performance flaws that rendered them ineffective. The current system has a capacity of 60 gallons total. The system itself can be divided into three main functional units. The first is a store-bought pond biofilter with a UV light that removes solids and disinfects the water to prevent unwanted viral, algal, and bacterial growth. The biofilter is intended to develop a thin film of beneficial bacteria that fluctuate in species depending on the chemical inputs they are exposed to. The next unit is a 45-gallon sump tank that acts as a place to house the pump and provide a settling area. These units can be seen in Figure 4. The final unit is a vertical flow greywater processing area seen in Figure 5. It is unique in that it is exclusively gravity fed with the exception of the sump pump to provide the initial input. It is a three-trough system that flows via aeration siphons from a top-center trough then down to two troughs adjacent and below the center trough. An additional innovation from previous designs was using these siphon outlets from the top to the lower trough, which passively aerates the system. An aeration siphon is shown in Figure 6. Each trough has an internal compartment that serves two functions: storing water for times of intermittent use and increasing total storage within the system. The troughs are designed to hold eight-inch hydroponic baskets in which hydrocorn or a similar grow medium can be used. From the lower trough, the water flows back into the biofilter and completes the processing loop with a total flow rate of ten gallons per minute. The full system is shown in Figures 7 and 8, which include plants and the fully developed biofilter.

Figure 4. Sump tank and biofilter units.

Figure 5. Modified vertical flow greywater processing unit.

Figure 6. Siphon aeration outlet.

Figure 7. Full system.

Figure 8. Full system showing trough compartments.

Plants

The plants used in this study were selected for aesthetics and had no intended effect on the results/performance of the system. Although they may have had some effect, specifics in regards to mechanisms and uptake were not within the scope of this research. The plant species used were beauty pageant angel-wing begonia (a hybrid of *Begonia aconitifolia* and *Begonia coccinea*). They were chosen because of their long-lasting flowers and high water needs. They are easy growing and serve as an excellent way to "disguise" the system's components when implemented in a business setting. The plants were supplemented with fluorescent light to increase growth. The light cycle lasted eight hours per day (10 a.m to 5 p.m). In total, 15 plants were used that were rooted into a hydrocorn expanded clay medium. Each trough housed five plants.

Data Collection Methodology

The methodology in this study was based on the methodology used by Gross et al. (2007). There were two phases to the study that included a short-term study consisting of four variations, and a 16-day “batch” study. These four variations included a Baseline Assessment, no plants with only the biofilter, no biofilter with plants only, and Complete System. The Baseline Assessment exclusively examined the performance of mechanical aspects of the system. The latter studies assessed performance of the system with biological components that included the biofilter and plants. Before the short-term study and batch study, with exception to the Baseline Assessment, the system was allowed to cycle continuously for two months, allowing it to fully mature. This procedure ensured the development of the bio-film on the biofilter, allowed for plant maturation, and allowed the system to stabilize as a whole. Once performance was assessed for a baseline, this was compared to further performance data (short-term and batch) in order to isolate contributions due to each system component. The Baseline Assessment and short-term study took place over 96 hours. The batch study provided fluctuating performance data over a period of 16 days. In all of the studies a 60-gallon sample of greywater was prepared having identical concentrations and quantities throughout the experiment. A new batch of greywater was mixed for each study, just before the study took place. The greywater was composed of known quantities of hair products and measured for initial concentrations using the described instruments/methods in the section titled “Methods for Testing Water Quality” to ensure consistency for further greywater makeup compositions. The greywater was composed of three different colors of hair dye (10 mL each), hair dye activator (45 mL), shampoo (30 mL), and conditioner (30 mL).

For the purpose of this study NSF 350 & 350-1 guidelines were used for influent acceptance/rejection for all parameters. NSF 350 & 350-1 influent guidelines call for a pH between 6.5 and 8, turbidity of between 50 and 100 NTU, COD between 250 and 400 mg/L, and TSS must be between 80 and 160 mg/L.

NSF 350 & 350-1 effluent guidelines (Table 3) were used for acceptance/rejection of all parameters to be reused for lavatory flushing. Average effluent values must be between 6.5 and 8.5 for pH. Turbidity must be 2 NTU or less, CBOD 10 mg/L or less, and TSS must be 10 mg/L or less. Turbidity is a factor of particular importance because it provides a visible indicator when the water is reused for lavatory flushing. High turbidity could be off-putting to the user. In this study COD was measured rather than CBOD. BOD is biochemical oxygen demand and CBOD is carbonaceous BOD, where microbes that can oxidize nitrogen sources are inhibited. As explained previously, COD is chemical oxygen demand that uses Cr(VI) as the oxidant. The effluent criteria only list CBOD, not COD. This complicates comparisons, but, in essence, BOD, COD and CBOD all give roughly the same numbers (Michael Hambourger, personal communication, November 27, 2016). Therefore, the CBOD values of the NSF guidelines were used as surrogate values for the COD values measured in this research. Given that Cr(VI) is a more universal oxidant than biological processes, if anything, COD values can be expected to be modestly larger than the corresponding BOD and CBOD measurements.

Short-Term Study

Baseline Assessment, Biofilter only, Plants only, and Complete System

The Baseline Assessment portion of the study quantified the performance of short-term treatments of greywater through the constructed onsite bioremediation system. This evaluated the mechanical contributions of the system; no plants or biofilter were implemented. The biofilter only portion demonstrated performance based on the biofilter alone. No plants were used. The plants-only portion demonstrated the effects of only plants on the treatment process. No biofilter was used. Finally the complete system was tested, which implemented all components of the system. The plants and biofilter were implemented in conjunction with the mechanical aspects of the system. In all four variations the system was filled with tap water from the town of Boone, NC (approximately 40 gallons). Next, 20 gallons of fresh greywater concentrate previously described were added to the system into the biofilter input. Once the 20 gallons of greywater concentrate had been added it was allowed to cycle through the system for four cycles (pump on/off, ~6 minutes). This ensured a homogenous mixture. An initial sample was collected from the biofilter outlet for consistency. The greywater was measured for initial concentrations using the instruments to ensure consistency for further greywater makeup compositions. These initial measurements included D.O, temperature, pH, Turbidity, COD, and TSS. Then an additional sample was collected from the biofilter outlet, representing time zero. Samples were taken at time zero and then at 2, 4, 8, 12, 24, 48, 72, and 96 hours. The samples were analyzed for total suspended solids (TSS), dissolved oxygen (DO), turbidity, temperature, pH and chemical oxygen demand (COD).

Batch Study

This portion of the study assessed the performance of the greywater system as a whole. Mechanical and biological components were all implemented in order to test how the system performed over time with fluctuating concentrations of greywater as would be observed in a fully operating system. The system was filled with tap water from the town of Boone, NC (approximately 40 gallons). Next 20 gallons of fresh greywater concentrate was added to the system into the biofilter input. Once the 20 gallons of greywater concentrate had been added it was allowed to cycle through the system for four cycles (pump on/off, ~6 minutes). This ensured a homogenous mixture. The greywater was measured for initial concentrations using the instruments to ensure consistency for further greywater makeup compositions. These initial measurements include D.O, temperature, pH, Turbidity, COD, and TSS. An initial sample was taken from the biofilter outlet for consistency. Then an additional sample was taken and measurements were recorded, representing time zero. The system processed the greywater for 48 hours then a sample was taken and parameters were documented. Next a 20-gallon sample of treated greywater was removed and discarded, then replaced with 20 gallons of freshly prepared greywater immediately after documentation. The system went through four cycles to ensure a homogenous mixture (~6 minutes). The new initial measurements (D.O, temperature, pH, turbidity, COD, and TSS) were then documented and compared to the previous sample. Every other day (48hrs) a sample of greywater was tested to document changes compared to time zero (or the previous measurement). This process continued for 16 days. This provided data over a time period in which concentrations varied as they would in a fully functional setting such as a hair salon.

Sampling Procedures

The data collection for the short-term study occurred over four 96-hour periods. Data collection for the batch study occurred every 48 hours for a time period of 16 days. Samples were collected from the biofilter outlet. These samples were processed using an electronic thermometer, EXTECH PH220 electronic pH meter, sensION™ DO6 dissolved oxygen meter, and a Thermo Scientific Orion AQ4500 electronic turbidimeter. COD measurements were processed using CHEMetrics K7365 HR COD vials. Two milliliters of COD sample were added to each vial and then digested at 150 ^{o}C for two hours using a WTW CR2200 Thermoreaktor. Next the COD samples were quantified using a CHEMetrics A-7325 high range COD photometer. Total suspended solids were quantified by filtering 50ml of sample through a 47mm Environmental Express ProWeigh® glass-fiber filter (1.5 μm porosity) under reduced pressure. The glass-fiber filter (pre-dried) was then placed in an aluminum-weighing dish and processed in a Thermo Scientific F6010 Thermolyne furnace for one hour at 104 ^{o}C. The glass-fiber filter was then weighed for total suspended solids. The weight of the filter was subtracted out and data was then converted to mg solid/L sample. These data were then recorded and statistical parameters including standard deviation and margin of error were calculated using Equations 1 and 2. Three duplicate measurements were taken for each variable to ensure reliability of data measurements. Accuracy depended on taking sample blanks, which gave the difference of field measurements compared to true values of the control blanks of known values. All equipment/instruments were calibrated according to their manual per the *Standard Methods for the Examination of Water and Wastewater* (Clesceri et al., 1998). The output data was then compared to the input data and provided the performance data of the system. The output water was compared to the NSF 350 and 350-1 standards and USEPA suggested guidelines to further assess the viability of implementation of such a system in an actual facility. This enabled analysis of the performance of the system in comparison to the type of inputs being processed.

Data Analysis

The average is equal to the sum of all values divided by n (the number of samples). The standard deviation was found using the equation seen in Equation 1. The margin of error was found using the formula in Equation 2 where σ represents the standard deviation The confidence interval at p=0.05 (2 degrees of freedom) is equal to 2.92.

$$\boldsymbol{Standard\ Deviation} = \frac{\sqrt{(\sum_{i=1}^{n}(x - \bar{\mathrm{x}})^2}}{\sqrt{(\mathrm{n}-1)}} \qquad \textbf{(1)}$$

Where:

x = sample value

x̄ = average of samples

n = number of samples

$$\boldsymbol{Margin\ of\ Error} = \mathbf{2.92}\ (\frac{s}{\sqrt{n}}) \qquad \textbf{(2)}$$

CHAPTER 4: RESULTS

The short-term study focused on four variations of the system: Baseline Assessment, which only included mechanical aspects of the system; Biofliter Only; Plants Only; and Complete System. The results from the short-term study portrayed performance aspects of each component of the system as well as the performance of the entire system after treating greywater for 96 hours.

The batch study focused on the performance of the system as would be observed in a small business setting. It demonstrated the fluctuations of new greywater being inputted while also discharging treated greywater for lavatory flushing.

Short-Term Study

Dissolved Oxygen

Dissolved oxygen ranged from 2.01(0.01) mg/L to 6.63(0.04) mg/L throughout the short-term studies. The highest DO was recorded in the Baseline Assessment while the lowest DO measured occurred during the Biofilter Only test. This data is shown in Appendix B.

Temperature

Measurements from the short-term studies ranged in temperature from 53.30(0.45) °F to 70.23(0.42) °F. The lowest temperature was measured during the Complete System test.

The highest temperature was recorded during the Plants Only test. This data is shown in Appendix B.

pH

The pH data can be seen in Figure 9. This data suggests that the relative change was not attributable to one component individually or collectively as a whole. The data for the short term suggests that according to NSF 350 and 350-1 guidelines depicted in Table 3, the pH was acceptable for reuse in as low as four hours for the Complete System. All short-term study data can be found in Appendix B.

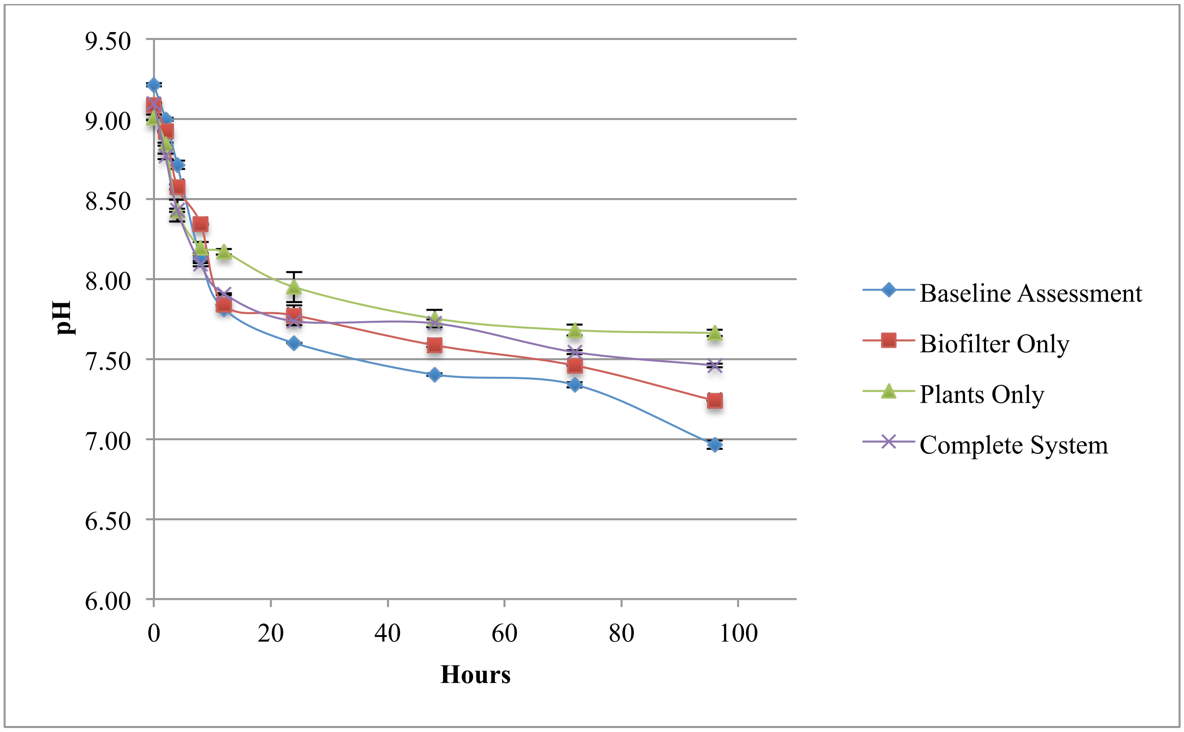


Figure 9. pH as a function of time during the short-term study. The graph represents the average of the measurements for each time period. (n=3 unless otherwise noted in Appendix C).

