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# ANALYSIS OF THE FLORIDA'S SHOWCASE GREEN ENVIROHOME WATER/WASTEWATER SYSTEMS AND DEVELOPMENT OF A COST-BENEFIT GREEN ROOF OPTIMIZATION MODEL

by

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B.S University of Central Florida, 2008

A thesis submitted in partial fulfillment of the requirements
for the degree of Master of Science
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# ABSTRACT

The Florida Showcase Green Envirohome (FSGE) incorporates many green technologies. FSGE is built to meet or exceed 12 green building guidelines and obtain 8 green building certificates. The two-story 3292 $ft^2$ home is a “Near Zero-Loss Home™”, “Near Zero-Energy Home™”, "Near Zero-Runoff Home™", and “Near Zero-Maintenance Home™”. It is spawned from the consumer-driven necessity to build a home resistant to hurricanes, tornadoes, floods, fire, mold, termites, impacts, and even earthquakes given up to 500% increase in insurance premiums in