Turbidity

Turbidity was altered differently in each part of this study. Reductions amounted to 70%, 93%, 88%, and 88% for the Baseline Assessment, Biofilter Only, Plants Only, and

Complete System, respectively. The Biofilter Only observed the highest reduction. It demonstrated a reduction from 64.03(0.24) NTU to 4.58(0.02) NTU. Using Table 3, the data suggests that turbidity was acceptable in 96 hours for the Biofilter Only but was never acceptable for the other short-term studies. The data can be seen in Figure 10. All short-term study data can be found in Appendix B.

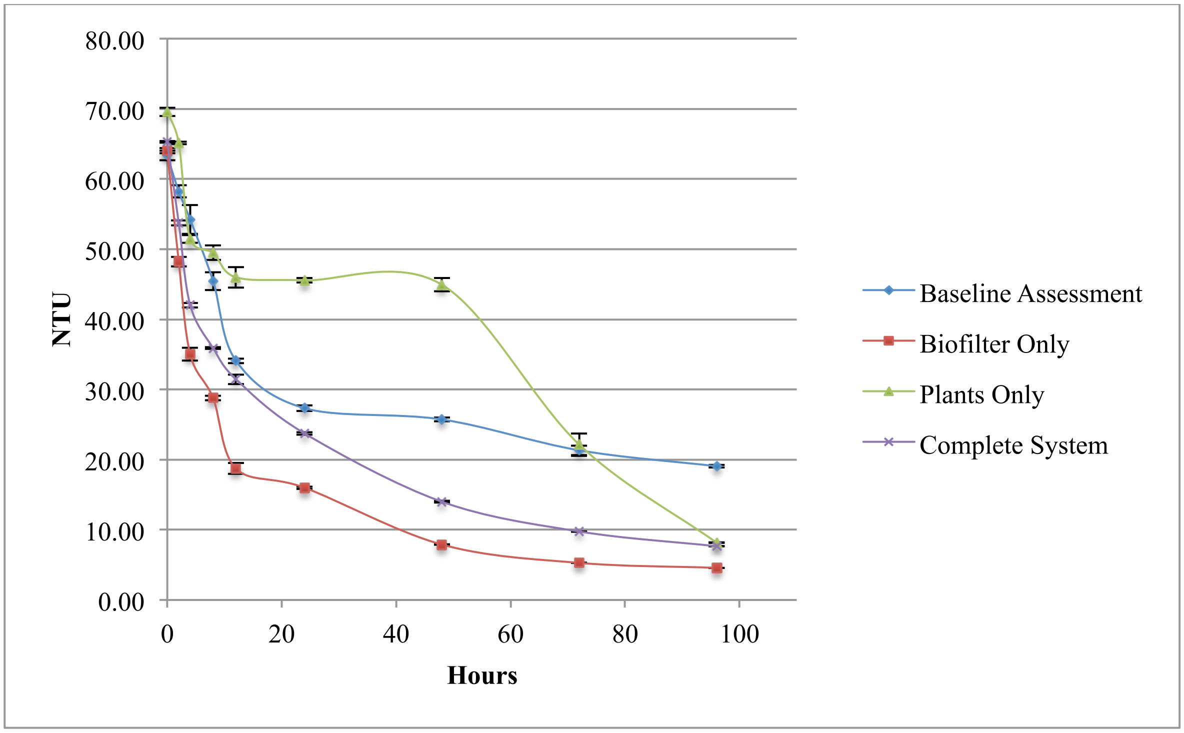


Figure 10. Turbidity as a function of time during the short-term study. The graph represents the average of the measurements for each time period. (n=3 unless otherwise noted in Appendix C)

COD

The reductions in COD were found to be highest for the Plants Only. Reduction values amounted to 58%, 78%, 79%, and 72% for Baseline Assessment, Biofilter Only, Plants Only, and Complete System, respectively. The Plants Only study percent reduction was slightly higher than the Biofilter Only. The Biofilter Only study showed a reduction from 592.33(0.65) mg/L to 131.33(0.65) mg/L while the Plants Only study demonstrated a change from 818.67(0.65) mg/L to 175.33(0.65) mg/L. COD was never found to be acceptable according to NSF 350 and 350-1 (using CBOD values as a surrogate for COD as mentioned previously), as shown in Table 3. COD needed an average value of 10 mg/L to be acceptable for reuse. COD data can be seen in Figure 11.

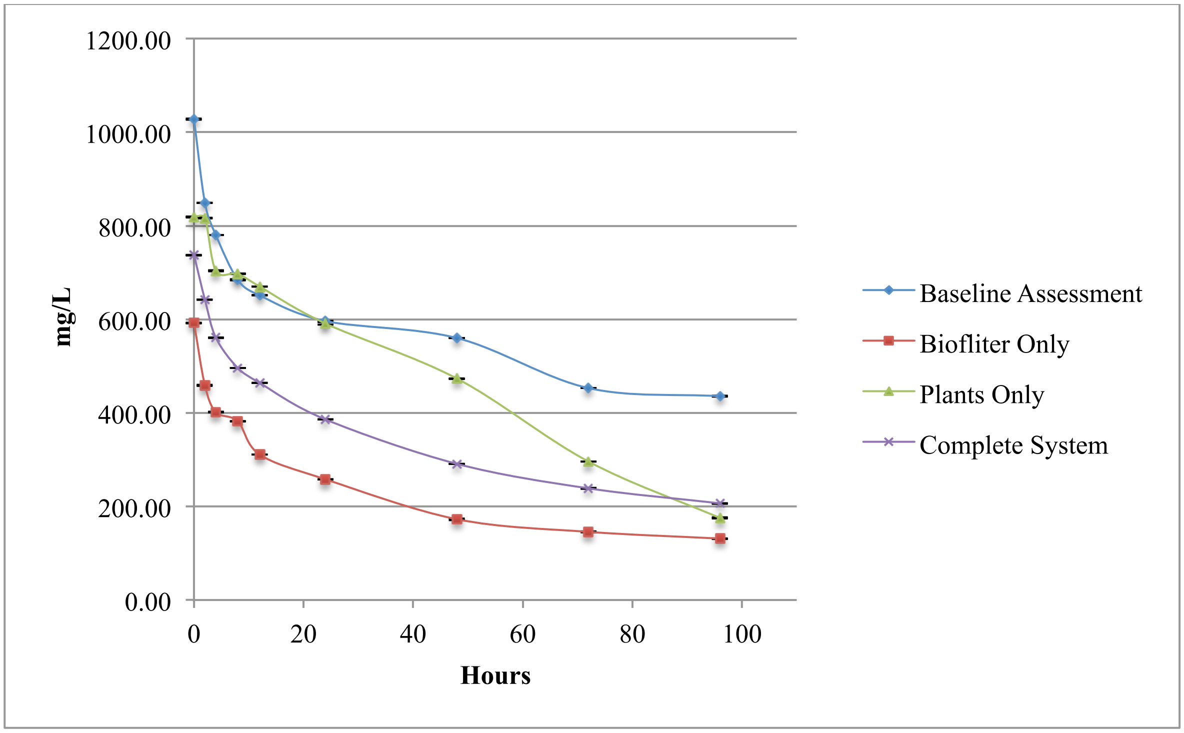


Figure 11. COD as a function of time during the short-term study. The graph represents the average of the measurements for each time period. (n=3 unless otherwise noted in Appendix C).

TSS

Total suspended solids showed similar reductions for all studies with exception of the Plants Only study. The percent reductions were found to be up to 96%, 82%, 69%, and 98% for the Baseline Assessment, Biofilter Only, Plants Only, and Complete System, respectively. The Complete System study had just a 2% advantage to the Baseline Assessment. In the Complete System study the values were reduced from 107.3333(1.306) mg/L to 2.0000(0) mg/L. Table 3 can be used to compare results for acceptability. TSS was acceptable in as little as two hours in the Biofilter Only test. Expanded short-term TSS data can be found in Appendix B and are also shown in Figure 12.

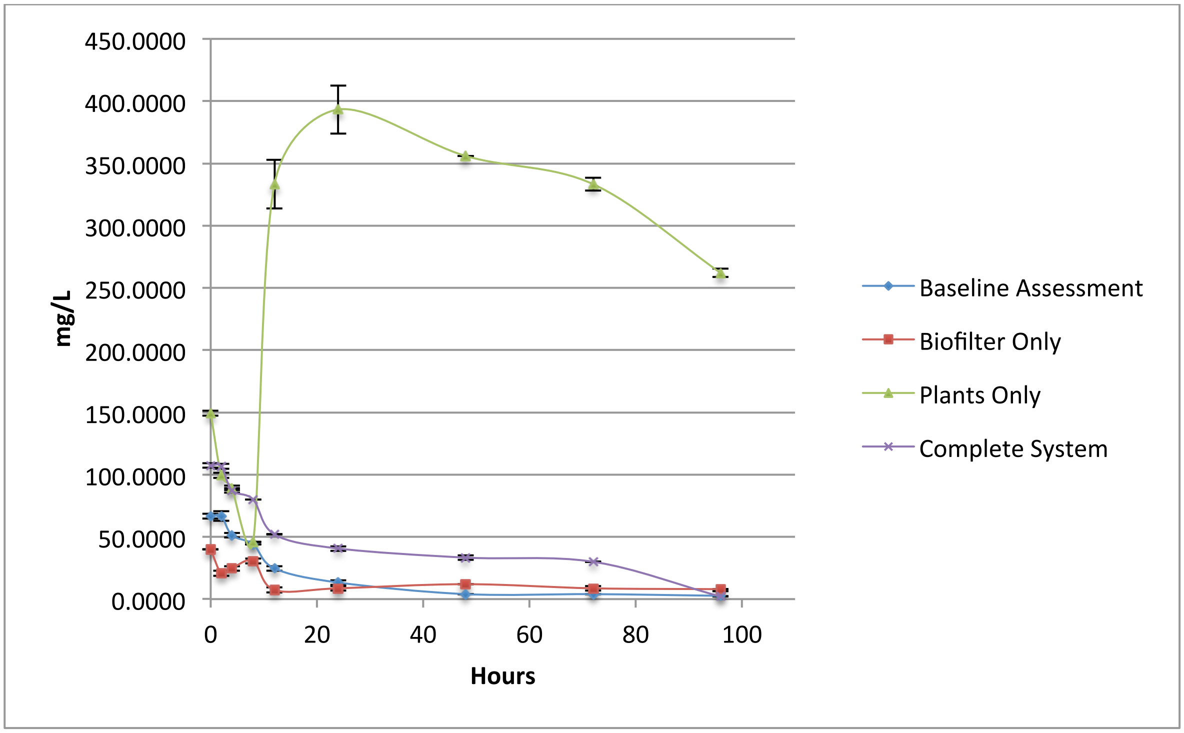


Figure 12. TSS as a function of time during the short-term study. The graph represents the average of the measurements for each time period. (n=3 unless otherwise noted in Appendix C).

Batch Study

Dissolved Oxygen

Dissolved oxygen levels during the batch study are shown in Appendix C. Values ranged from 9.88(0.01) to 4.04(0.01) mg/L. These values were higher than those found in the short-term study.

Temperature

During the batch study the temperature was observed to have a maximum of 69.90(0.11) and a minimum of 57.23(0.24) ^{o}F, and can be seen in Appendix C. Temperatures fluctuated less in this study than those recorded in the short-term study.

pH

pH values for this study are shown in Appendix C. The pH was found to have a range of 8.67(0.01) to 7.03(0.01). Figure 13 shows the fluctuations in pH.

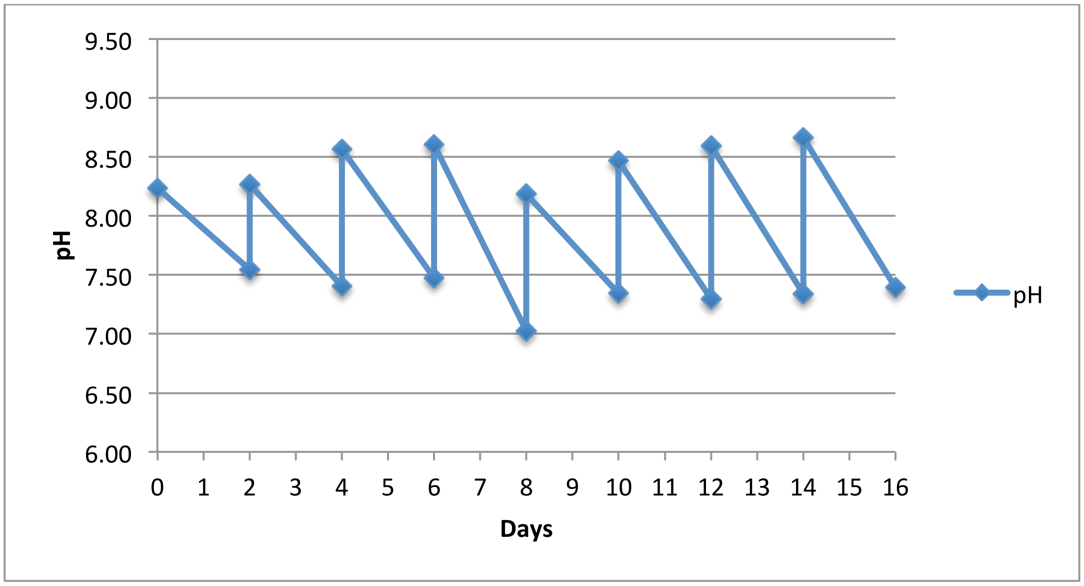


Figure 13. pH fluctuations shown in 48-hour intervals during the batch study. Every 48 hours, treated greywater was removed, then untreated greywater was added. (n=3 unless noted otherwise in Appendix C).

Turbidity

Turbidity fluctuated from a maximum of 33.03(0.72) NTU to a minimum of 3.72(0.02) NTU. This is presented in Appendix C and shown in Figure 14. Reductions are depicted in Figure 17. Reductions ranged from 77% to 87%.

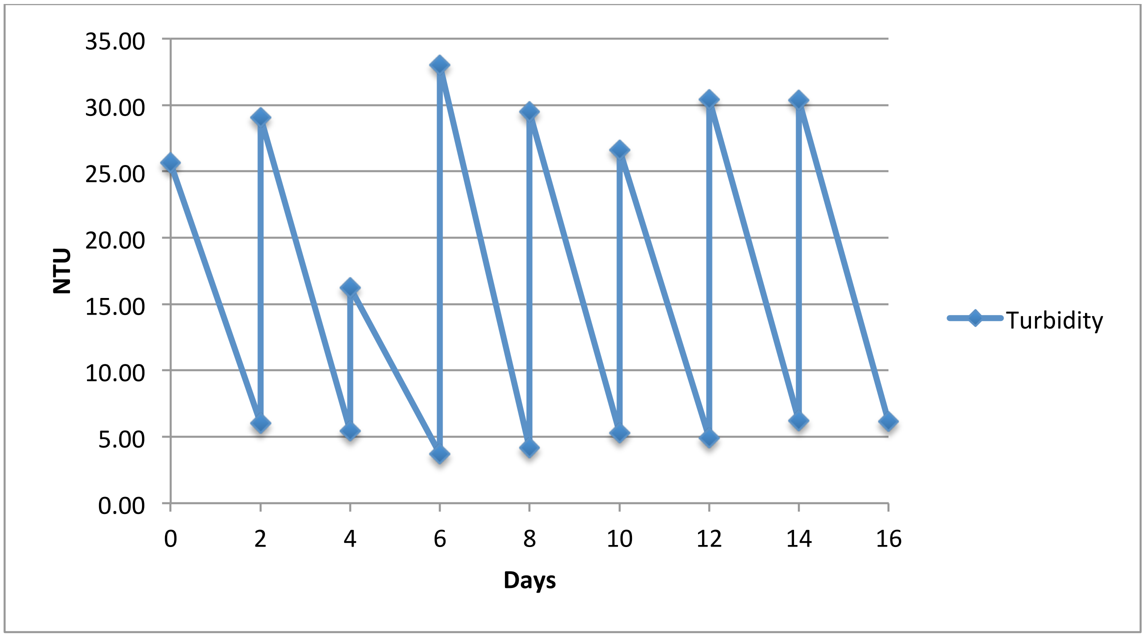


Figure 14. Turbidity fluctuations shown in 48-hour intervals during the batch study. Every 48 hours, treated greywater was removed, then untreated greywater was added. (n=3 unless noted otherwise in Appendix C).

COD

Chemical oxygen demand ranged from 683.67(0.65) mg/L to 147.33(0.65) mg/L. This is shown in Appendix C and also demonstrated in Figure 15. Reductions ranged from 45% to 74%. Reduction data is shown in Figure 17 and expanded upon in Appendix C.

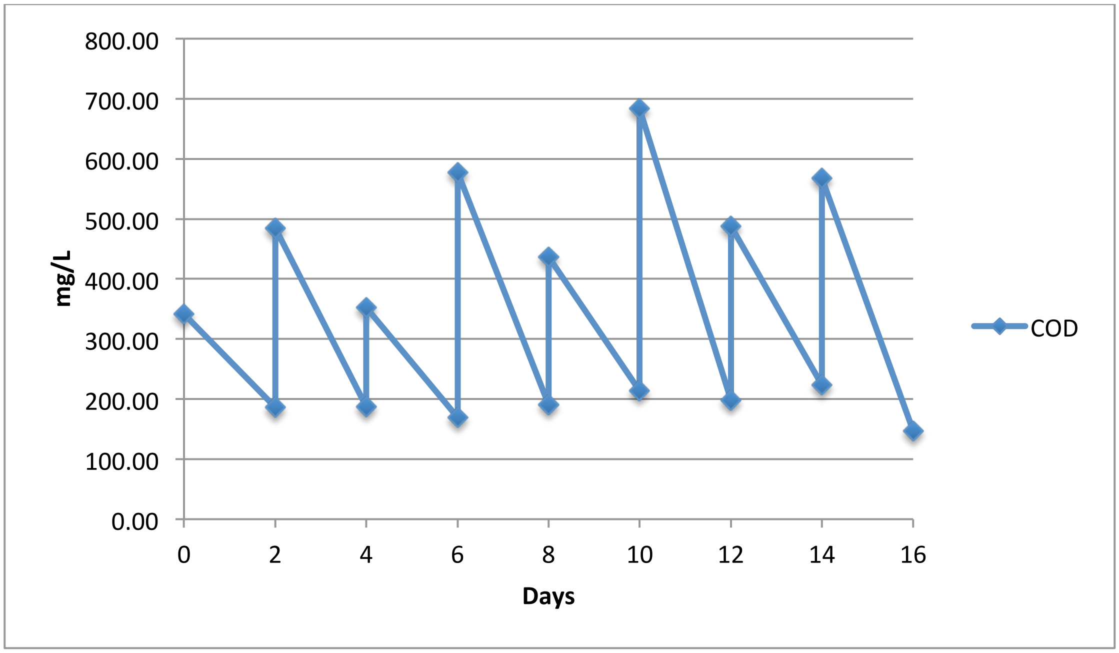


Figure 15. COD fluctuations shown in 48-hour intervals during the batch study. Every 48 hours, treated greywater was removed, then untreated greywater was added. (n=3 unless noted otherwise in Appendix C).

TSS

Total suspended solids were found to have a maximum of 104.00(0) mg/L and a minimum of 10.00(0) mg/L. Figure 16 shows the fluctuation over the course of the batch study. Appendix C expands on statistical data associated with this portion of the study. Appendix C also shows reduction data and Figure 17 shows average percent change after 48 hours of treatment.

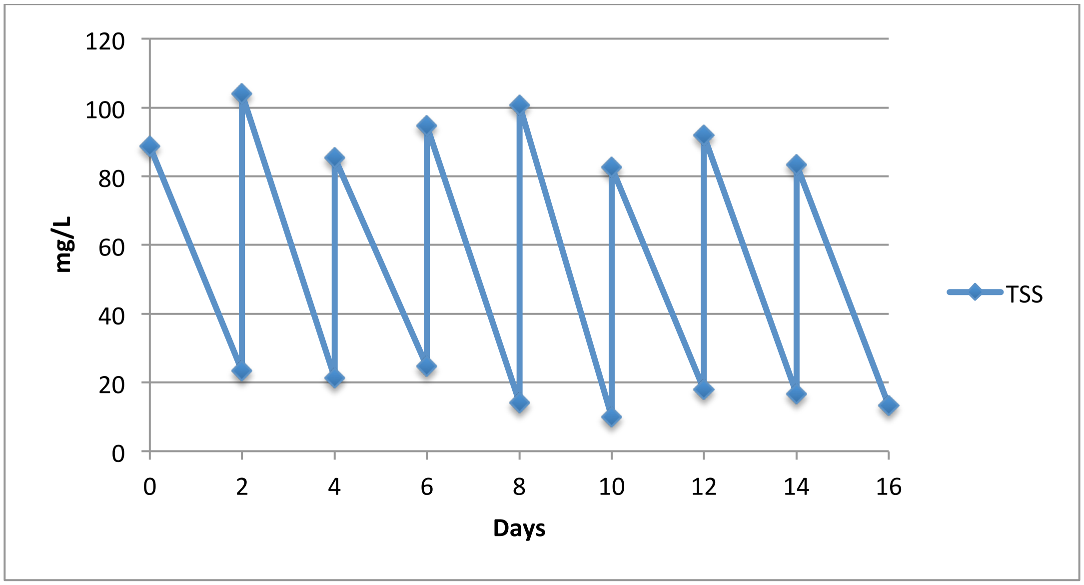


Figure 16. TSS fluctuations shown in 48-hour intervals during the batch study. Every 48 hours, treated greywater was removed, then untreated greywater was added. (n=3 unless noted otherwise in Appendix C).

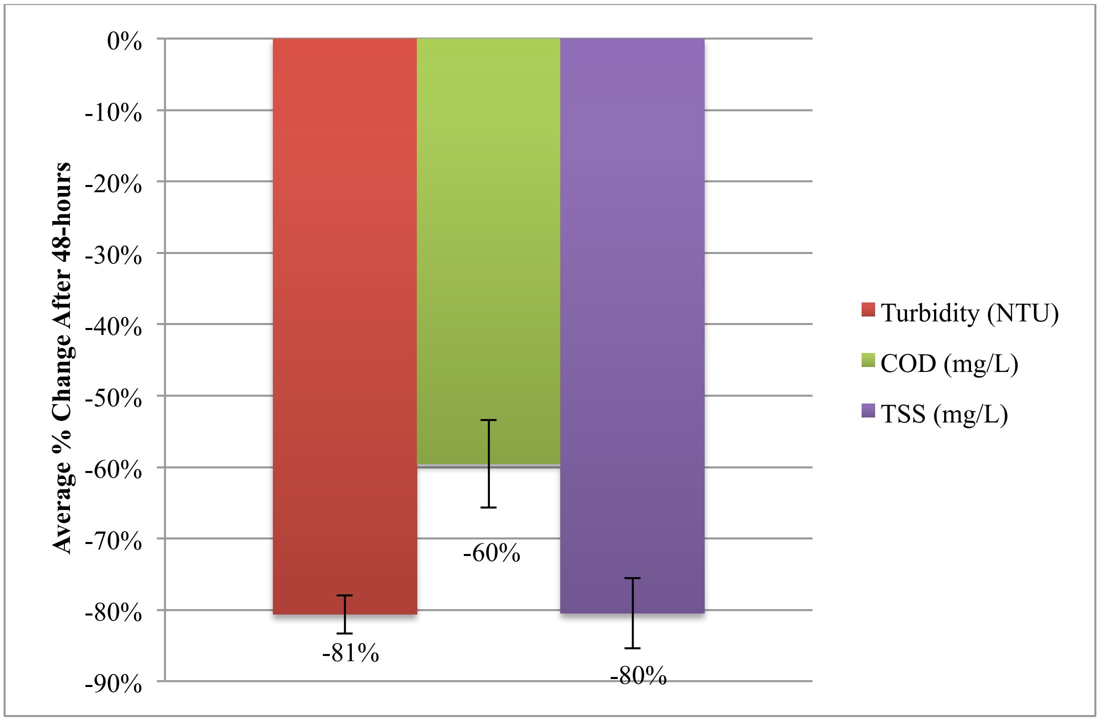


Figure 17. Average % change after 48 hours of treatment (n=24 for each parameter).

CHAPTER 5: DISCUSSION AND CONCLUSION

Short-Term Study

Baseline Assessment

The Baseline Assessment revealed what changes in water quality were observed due only to the mechanical components of the system. The color appeared to dissipate in just 12 hours but was still observable to some degree throughout the rest of the study. Dissolved oxygen levels ranged from a maximum of 6.63(0.02) mg/L to a minimum of 5.58(0.01) mg/L. This can be seen in Appendix B. Temperature was found to range from 57.67(0.29) to 55.23(0.56) ^{o}F. The pH of the system declined from 9.21(0.01) (alkaline) to 6.96(0.02), which is nearly neutral. This can be seen in Figure 9 and in Appendix B. This reduction may be due to the aeration siphons. The system expressed a 70% turbidity reduction from 63.37(0.46) NTU to 19.07(0.13) NTU. This can be seen in Figure 10 and in Appendix B. Turbidity in this test was assumed to be exclusively due to hair products because no biological components had been introduced to the system at that point. Reductions in turbidity may have been a result of oxidation from the aeration siphons or settling within the system. COD values remained relatively high, having a 96-hour value of 435.67(0.65) mg/L. This was attributable to the lack of organisms present to consume organic material. COD data is shown in Figure 11 and in Appendix B. Total suspended solids were low at the start of the experiment and were composed of only solids originating from hair products. Shown in

Figure 12 and Appendix B, the values ranged from 66.67(1.31) mg/L to 2.67(2.61) mg/l, a 96% reduction. Because there was no biofilter present, it can be assumed this was almost exclusively due to settling within the system and its various compartments.

When comparing the Baseline Assessment data to the NSF 350 & 3501-1, one can assess the acceptability of water quality during this test. NSF 350 & 350-1 guidelines are shown in Table 3. pH was acceptable according to NSF 350 & 350-1 guidelines after eight hours. The pH never fell below the acceptable range and had a tendency to trend towards neutral. Turbidity was never acceptable. COD did not meet requirements as compared to NSF 350 & 350-1, having a value of 435.67(0.653) and needing a value of 10 mg/L. Total suspended solids were acceptable after 24 hours. TSS requirements had to meet guidelines for the purpose of this study and must remain low in order for this water to be used to flush toilets.

No Plants, Biofilter Only

The biofilter data revealed parameters affected by only the biofilter implementation. The biofilter was fully matured and expected to reduce total suspended solids more than any other reduction being measured. The biofilter has properties that are designed to remove solids, but as the test proceeded it was apparent that the color was also affected (an indication of turbidity). Color was reduced notably after just 12 hours. Upon reaching the end of the 96-hour study this color had been reduced even further, yielding nearly colorless samples. Dissolved oxygen levels varied throughout the study, with a maximum of 4.55(0.01) mg/L and a minimum of 2.01(0.01) mg/L (seen in Appendix B). Temperatures fluctuated from 65.33(0.35) to 57.00(0.23) ^{o}F and can be seen in Appendix B. pH showed a trend toward neutral over the course of this study, bringing the pH from a value of 9.01(0.01) down to

7.66(0.01). pH data is shown in Figure 9 and Appendix B. The pH did not come as close to neutral as in the Baseline Assessment but in this case there was a biological component that also affected the pH of the system. pH was acceptable after just eight hours. Turbidity had a reduction of up to 93%. This reduction was greatly attributable to the biofilter, in conjunction with the mechanical aeration siphons. Turbidity is the prominent indicator of water quality acceptance in this system and had a reduction of 59.45 (93% reduction) NTU compared to a 44.30 (70% reduction) NTU reduction found in the Baseline Assessment. This can be seen in Figure 10 and Appendix B. Turbidity levels never reached the standard of 2 NTU (Table 3) but were close (4.58 NTU) after 96 hours. The system expressed reductions in COD from a high of 592.33(0.65) to a low of 131.33(0.65), a 78% reduction (shown in Figure 11 and Appendix B). Compared to a 58% reduction in the Baseline Assessment, this was a large increase in performance. It would be expected that this would be observed because biological components were in the test, specifically the biofilter. The biofilter is designed to remove solids and allow for the breakdown of material through interaction with the microbial populations that inhabit the biofilter itself. Total suspended solids were reduced by 80%, bringing the observed values from 40.00(0) mg/L to 7.33(1.31) mg/L (shown in Figure 1 and Appendix B). The Baseline Assessment had a reduction of 96% compared to an 80% reduction in this test. It should be noted that TSS had a lower maximum than the Baseline Assessment, having a value of 66.67(1.31) mg/L. This could have been due to the implementation of the biofilter.

When comparing this test to the NSF 350 & 350-1 guidelines one may be able to see whether the system produced acceptable effluent results for discharge. NSF 350 & 350-1 guidelines are depicted in Table 3. After just eight hours the pH levels were acceptable for

NSF 3501 & 350-1. Turbidity was close to the range for NSF 350 & 3501-1 after 96 hours. COD was not found to be acceptable according to NSF 350 & 350-1 at any time during this study. Total suspended solids were found to be acceptable after 12 hours. The performance of the biofilter proved to be consistent in most parameters based on the data retrieved from the study.

No Biofilter, Plants Only

The system was tested using only the mechanical components with the addition of plants. The plants served to help blend the system into the hair salon's atmosphere and may have removed excess nutrients to benefit system performance. After 12 hours the color of the greywater had subsided and at the 72 hour collection it was nearly clear. During this test the DO content was recorded to have a maximum of 4.62(0.05) mg/L and a minimum of 2.42(0.01) mg/L (shown in Appendix B). This range is suitable for beneficial bacteria growth and plant life. Temperature was found to be between 64.60(0) and 70.23(0.29) ^{o}F (shown in Appendix B). This is acceptable for the health of the system and the biological components that are implemented in it. The pH in this test trended towards neutral from 9.01(0.01) to 7.66(0.01). pH was most likely reduced due to the mechanical aeration siphons and potentially from the hydrocorn expanded clay medium (grow medium for plants). pH data is shown in Figure 9 and Appendix B. Turbidity was shown to have a decrease of up to 88%. This reduction was from 69.60(0.41) to 8.16(0.02) and can be seen in Figure 10. Appendix B shows additional turbidity data for this study. Surprisingly, this was the greatest decrease recorded thus far, with a total reduction of 61.44 NTU versus 44.30 and 59.45 NTU for the Baseline Assessment and Biofilter Only, respectively. COD was observed to have a 79% reduction, a drop of 643.33 mg/L, and the highest of all of the tests (seen in Figure 11). Total suspended solids would be expected to be higher than that of the biofilter only test because there is no physical filtration device in place. Reductions were primarily due to settling in the system's compartments. TSS was indeed found to have the highest values thus far and was most likely due to the additional solids introduced to the system via the grow medium of the plants. The maximum was 393.33(13.07) mg/L with a value of 262(2.26) mg/L after 96 hours. This data can be seen in Figure 12 and in Appendix B.

According to NSF 350 & 3501-1 depicted in Table 3, the pH was acceptable after four hours for NSF 3501 &350-1 criteria. Turbidity was not within range for NSF 350 & 350-1 during this test. COD was also not found to be acceptable. Criteria for TSS were never met for NSF 350 & 350-1. This may be due to a lack of filtration and settling/relocation of solids. The TSS levels were somewhat within the range expected due to the lack of system components previously mentioned. There was no major effect of plants on any of the parameters being observed in this test, with the exception of turbidity. This does not mean the plants are inactive in the bioremediation process, it simply means there was no significant effect to the parameters within this study.

Complete System

The Complete System utilized all components from previous tests. This included implementing the biofilter, plants, and all mechanical components. During this test the color was greatly reduced after 12 hours and virtually colorless at the 48-hour mark. The fully developed system had DO levels ranging from 4.83 mg/L to 2.59 mg/L. Temperatures for this test were found to have a high of 62.77(0.07) and a low of 53.30(0.29) ^{o}F. The pH showed a reduction from 9.10(0.01) to 7.46(0.01), which falls within the range acceptable for the system. Turbidity was observed to have an 88% decrease, 65.30(0.11) to 7.66(0.02). This was a reduction of 57.64 NTU. Although this was also not the highest recorded reduction in turbidity, it does represent a meaningful reduction. COD was reduced from 737.33(0.65) to 206.67(0.65), a 72% reduction. The complete system expressed a reduction in TSS of 98%. With exception of the Plants Only test, the reduction was highest in this test. The system removed 105.33 mg/L versus 32.67 and 64.00 mg/L for the Biofilter Only and Baseline Assessment, respectively. TSS were reduced in the complete system test from 107.33(1.31) mg/L to 2.00(0) mg/L.

When comparing this test to Table 3, one can explore whether or not these reductions were significant enough to be acceptable for discharge. NSF 350 & 350-1 guidelines indicate that the pH was acceptable after just four hours into the test. Turbidity values were not acceptable during the entire test, based on the NSF 350 & 350-1 guidelines. COD was not acceptable when compared to the NSF 350 & 350-1 guidelines. According to Table 3, the TSS was acceptable after 96 hours.

Batch Study

The batch study was used to demonstrate the cyclic pattern of use as would be seen in a system installed in a small business such as a hair salon. The cycle included fresh greywater mixing with the greywater being treated and greywater being discharged simultaneously for use. An average of all measurements in the batch study were taken as an indicator of the overall system during the course of the study. In addition a *48-hour average* was measured, which was the average of all 48-hour batch study measurements (measurements after 48 hours in the system) from that point forward. This value was used as an indicator for discharge requirements.

Dissolved Oxygen (DO)

Dissolved oxygen was found to have a range of 9.88(0.007) mg/L to 4.04(0.007) mg/L. There was a distinctive pattern of a high DO measurement at each time zero, which was assumed to be due to the mixing and addition of new greywater. This can be seen in Appendix C. The average for DO during the batch study was 6.14 mg/L.

Temperature

The temperature over this 16-day test was found to have values ranging from 69.90(0.113) to 57.23(0.236) ^{o}F. The average was 63.97 ^{o}F. This is acceptable for the health of the system and would allow for a healthy population of beneficial bacteria as well as providing correct temperatures for the plants.

pH

During the course of the batch study the pH ranged from 8.67(0.006) to 7.03(0.015). The average over the batch study was 7.90. The 48-hour average was found to be 7.35. According to the NSF 350 & 350-1 found in Table 3, the average pH was acceptable nearly the entire batch study.

Turbidity

Turbidity is the primary indicator used for discharge acceptability. Turbidity ranged from 33.03(0.719) NTU to 3.72(0.024) NTU during the batch study. The average was found to be 16.43 NTU over the course of this study. The 48-hour average was found to be 5.25 NTU. Reductions were found to be between 77% and 87%, an average reduction of 81%. The 48-hour average was nearly acceptable when compared to NSF 350 & 350-1 guidelines depicted in Table 3.

Chemical Oxygen Demand (COD)

COD was quite variable, ranging from a maximum of 683.67(0.653) mg/L to a minimum of 147.33(0.653) mg/L. Over the course of the batch study the average was found to be 340.67 mg/L. The average reduction (average of all reductions) was found to be 60%, with a maximum of 74% and a minimum of 45%. The system was not acceptable for discharge in any of the measurements. The 48-hour average of 189.58 mg/L indicated that after 48 hours all water quality measurements did not meet the NSF 350 & 350-1 guidelines found in Table 3.

Total Suspended Solids (TSS)

Total suspended solids ranged from 104.00 mg/L to 10 mg/L. The average value over the 16-day study was 54.54 mg/L with a 48-hour average of 17.67 mg/L. Reductions amounted to as high as 90% with a minimum of 71%. This resulted in an average reduction of 80%. Using Table 3 for comparison, the 48-hour average shows that water quality was not acceptable.

Study Comparison

When comparing results observed by Gross et al. (2007), one can see that in their study approximately 80% of COD was removed after eight hours, whereas this study achieved only a 33% reduction in this time period. Gross et al. (2007) also reported that after 12 hours most parameters had met a steady state, which is extremely similar to the results achieved through this greywater system. Gross et al. found 90-99% of TSS was removed compared to 98% (complete system) in this study. When comparing the batch studies, the pH was found to be 8.5 for the study by Gross et al. (2007) and the pH of this study was found to be 7.9; the remaining parameters were not compared due to lack of disclosure by Gross et al. (2007).

The study by Friedler and Hadari (2005) measured reductions of 75%, 82%, and 98% for COD, TSS, and turbidity, respectively. This study that had reductions of up to 72%, 98%, and 88% for COD, TSS, and turbidity, respectively (complete system). These results were quite similar, demonstrating adequate performance compared to a larger, more sophisticated system.

Conclusions

When comparing to the NSF 350 & 350-1 standards, the system performance was adequate in a few areas, but needs improvement in the critical turbidity and TSS standards. Nevertheless, the system approached acceptable water quality within 48 hours or less (except for COD). More work needs to be done in order to make this particular system an effective greywater treatment solution. In the short-term study the main focus was the Complete System. The baseline revealed results in reducing color and achieving neutral pH. When utilizing only plants, results were demonstrated in turbidity and COD reductions, although they did not meet NSF 350 & 350-1 guidelines depicted in Table 3. In 96 hours the complete system satisfied TSS requirements and fell just short of turbidity guidelines, but the COD was well above the CBOD standard. The batch study was inherently important in demonstrating the feasibility of using such a system in a small business. In all 48-hour periods over 16 days, the water quality did not meet the guidelines for discharge of the measured parameters in this study except for pH, but came close for turbidity and TSS. It may be noted that the most essential component was the biofilter. The biofilter was responsible for the greatest reductions in all parameters; this can be seen in Figures 9, 10, 11, and 12. Further system designs should consider this component a priority. In addition, the temperature was not significantly affected and remained relatively stable throughout the course of the study.

It is important to recognize that the results produced do not utilize a key step that will be included in the final installation: a store-bought chlorine filter. This filter will serve to chlorinate the water before it enters the toilet or other outlet. The filter will treat the water after it has exited the greywater system and before it is discharged for its final reuse.

Overall it appears that 48 hours is not an adequate timeframe to allow the greywater treatment process to meet NSF standards, although currently compliance with these standards is only recommended. The residence time of water being treated may need to be increased and/or a larger, more effective biofilter may be needed to address turbidity, TSS, and COD performance. In addition, a filtration medium such as sand could offer improved performance and should be explored. The results were promising in this system's design, showing substantial improvements in water quality even if certain metrics (TSS and turbidity) were not quite sufficiently reduced to meet the industry guidelines. Using this study one can expand upon efforts to reduce costs in small businesses and increase environmental responsibility. Hair salons are just a starting point; further research could be performed to test this system on other greywater sources. The results of this study could impact decisions to implement a greywater system in a small business. Water resources do not have to be strained at the expense of a small business. Water can be saved and can be done in a way that is both aesthetically pleasing and fully functional. This work helps to solve water depletion and reduce the need for central water treatment facilities to treat water that can simply be reused.

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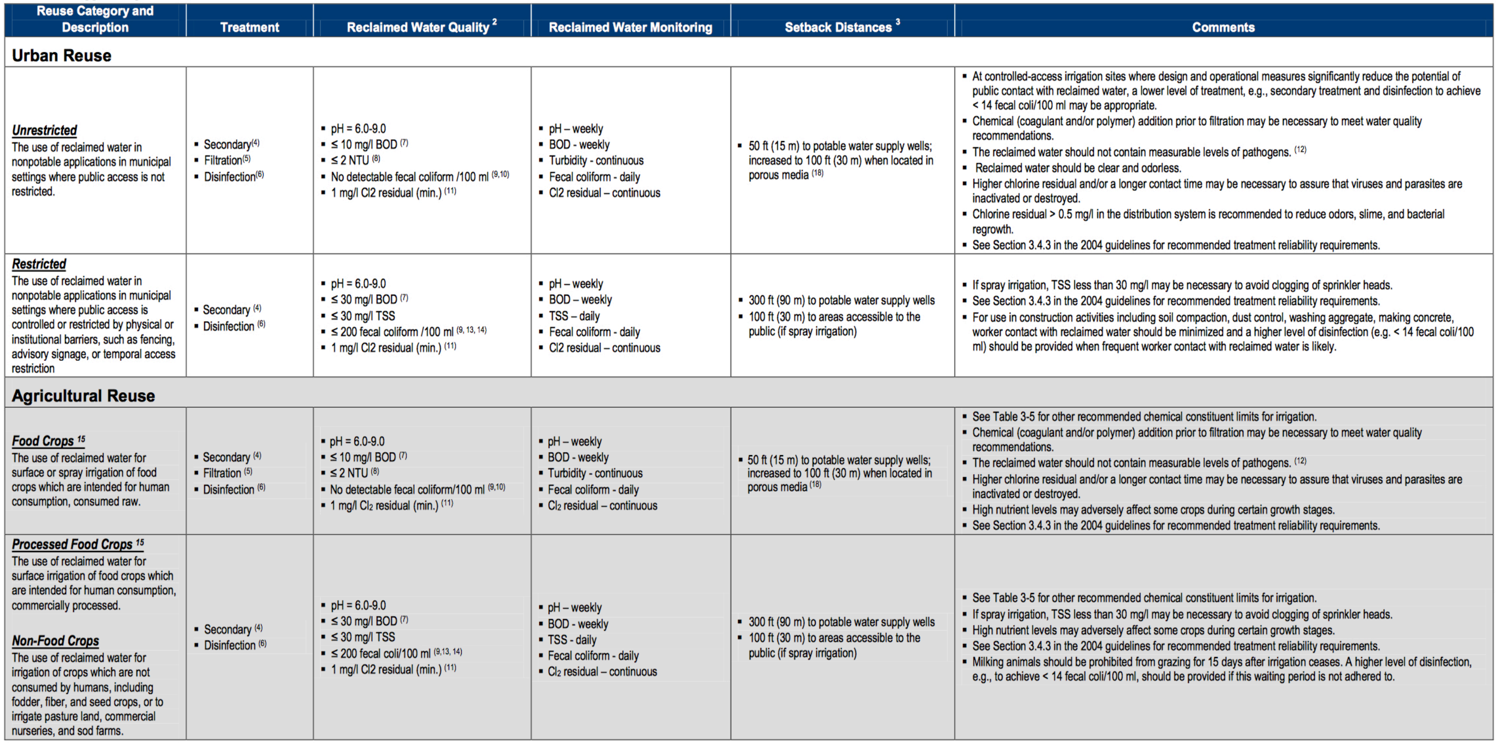
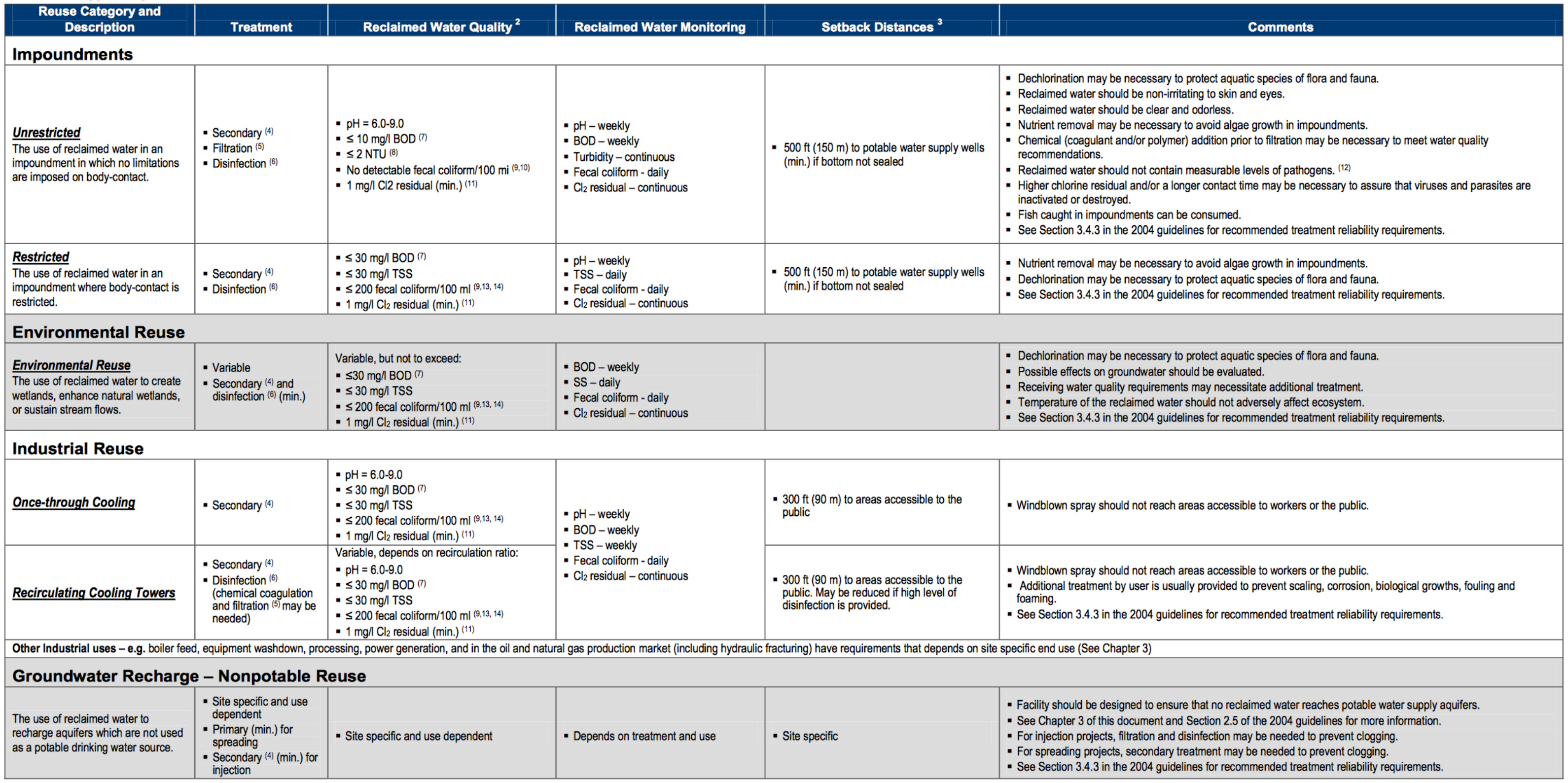
APPENDIX A

Suggested guidelines for water reuse (USEPA, 2012, p. 167-169)



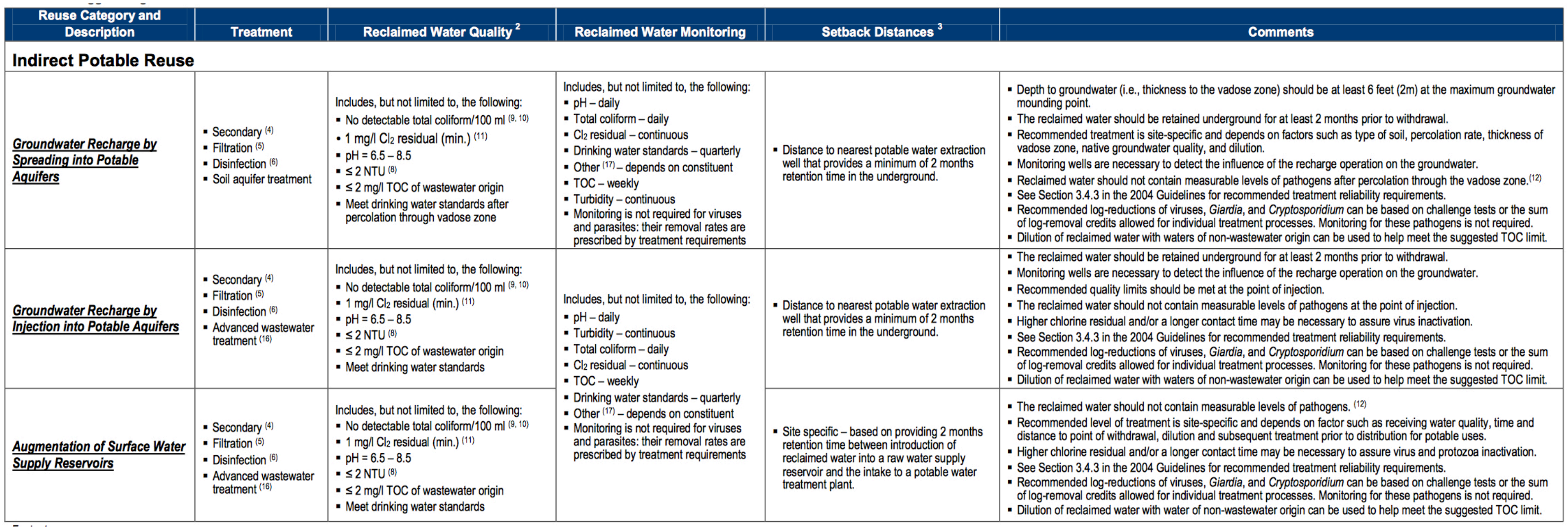
Reuse Category and Description	Treatment	Reclaimed Water Quality [2]	Reclaimed Water Monitoring	Setback Distances [3]	Comments
Urban Reuse					
Unrestricted The use of reclaimed water in nonpotable applications in municipal settings where public access is not restricted.	▪ Secondary(4) ▪ Filtration(5) ▪ Disinfection(6)	▪ pH = 6.0-9.0 ▪ ≤ 10 mg/l BOD (7) ▪ ≤ 2 NTU (8) ▪ No detectable fecal coliform /100 ml (9,10) ▪ 1 mg/l Cl2 residual (min.) (11)	▪ pH – weekly ▪ BOD - weekly ▪ Turbidity - continuous ▪ Fecal coliform - daily ▪ Cl2 residual – continuous	▪ 50 ft (15 m) to potable water supply wells; increased to 100 ft (30 m) when located in porous media (18)	▪ At controlled-access irrigation sites where design and operational measures significantly reduce the potential of public contact with reclaimed water, a lower level of treatment, e.g., secondary treatment and disinfection to achieve < 14 fecal coli/100 ml may be appropriate. ▪ Chemical (coagulant and/or polymer) addition prior to filtration may be necessary to meet water quality recommendations. ▪ The reclaimed water should not contain measurable levels of pathogens. (12) ▪ Reclaimed water should be clear and odorless. ▪ Higher chlorine residual and/or a longer contact time may be necessary to assure that viruses and parasites are inactivated or destroyed. ▪ Chlorine residual > 0.5 mg/l in the distribution system is recommended to reduce odors, slime, and bacterial regrowth. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Restricted The use of reclaimed water in nonpotable applications in municipal settings where public access is controlled or restricted by physical or institutional barriers, such as fencing, advisory signage, or temporal access restriction	▪ Secondary (4) ▪ Disinfection (6)	▪ pH = 6.0-9.0 ▪ ≤ 30 mg/l BOD (7) ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coliform /100 ml (9, 13, 14) ▪ 1 mg/l Cl2 residual (min.) (11)	▪ pH – weekly ▪ BOD – weekly ▪ TSS – daily ▪ Fecal coliform - daily ▪ Cl2 residual – continuous	▪ 300 ft (90 m) to potable water supply wells ▪ 100 ft (30 m) to areas accessible to the public (if spray irrigation)	▪ If spray irrigation, TSS less than 30 mg/l may be necessary to avoid clogging of sprinkler heads. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements. ▪ For use in construction activities including soil compaction, dust control, washing aggregate, making concrete, worker contact with reclaimed water should be minimized and a higher level of disinfection (e.g. < 14 fecal coli/100 ml) should be provided when frequent worker contact with reclaimed water is likely.
Agricultural Reuse					
Food Crops [15] The use of reclaimed water for surface or spray irrigation of food crops which are intended for human consumption, consumed raw.	▪ Secondary (4) ▪ Filtration (5) ▪ Disinfection (6)	▪ pH = 6.0-9.0 ▪ ≤ 10 mg/l BOD (7) ▪ ≤ 2 NTU (8) ▪ No detectable fecal coliform/100 ml (9,10) ▪ 1 mg/l Cl_2 residual (min.) (11)	▪ pH – weekly ▪ BOD - weekly ▪ Turbidity - continuous ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous	▪ 50 ft (15 m) to potable water supply wells; increased to 100 ft (30 m) when located in porous media (18)	▪ See Table 3-5 for other recommended chemical constituent limits for irrigation. ▪ Chemical (coagulant and/or polymer) addition prior to filtration may be necessary to meet water quality recommendations. ▪ The reclaimed water should not contain measurable levels of pathogens. (12) ▪ Higher chlorine residual and/or a longer contact time may be necessary to assure that viruses and parasites are inactivated or destroyed. ▪ High nutrient levels may adversely affect some crops during certain growth stages. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Processed Food Crops [15] The use of reclaimed water for surface irrigation of food crops which are intended for human consumption, commercially processed. ***Non-Food Crops*** The use of reclaimed water for irrigation of crops which are not consumed by humans, including fodder, fiber, and seed crops, or to irrigate pasture land, commercial nurseries, and sod farms.	▪ Secondary (4) ▪ Disinfection (6)	▪ pH = 6.0-9.0 ▪ ≤ 30 mg/l BOD (7) ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coli/100 ml (9,13, 14) ▪ 1 mg/l Cl2 residual (min.) (11)	▪ pH – weekly ▪ BOD - weekly ▪ TSS - daily ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous	▪ 300 ft (90 m) to potable water supply wells ▪ 100 ft (30 m) to areas accessible to the public (if spray irrigation)	▪ See Table 3-5 for other recommended chemical constituent limits for irrigation. ▪ If spray irrigation, TSS less than 30 mg/l may be necessary to avoid clogging of sprinkler heads. ▪ High nutrient levels may adversely affect some crops during certain growth stages. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements. ▪ Milking animals should be prohibited from grazing for 15 days after irrigation ceases. A higher level of disinfection, e.g., to achieve < 14 fecal coli/100 ml, should be provided if this waiting period is not adhered to.

Suggested guidelines for water reuse (USEPA, 2012, p. 167-169)



Reuse Category and Description	Treatment	Reclaimed Water Quality ^{2}	Reclaimed Water Monitoring	Setback Distances ^{3}	Comments
Impoundments					
Unrestricted The use of reclaimed water in an impoundment in which no limitations are imposed on body-contact.	▪ Secondary $^{(4)}$ ▪ Filtration $^{(5)}$ ▪ Disinfection $^{(6)}$	▪ pH = 6.0-9.0 ▪ ≤ 10 mg/l BOD $^{(7)}$ ▪ ≤ 2 NTU $^{(8)}$ ▪ No detectable fecal coliform/100 mi $^{(9,10)}$ ▪ 1 mg/l Cl2 residual (min.) $^{(11)}$	▪ pH – weekly ▪ BOD – weekly ▪ Turbidity – continuous ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous	▪ 500 ft (150 m) to potable water supply wells (min.) if bottom not sealed	▪ Dechlorination may be necessary to protect aquatic species of flora and fauna. ▪ Reclaimed water should be non-irritating to skin and eyes. ▪ Reclaimed water should be clear and odorless. ▪ Nutrient removal may be necessary to avoid algae growth in impoundments. ▪ Chemical (coagulant and/or polymer) addition prior to filtration may be necessary to meet water quality recommendations. ▪ Reclaimed water should not contain measurable levels of pathogens. $^{(12)}$ ▪ Higher chlorine residual and/or a longer contact time may be necessary to assure that viruses and parasites are inactivated or destroyed. ▪ Fish caught in impoundments can be consumed. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Restricted The use of reclaimed water in an impoundment where body-contact is restricted.	▪ Secondary $^{(4)}$ ▪ Disinfection $^{(6)}$	▪ ≤ 30 mg/l BOD $^{(7)}$ ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coliform/100 ml $^{(9,13, 14)}$ ▪ 1 mg/l Cl_2 residual (min.) $^{(11)}$	▪ pH – weekly ▪ TSS – daily ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous	▪ 500 ft (150 m) to potable water supply wells (min.) if bottom not sealed	▪ Nutrient removal may be necessary to avoid algae growth in impoundments. ▪ Dechlorination may be necessary to protect aquatic species of flora and fauna. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Environmental Reuse					
Environmental Reuse The use of reclaimed water to create wetlands, enhance natural wetlands, or sustain stream flows.	▪ Variable ▪ Secondary $^{(4)}$ and disinfection $^{(6)}$ (min.)	Variable, but not to exceed: ▪ ≤30 mg/l BOD $^{(7)}$ ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coliform/100 ml $^{(9,13, 14)}$ ▪ 1 mg/l Cl_2 residual (min.) $^{(11)}$	▪ BOD – weekly ▪ SS – daily ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous		▪ Dechlorination may be necessary to protect aquatic species of flora and fauna. ▪ Possible effects on groundwater should be evaluated. ▪ Receiving water quality requirements may necessitate additional treatment. ▪ Temperature of the reclaimed water should not adversely affect ecosystem. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Industrial Reuse					
Once-through Cooling	▪ Secondary $^{(4)}$	▪ pH = 6.0-9.0 ▪ ≤ 30 mg/l BOD $^{(7)}$ ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coliform/100 ml $^{(9,13, 14)}$ ▪ 1 mg/l Cl_2 residual (min.) $^{(11)}$	▪ pH – weekly ▪ BOD – weekly ▪ TSS – weekly ▪ Fecal coliform - daily ▪ Cl_2 residual – continuous	▪ 300 ft (90 m) to areas accessible to the public	▪ Windblown spray should not reach areas accessible to workers or the public.
Recirculating Cooling Towers	▪ Secondary $^{(4)}$ ▪ Disinfection $^{(6)}$ (chemical coagulation and filtration $^{(5)}$ may be needed)	Variable, depends on recirculation ratio: ▪ pH = 6.0-9.0 ▪ ≤ 30 mg/l BOD $^{(7)}$ ▪ ≤ 30 mg/l TSS ▪ ≤ 200 fecal coliform/100 ml $^{(9,13, 14)}$ ▪ 1 mg/l Cl_2 residual (min.) $^{(11)}$		▪ 300 ft (90 m) to areas accessible to the public. May be reduced if high level of disinfection is provided.	▪ Windblown spray should not reach areas accessible to workers or the public. ▪ Additional treatment by user is usually provided to prevent scaling, corrosion, biological growths, fouling and foaming. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.
Other Industrial uses – e.g. boiler feed, equipment washdown, processing, power generation, and in the oil and natural gas production market (including hydraulic fracturing) have requirements that depends on site specific end use (See Chapter 3)					
Groundwater Recharge – Nonpotable Reuse					
The use of reclaimed water to recharge aquifers which are not used as a potable drinking water source.	▪ Site specific and use dependent ▪ Primary (min.) for spreading ▪ Secondary $^{(4)}$ (min.) for injection	▪ Site specific and use dependent	▪ Depends on treatment and use	▪ Site specific	▪ Facility should be designed to ensure that no reclaimed water reaches potable water supply aquifers. ▪ See Chapter 3 of this document and Section 2.5 of the 2004 guidelines for more information. ▪ For injection projects, filtration and disinfection may be needed to prevent clogging. ▪ For spreading projects, secondary treatment may be needed to prevent clogging. ▪ See Section 3.4.3 in the 2004 guidelines for recommended treatment reliability requirements.

Suggested guidelines for water reuse (USEPA, 2012, p. 167-169)



Reuse Category and Description	Treatment	Reclaimed Water Quality [2]	Reclaimed Water Monitoring	Setback Distances [3]	Comments
Indirect Potable Reuse					
Groundwater Recharge by Spreading into Potable Aquifers	▪ Secondary (4) ▪ Filtration (5) ▪ Disinfection (6) ▪ Soil aquifer treatment	Includes, but not limited to, the following: ▪ No detectable total coliform/100 ml (9, 10) ▪ 1 mg/l Cl_2 residual (min.) (11) ▪ pH = 6.5 – 8.5 ▪ ≤ 2 NTU (8) ▪ ≤ 2 mg/l TOC of wastewater origin ▪ Meet drinking water standards after percolation through vadose zone	Includes, but not limited to, the following: ▪ pH – daily ▪ Total coliform – daily ▪ Cl_2 residual – continuous ▪ Drinking water standards – quarterly ▪ Other (17) – depends on constituent ▪ TOC – weekly ▪ Turbidity – continuous ▪ Monitoring is not required for viruses and parasites: their removal rates are prescribed by treatment requirements	▪ Distance to nearest potable water extraction well that provides a minimum of 2 months retention time in the underground.	▪ Depth to groundwater (i.e., thickness to the vadose zone) should be at least 6 feet (2m) at the maximum groundwater mounding point. ▪ The reclaimed water should be retained underground for at least 2 months prior to withdrawal. ▪ Recommended treatment is site-specific and depends on factors such as type of soil, percolation rate, thickness of vadose zone, native groundwater quality, and dilution. ▪ Monitoring wells are necessary to detect the influence of the recharge operation on the groundwater. ▪ Reclaimed water should not contain measurable levels of pathogens after percolation through the vadose zone.(12) ▪ See Section 3.4.3 in the 2004 Guidelines for recommended treatment reliability requirements. ▪ Recommended log-reductions of viruses, *Giardia*, and *Cryptosporidium* can be based on challenge tests or the sum of log-removal credits allowed for individual treatment processes. Monitoring for these pathogens is not required. ▪ Dilution of reclaimed water with waters of non-wastewater origin can be used to help meet the suggested TOC limit.
Groundwater Recharge by Injection into Potable Aquifers	▪ Secondary (4) ▪ Filtration (5) ▪ Disinfection (6) ▪ Advanced wastewater treatment (16)	Includes, but not limited to, the following: ▪ No detectable total coliform/100 ml (9, 10) ▪ 1 mg/l Cl_2 residual (min.) (11) ▪ pH = 6.5 – 8.5 ▪ ≤ 2 NTU (8) ▪ ≤ 2 mg/l TOC of wastewater origin ▪ Meet drinking water standards	Includes, but not limited to, the following: ▪ pH – daily ▪ Turbidity – continuous ▪ Total coliform – daily ▪ Cl_2 residual – continuous ▪ TOC – weekly ▪ Drinking water standards – quarterly ▪ Other (17) – depends on constituent ▪ Monitoring is not required for viruses and parasites: their removal rates are prescribed by treatment requirements	▪ Distance to nearest potable water extraction well that provides a minimum of 2 months retention time in the underground.	▪ The reclaimed water should be retained underground for at least 2 months prior to withdrawal. ▪ Monitoring wells are necessary to detect the influence of the recharge operation on the groundwater. ▪ Recommended quality limits should be met at the point of injection. ▪ The reclaimed water should not contain measurable levels of pathogens at the point of injection. ▪ Higher chlorine residual and/or a longer contact time may be necessary to assure virus inactivation. ▪ See Section 3.4.3 in the 2004 Guidelines for recommended treatment reliability requirements. ▪ Recommended log-reductions of viruses, *Giardia*, and *Cryptosporidium* can be based on challenge tests or the sum of log-removal credits allowed for individual treatment processes. Monitoring for these pathogens is not required. ▪ Dilution of reclaimed water with waters of non-wastewater origin can be used to help meet the suggested TOC limit.
Augmentation of Surface Water Supply Reservoirs	▪ Secondary (4) ▪ Filtration (5) ▪ Disinfection (6) ▪ Advanced wastewater treatment (16)	Includes, but not limited to, the following: ▪ No detectable total coliform/100 ml (9, 10) ▪ 1 mg/l Cl_2 residual (min.) (11) ▪ pH = 6.5 – 8.5 ▪ ≤ 2 NTU (8) ▪ ≤ 2 mg/l TOC of wastewater origin ▪ Meet drinking water standards		▪ Site specific – based on providing 2 months retention time between introduction of reclaimed water into a raw water supply reservoir and the intake to a potable water treatment plant.	▪ The reclaimed water should not contain measurable levels of pathogens. (12) ▪ Recommended level of treatment is site-specific and depends on factor such as receiving water quality, time and distance to point of withdrawal, dilution and subsequent treatment prior to distribution for potable uses. ▪ Higher chlorine residual and/or a longer contact time may be necessary to assure virus and protozoa inactivation. ▪ See Section 3.4.3 in the 2004 Guidelines for recommended treatment reliability requirements. ▪ Recommended log-reductions of viruses, *Giardia*, and *Cryptosporidium* can be based on challenge tests or the sum of log-removal credits allowed for individual treatment processes. Monitoring for these pathogens is not required. ▪ Dilution of reclaimed water with water of non-wastewater origin can be used to help meet the suggested TOC limit.

APPENDIX B

Short-Term Study: Baseline Assessment

Statistical Data

Table B1

Dissolved Oxygen as measured during the Short-Term Study: Baseline Assessment

Dissolved Oxygen (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	6.63	0.02081666	0.035094032
2	6.20	0.02	0.033717256
4	5.74	0.045825757	0.077255938
8	5.59	0.005773503	0.009733333
12	5.72	0.035118846	0.059205555
24	5.66	0.015275252	0.025751979
48	5.59	0.015275252	0.025751979
72	5.72	0.011547005	0.019466667
96	5.58	0.005773503	0.009733333

n=3 and Confidence Coefficient is 2.92 (95% level of confidence)

Table B2

Temperature as measured during the Short-Term Study: Baseline Assessment

Temperature (°F)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	56.20	0.1	0.168586279
2	55.77	0.152752523	0.257519794
4	55.87	0.251661148	0.424266164
8	56.73	0.057735027	0.097333333
12	55.23	0.493288286	0.831616365
24	56.37	0.230940108	0.389333333
***48**	55.40	N/A	N/A
72	56.03	0.2081666	0.350940324
96	57.67	0.251661148	0.424266164

n=3 and Confidence Coefficient is 2.92 (95% level of confidence);
* represents n=1 for that data

Short-Term Study: Baseline Assessment

Statistical Data

Table B3

pH as measured during the Short-Term Study: Baseline Assessment			
pH			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	9.21	0.005773503	0.009733333
2	9.00	0.005773503	0.009733333
4	8.71	0.015275252	0.025751979
8	8.13	0.01	0.016858628
12	7.81	0.005773503	0.009733333
24	7.60	1.08779E-15	1.83387E-15
48	7.40	0.005773503	0.009733333
72	7.34	0.01	0.016858628
96	6.96	0.015275252	0.025751979
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Table B4

Turbidity as measured during the Short-Term Study: Baseline Assessment			
Turbidity (NTU)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	63.37	0.404145188	0.681333333
2	58.23	0.513160144	0.86511759
4	54.23	1.234233905	2.08074901
8	45.47	0.763762616	1.287598971
12	34.10	0.2	0.337172557
24	27.33	0.230940108	0.389333333
48	25.73	0.152752523	0.257519794
72	21.33	0.404145188	0.681333333
96	19.07	0.115470054	0.194666667
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Short-Term Study: Baseline Assessment

Statistical Data

Table B5

Chemical Oxygen Demand as measured during the Short-Term Study: Baseline Assessment

COD (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	1027.67	0.577350269	0.973333333
***2**	849.00	N/A	N/A
***4**	780.00	N/A	N/A
8	684.33	0.577350269	0.973333333
***12**	651.00	N/A	N/A
24	596.33	0.577350269	0.973333333
***48**	560.00	N/A	N/A
***72**	453.00	N/A	N/A
96	435.67	0.577350269	0.973333333

n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data

Table B6

Total Suspended Solids as measured during the Short-Term Study: Baseline Assessment

TSS (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	66.6667	1.154700538	1.946666667
2	66.6667	2.309401077	3.893333333
4	51.3333	1.154700538	1.946666667
***8**	44.0000	N/A	N/A
12	24.6667	1.154700538	1.946666667
24	13.3333	1.154700538	1.946666667
***48**	4.0000	N/A	N/A
***72**	4.0000	N/A	N/A
96	2.6667	2.309285607	3.893138667

n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data

Short-Term Study: Baseline Assessment

Nominal and % Difference since time zero

Table B7

Dissolved Oxygen nominal and % difference since time zero as measured during the Short-Term Study: Baseline Assessment		
Dissolved Oxygen (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-0.43	-6%
4	-0.89	-13%
8	-1.04	-16%
12	-0.91	-14%
24	-0.97	-15%
48	-1.03	-16%
72	-0.92	-14%
96	-1.05	-16%

Table B8

Temperature nominal and % difference since time zero as measured during the Short-Term Study: Baseline Assessment		
Temperature (°F)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-0.43	-1%
4	-0.33	-1%
8	0.53	1%
12	-0.97	-2%
24	0.17	0%
48	-0.80	-1%
72	-0.17	0%
96	1.47	3%

Short-Term Study: Baseline Assessment

Nominal and % Difference since time zero

Table B9

pH nominal difference since time zero as measured during the Short-Term Study: Baseline Assessment

pH	
Time (hrs)	**Nominal**
0	0
2	-0.22
4	-0.50
8	-1.08
12	-1.40
24	-1.61
48	-1.81
72	-1.87
96	-2.25

Table B10

Turbidity nominal and % difference since time zero as measured during the Short-Term Study: Baseline Assessment

Turbidity (NTU)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-5.13	-8%
4	-9.13	-14%
8	-17.90	-28%
12	-29.27	-46%
24	-36.03	-57%
48	-37.63	-59%
72	-42.03	-66%
96	-44.30	-70%

Short-Term Study: Baseline Assessment

Nominal and % Difference since time zero

Table B11

Chemical Oxygen Demand nominal and % difference since time zero as measured during the Short-Term Study: Baseline Assessment

COD (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-178.67	-17%
4	-247.67	-24%
8	-343.33	-33%
12	-376.67	-37%
24	-431.33	-42%
48	-467.67	-46%
72	-574.67	-56%
96	-592.00	-58%

Table B12

Total Suspended Solids nominal and % difference since time zero as measured during the Short-Term Study: Baseline Assessment

TSS (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	0.0000	0%
4	-15.3333	-23%
8	-22.6667	-34%
12	-42.0000	-63%
24	-53.3333	-80%
48	-62.6667	-94%
72	-62.6667	-94%
96	-63.9999	-96%

Short-Term Study: No Plants, Biofilter only

Statistical Data

Table B13

Dissolved Oxygen as measured during the Short-Term Study: No Plants, Biofilter only			
Dissolved Oxygen (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	3.20	0.056862407	0.095862216
2	4.10	0.015275252	0.025751979
4	3.66	0.037859389	0.063825735
8	4.55	0.005773503	0.009733333
12	3.42	0.02081666	0.035094032
24	2.88	0.015275252	0.025751979
48	3.15	0.01	0.016858628
72	2.01	0.005773503	0.009733333
96	4.42	0.005773503	0.009733333
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Table B14

Temperature as measured during the Short-Term Study: No Plants, Biofilter only			
Temperature (°F)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	61.07	0.115470054	0.194666667
2	59.67	0.057735027	0.097333333
4	59.63	0.321455025	0.541929065
8	57.00	0.2	0.337172557
12	58.67	0.115470054	0.194666667
24	65.33	0.305505046	0.515039589
48	60.80	0.2	0.337172557
72	64.93	0.057735027	0.097333333
96	63.37	0.321455025	0.541929065
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Short-Term Study: No Plants, Biofilter only

Statistical Data

Table B15

pH as measured during the Short-Term Study: No Plants, Biofilter only			
pH			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	9.09	0.005773503	0.009733333
2	8.92	0.005773503	0.009733333
4	8.58	0.015275252	0.025751979
8	8.34	0.005773503	0.009733333
***12**	7.84	N/A	N/A
24	7.77	0.055075705	0.092850082
48	7.59	0.011547005	0.019466667
***72**	7.46	N/A	N/A
96	7.24	1.08779E-15	1.83387E-15
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Table B16

Turbidity as measured during the Short-Term Study: No Plants, Biofilter only			
Turbidity (NTU)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	64.03	0.2081666	0.350940324
2	48.23	0.404145188	0.681333333
4	35.03	0.550757055	0.928500823
8	28.80	0.2	0.337172557
12	18.73	0.472581563	0.79670767
24	16.00	0.1	0.168586279
48	7.90	0.015275252	0.025751979
72	5.29	0.011547005	0.019466667
96	4.58	0.017320508	0.0292
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Short-Term Study: No Plants, Biofilter only

Statistical Data

Table B17

Chemical Oxygen Demand as measured during the Short-Term Study: No Plants, Biofilter only

COD (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	592.33	0.577350269	0.973333333
2	458.67	0.577350269	0.973333333
4	401.67	0.577350269	0.973333333
***8**	382.00	N/A	N/A
***12**	311.00	N/A	N/A
***24**	258.00	N/A	N/A
48	172.67	1.154700538	1.946666667
72	145.67	0.577350269	0.973333333
96	131.33	0.577350269	0.973333333

n=3 and Confidence Coefficient is 2.92 (95% level of confidence);
* represents n=1 for that data

Table B18

Total Suspended Solids as measured during the Short-Term Study: No Plants, Biofilter only

TSS (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
***0**	40	N/A	N/A
2	20.6667	1.154700538	1.946666667
4	24.6667	1.154700538	1.946666667
8	30.6667	1.154700538	1.946666667
12	7.3333	1.154700538	1.946666667
24	8.6667	1.154700538	1.946666667
***48**	12.0000	N/A	N/A
72	8.6667	1.154700538	1.946666667
***96**	8.0000	N/A	N/A

n=3 and Confidence Coefficient is 2.92 (95% level of confidence);
* represents n=1 for that data

Short-Term Study: No Plants, Biofilter only

Nominal and % Difference since time zero

Table B19

Dissolved Oxygen nominal and % difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

Dissolved Oxygen (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	0.90	28%
4	0.46	14%
8	1.34	42%
12	0.22	7%
24	-0.33	-10%
48	-0.05	-2%
72	-1.19	-37%
96	1.22	38%

Table B20

Temperature nominal and % difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

Temperature (°F)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-1.40	-2%
4	-1.43	-2%
8	-4.07	-7%
12	-2.40	-4%
24	4.27	7%
48	-0.27	0%
72	3.87	6%
96	2.30	4%

Short-Term Study: No Plants, Biofilter only

Nominal and % Difference since time zero

Table B21

pH nominal difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

pH	
Time (hrs)	**Nominal**
0	0
2	-0.16
4	-0.51
8	-0.74
12	-1.25
24	-1.31
48	-1.50
72	-1.63
96	-1.85

Table B22

Turbidity nominal and % difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

Turbidity (NTU)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-15.80	-25%
4	-29.00	-45%
8	-35.23	-55%
12	-45.30	-71%
24	-48.03	-75%
48	-56.14	-88%
72	-58.75	-92%
96	-59.45	-93%

Short-Term Study: No Plants, Biofilter only

Nominal and % Difference since time zero

Table B23

Chemical Oxygen Demand nominal and % difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

COD (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-133.67	-23%
4	-190.67	-32%
8	-210.33	-36%
12	-281.33	-47%
24	-334.33	-56%
48	-419.67	-71%
72	-446.67	-75%
96	-461.00	-78%

Table B24

Total Suspended Solids nominal and % difference since time zero as measured during the Short-Term Study: No Plants, Biofilter only

TSS (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-19.3333	-48%
4	-15.3333	-38%
8	-9.3333	-23%
12	-32.6667	-82%
24	-31.3333	-78%
48	-28.0000	-70%
72	-31.3333	-78%
96	-32.0000	-80%

Short-Term Study: No biofilter, Plants only

Statistical Data

Table B25

Dissolved Oxygen as measured during the Short-Term Study: No biofilter, Plants only			
Dissolved Oxygen (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	3.15	0.079372539	0.13381121
2	3.79	0.076376262	0.128759897
4	3.26	0.02081666	0.035094032
8	3.64	0.055677644	0.093864867
12	4.62	0.04163332	0.070188065
24	2.88	0.025166115	0.042426616
48	2.42	0.01	0.016858628
72	2.60	0.02081666	0.035094032
96	2.95	0.060277138	0.101618983
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Table B26

Temperature as measured during the Short-Term Study: No biofilter, Plants only			
Temperature (°F)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	67.17	0.115470054	0.194666667
2	65.93	0.230940108	0.389333333
4	68.13	0.115470054	0.194666667
8	67.33	0.2081666	0.350940324
***12**	64.60	N/A	N/A
24	68.07	0.602771377	1.016189834
48	70.23	0.251661148	0.424266164
72	68.03	0.2081666	0.350940324
96	66.80	0.1	0.168586279
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Short-Term Study: No biofilter, Plants only

Statistical Data

Table B27

pH as measured during the Short-Term Study: No biofilter, Plants only

pH			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	9.01	0.01	0.016858628
2	8.84	0.005773503	0.009733333
4	8.43	0.040414519	0.068133333
8	8.20	0.02081666	0.035094032
12	8.17	0.01	0.016858628
24	7.95	0.055677644	0.093864867
48	7.75	0.032145503	0.054192906
72	7.68	0.02	0.033717256
96	7.66	0.011547005	0.019466667

n=3 and Confidence Coefficient is 2.92 (95% level of confidence)

Table B28

Turbidity as measured during the Short-Term Study: No biofilter, Plants only

Turbidity (NTU)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	69.60	0.360555128	0.607846472
2	65.17	0.115470054	0.194666667
4	51.43	0.321455025	0.541929065
8	49.50	0.608276253	1.025470299
12	46.00	0.871779789	1.469701103
24	45.57	0.2081666	0.350940324
48	44.93	0.550757055	0.928500823
72	22.13	0.945163125	1.59341534
96	8.16	0.015275252	0.025751979

n=3 and Confidence Coefficient is 2.92 (95% level of confidence)

Short-Term Study: No biofilter, Plants only

Statistical Data

Table B29

Chemical Oxygen Demand as measured during the Short-Term Study: No biofilter, Plants only			
COD (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	818.67	0.577350269	0.973333333
2	816.33	0.577350269	0.973333333
4	703.67	0.577350269	0.973333333
8	697.33	0.577350269	0.973333333
***12**	670.00	N/A	N/A
24	591.00	1.732050808	2.92
48	473.33	0.577350269	0.973333333
***72**	296.00	N/A	N/A
96	175.33	0.577350269	0.973333333
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Table B30

Total Suspended Solids as measured during the Short-Term Study: No biofilter, Plants only			
TSS (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	149.3333	1.154700538	1.946666667
2	99.3333	1.154700538	1.946666667
4	89.3333	1.154700538	1.946666667
***8**	46.0000	N/A	N/A
12	333.3333	11.54700538	19.46666667
24	393.3333	11.54700538	19.46666667
***48**	356.0000	N/A	N/A
72	333.3333	3.055050463	5.150395886
96	262.0000	2	3.371725572
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Short-Term Study: No biofilter, Plants only

Nominal and % Difference since time zero

Table B31

Dissolved Oxygen nominal and % difference since time zero as measured during the Short-Term Study: No biofilter, Plants only

Dissolved Oxygen (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	0.64	20%
4	0.11	4%
8	0.49	16%
12	1.47	47%
24	-0.27	-9%
48	-0.73	-23%
72	-0.55	-18%
96	-0.20	-6%

Table B32

Temperature nominal and % difference since time zero as measured during the Short-Term Study: No biofilter, Plants only

Temperature (°F)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-1.23	-2%
4	0.97	1%
8	0.17	0%
12	-2.57	-4%
24	0.90	1%
48	3.07	5%
72	0.87	1%
96	-0.37	-1%

Short-Term Study: No biofilter, Plants only

Nominal and % Difference since time zero

Table B33

pH nominal difference since time zero as measured during the Short-Term Study: No biofilter, Plants only	
pH	
Time (hrs)	**Nominal**
0	0
2	-0.17
4	-0.58
8	-0.81
12	-0.84
24	-1.06
48	-1.26
72	-1.33
96	-1.35

Table B34

Turbidity nominal and % difference since time zero as measured during the Short-Term Study: No biofilter, Plants only		
Turbidity (NTU)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-4.43	-6%
4	-18.17	-26%
8	-20.10	-29%
12	-23.60	-34%
24	-24.03	-35%
48	-24.67	-35%
72	-47.47	-68%
96	-61.44	-88%

Short-Term Study: No biofilter, Plnts only

Nominal and % Difference since time zero

Table B35

Chemical Oxygen Demand nominal and % difference since time zero as measured during the Short-Term Study: No biofilter, Plants only

COD (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-2.33	0%
4	-115.00	-14%
8	-121.33	-15%
12	-148.67	-18%
24	-227.67	-28%
48	-345.33	-42%
72	-522.67	-64%
96	-643.33	-79%

Table B36

Total Suspended Solids nominal and % difference since time zero as measured during the Short-Term Study: No biofilter, Plants only

TSS (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-50.0000	-33%
4	-60.0000	-40%
8	-103.3333	-69%
12	184.0000	123%
24	244.0000	163%
48	206.6667	138%
72	184.0000	123%
96	112.6667	75%

Short-Term Study: Complete System

Statistical Data

Table B37

Dissolved Oxygen as measured during the Short-Term Study: Complete System			
Dissolved Oxygen (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	3.93	0.005773503	0.009733333
2	4.31	0.015275252	0.025751979
4	4.03	0.015275252	0.025751979
8	4.02	0.01	0.016858628
12	3.94	0.035118846	0.059205555
24	2.67	0.005773503	0.009733333
48	2.59	0.011547005	0.019466667
72	4.83	0.005773503	0.009733333
***96**	4.48	N/A	N/A
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Table B38

Temperature as measured during the Short-Term Study: Complete System			
Temperature (°F)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	58.53	0.2081666	0.350940324
2	55.07	0.115470054	0.194666667
4	56.60	0.264575131	0.446037368
8	54.07	0.057735027	0.097333333
12	53.30	0.264575131	0.446037368
24	60.43	0.2081666	0.350940324
48	62.50	0.1	0.168586279
72	59.83	0.152752523	0.257519794
96	62.77	0.057735027	0.097333333
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Short-Term Study: Complete System

Statistical Data

Table B39

pH as measured during the Short-Term Study: Complete System			
pH			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	9.10	0.005773503	0.009733333
2	8.77	0.015275252	0.025751979
4	8.43	0.01	0.016858628
8	8.09	0.01	0.016858628
12	7.90	0.005773503	0.009733333
24	7.74	0.005773503	0.009733333
48	7.72	0.02081666	0.035094032
72	7.54	0.011547005	0.019466667
96	7.46	0.01	0.016858628
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Table B40

Turbidity as measured during the Short-Term Study: Complete System			
Turbidity (NTU)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	65.30	0.1	0.168586279
2	53.77	0.321455025	0.541929065
4	42.03	0.305505046	0.515039589
8	35.90	0.1	0.168586279
12	31.47	0.611010093	1.030079177
24	23.73	0.152752523	0.257519794
48	14.00	0.1	0.168586279
72	9.76	0.036055513	0.060784647
96	7.66	0.02	0.033717256
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Short-Term Study: Complete System

Statistical Data

Table B41

Chemical Oxygen Demand as measured during the Short-Term Study: Complete System			
COD (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	737.33	0.577350269	0.973333333
***2**	642.00	N/A	N/A
4	560.67	0.577350269	0.973333333
***8**	496.00	N/A	N/A
***12**	464.00	N/A	N/A
***24**	386.00	N/A	N/A
***48**	291.00	N/A	N/A
72	238.67	0.577350269	0.973333333
96	206.67	0.577350269	0.973333333
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Table B42

Total Suspended Solids as measured during the Short-Term Study: Complete System			
TSS (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	107.3333	1.154700538	1.946666667
2	106.6667	1.154700538	1.946666667
4	87.3333	1.154700538	1.946666667
***8**	80.0000	N/A	N/A
***12**	52.0000	N/A	N/A
24	40.6667	1.154700538	1.946666667
48	33.3333	1.154700538	1.946666667
***72**	30.0000	N/A	N/A
***96**	2.0000	N/A	N/A
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Short-Term Study: Complete System

Nominal and % Difference since time zero

Table B43

Dissolved Oxygen nominal and % difference since time zero as measured during the Short-Term Study: Complete System

Dissolved Oxygen (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	0.38	10%
4	0.09	2%
8	0.09	2%
12	0.00	0%
24	-1.26	-32%
48	-1.34	-34%
72	0.90	23%
96	0.55	14%

Table B44

Temperature nominal and % difference since time zero as measured during the Short-Term Study: Complete System

Temperature (°F)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-3.47	-6%
4	-1.93	-3%
8	-4.47	-8%
12	-5.23	-9%
24	1.90	3%
48	3.97	7%
72	1.30	2%
96	4.23	7%

Short-Term Study: Complete System

Nominal and % Difference since time zero

Table B45

pH nominal difference since time zero as measured during the Short-Term Study: Complete System

pH	
Time (hrs)	**Nominal**
0	0
2	-0.33
4	-0.67
8	-1.01
12	-1.19
24	-1.36
48	-1.37
72	-1.55
96	-1.64

Table B46

Turbidity nominal and % difference since time zero as measured during the Short-Term Study: Complete System

Turbidity (NTU)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-11.53	-18%
4	-23.27	-36%
8	-29.40	-45%
12	-33.83	-52%
24	-41.57	-64%
48	-51.30	-79%
72	-55.54	-85%
96	-57.64	-88%

Short-Term Study: Complete System

Nominal and % Difference since time zero

Table B47

Chemical Oxygen Demand nominal and % difference since time zero as measured during the Short-Term Study: Complete System

COD (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-95.33	-13%
4	-176.67	-24%
8	-241.33	-33%
12	-273.33	-37%
24	-351.33	-48%
48	-446.33	-61%
72	-498.67	-68%
96	-530.67	-72%

Table B48

Total Suspended Solids nominal and % difference since time zero as measured during the Short-Term Study: Complete System

TSS (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
2	-0.6667	-1%
4	-20.0000	-19%
8	-27.3333	-25%
12	-55.3333	-52%
24	-66.6667	-62%
48	-74.0000	-69%
72	-77.3333	-72%
96	-105.3333	-98%

APPENDIX C

Batch Study

Statistical Data

Table C1

Dissolved Oxygen as measured during the Batch Study			
Dissolved Oxygen (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	7.75	0.01	0.016858628
48	4.09	0.005773503	0.009733333
0	6.52	0.011547005	0.019466667
48	4.22	0.015275252	0.025751979
0	7.42	0.032145503	0.054192906
48	4.05	0.045825757	0.077255938
0	9.03	0.030550505	0.051503959
48	4.19	0.005773503	0.009733333
0	7.60	0.005773503	0.009733333
48	4.04	0.005773503	0.009733333
0	7.12	0.574485277	0.968503349
48	4.16	0.052915026	0.089207474
0	7.48	0.005773503	0.009733333
48	5.11	0.005773503	0.009733333
0	9.88	0.005773503	0.009733333
48	5.62	0.02081666	0.035094032
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Batch Study

Statistical Data

Table C2

Temperature as measured during the Batch Study			
Temperature (°F)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	64.80	0.1	0.168586279
48	69.90	0.1	0.168586279
0	69.03	0.057735027	0.097333333
48	69.77	0.321455025	0.541929065
0	67.70	0.1	0.168586279
48	63.07	0.057735027	0.097333333
0	62.37	0.057735027	0.097333333
***48**	68.60	N/A	N/A
0	66.07	0.115470054	0.194666667
48	61.07	0.115470054	0.194666667
0	63.17	0.057735027	0.097333333
48	60.63	0.472581563	0.79670767
0	62.17	0.152752523	0.257519794
48	57.23	0.2081666	0.350940324
0	57.33	0.115470054	0.194666667
48	60.67	0.305505046	0.515039589
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Batch Study

Statistical Data

Table C3

pH as measured during the Batch Study			
pH			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	8.23	0.005773503	0.009733333
48	7.54	0.005773503	0.009733333
0	8.27	0.02081666	0.035094032
48	7.41	0.005773503	0.009733333
0	8.57	0.005773503	0.009733333
48	7.47	0.011547005	0.019466667
0	8.61	0.011547005	0.019466667
48	7.03	0.005773503	0.009733333
0	8.19	0.005773503	0.009733333
48	7.34	0.005773503	0.009733333
0	8.47	0.01	0.016858628
48	7.29	0.005773503	0.009733333
0	8.59	0.011547005	0.019466667
48	7.34	0.036055513	0.060784647
0	8.67	0.005773503	0.009733333
48	7.39	0.005773503	0.009733333
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Batch Study

Statistical Data

Table C4

Turbidity as measured during the Batch Study			
Turbidity (NTU)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	25.63	0.251661148	0.424266164
48	6.02	0.02	0.033717256
0	29.07	0.802080628	1.352197882
48	5.46	0.193993127	0.327045794
0	16.27	0.2081666	0.350940324
48	3.72	0.02081666	0.035094032
0	33.03	0.635085296	1.070666667
48	4.16	0.015275252	0.025751979
0	29.50	0.1	0.168586279
48	5.30	0.005773503	0.009733333
0	26.60	0.2	0.337172557
48	4.91	0.036055513	0.060784647
0	30.43	0.076376262	0.128759897
48	6.24	0.035118846	0.059205555
0	30.40	0.4	0.674345114
48	6.15	0.011547005	0.019466667
n=3 and Confidence Coefficient is 2.92 (95% level of confidence)			

Batch Study

Statistical Data

Table C5

Chemical Oxygen Demand as measured during the Batch Study

COD (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	342.33	0.577350269	0.973333333
48	186.67	0.577350269	0.973333333
***0**	485.00	N/A	N/A
48	187.67	0.577350269	0.973333333
0	352.67	0.577350269	0.973333333
***48**	169.00	N/A	N/A
***0**	577.00	N/A	N/A
48	190.67	0.577350269	0.973333333
***0**	437.00	N/A	N/A
48	213.67	0.577350269	0.973333333
0	683.67	0.577350269	0.973333333
***48**	198.00	N/A	N/A
***0**	488.00	N/A	N/A
48	223.67	0.577350269	0.973333333
0	568.33	0.577350269	0.973333333
48	147.33	0.577350269	0.973333333

n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data

Batch Study

Statistical Data

Table C6

Total Suspended Solids as measured during the Batch Study			
TSS (mg/L)			
Time (hrs)	Average	Standard Deviation	Margin of Error
0	88.6666	5.773502692	9.733333333
48	23.3333	1.154700538	1.946666667
***0**	104.0000	N/A	N/A
48	21.3333	1.154700538	1.946666667
0	85.3333	1.154700538	1.946666667
48	24.6667	1.154700538	1.946666667
0	94.6667	1.154700538	1.946666667
***48**	14.0000	N/A	N/A
0	100.6667	1.154700538	1.946666667
***48**	10.0000	N/A	N/A
0	82.6667	1.154700538	1.946666667
***48**	18.0000	N/A	N/A
***0**	92.0000	N/A	N/A
48	16.6667	1.154700538	1.946666667
0	83.3333	1.154700538	1.946666667
48	13.3333	1.154700538	1.946666667
n=3 and Confidence Coefficient is 2.92 (95% level of confidence); * represents n=1 for that data			

Batch Study

Nominal and % Difference since time zero

Table C7

Dissolved Oxygen nominal and % difference since time zero as measured during the Batch Study

Dissolved Oxygen (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
48	-3.66	-47%
0	0.00	0%
48	-2.30	-35%
0	0.00	0%
48	-3.37	-45%
0	0.00	0%
48	-4.85	-54%
0	0.00	0%
48	-3.56	-47%
0	0.00	0%
48	-2.96	-42%
0	0.00	0%
48	-2.36	-32%
0	0.00	0%
48	-4.25	-43%

Batch Study

Nominal and % Difference since time zero

Table C8

Temperature nominal and % difference since time zero as measured during the Batch Study

Temperature (°F)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
48	5.10	8%
0	0.00	0%
48	0.73	1%
0	0.00	0%
48	-4.63	-7%
0	0.00	0%
48	6.23	10%
0	0.00	0%
48	-5.00	-8%
0	0.00	0%
48	-2.53	-4%
0	0.00	0%
48	-4.93	-8%
0	0.00	0%
48	3.33	6%

Batch Study

Nominal and % Difference since time zero

Table C9

pH nominal difference since time zero as measured during the Batch Study	
pH	
Time (hrs)	**Nominal**
0	0
48	-0.69
0	0.00
48	-0.86
0	0.00
48	-1.09
0	0.00
48	-1.58
0	0.00
48	-0.84
0	0.00
48	-1.18
0	0.00
48	-1.25
0	0.00
48	-1.27

Batch Study

Nominal and % Difference since time zero

Table C10

Turbidity nominal and % difference since time zero as measured during the Batch Study		
Turbidity (NTU)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
48	-19.61	-77%
0	0.00	0%
48	-23.60	-81%
0	0.00	0%
48	-12.54	-77%
0	0.00	0%
48	-28.87	-87%
0	0.00	0%
48	-24.20	-82%
0	0.00	0%
48	-21.69	-82%
0	0.00	0%
48	-24.20	-80%
0	0.00	0%
48	-24.25	-80%

Batch Study

Nominal and % Difference since time zero

Table C11

Chemical Oxygen Demand nominal and % difference since time zero as measured during the Batch Study

COD (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
48	-155.67	-45%
0	0.00	0%
48	-297.33	-61%
0	0.00	0%
48	-183.67	-52%
0	0.00	0%
48	-386.33	-67%
0	0.00	0%
48	-223.33	-51%
0	0.00	0%
48	-485.67	-71%
0	0.00	0%
48	-264.33	-54%
0	0.00	0%
48	-421.00	-74%

Batch Study

Nominal and % Difference since time zero

Table C12

Total Suspended Solids nominal and % difference since time zero as measured during the Batch Study		
TSS (mg/L)		
Time (hrs)	**Nominal**	**% Difference**
0	0	0%
48	-65.33	-74%
0	0.00	0%
48	-82.67	-79%
0	0.00	0%
48	-60.67	-71%
0	0.00	0%
48	-80.67	-85%
0	0.00	0%
48	-90.67	-90%
0	0.00	0%
48	-64.67	-78%
0	0.00	0%
48	-75.33	-82%
0	0.00	0%
48	-70.00	-84%

Vita

Benjamin Martin, son of Edlene and Thomas Martin, was born and raised in Raleigh, North Carolina. Benjamin graduated from Broughton High School in the spring of 2008 and quickly began his undergraduate studies at North Carolina State University in the fall of 2008. As a child, Benjamin always had a fondness for wild life and the environment. This love for the environment motivated Benjamin to major in Environmental Technology & Management at NC State. During his time at NC State, Benjamin worked on many projects, such as biomass production and assessing sustainable building materials. Benjamin graduated from North Carolina State University in December 2013 and immediately started looking at graduate programs to continue his environmental studies. Benjamin moved to Boone, North Carolina in the Fall of 2014 to pursue a Master's of Science degree with a dual concentration in Appropriate Technology and Building Science at Appalachian State University. During this two-year program, Benjamin developed an innovative greywater system and coordinated with the "living systems" research that includes a treatment designed to clean biofuel waste. Benjamin earned his master's degree in December 2016 and is now working as a Crew Leader for Sundance Power Systems in Asheville, North Carolina.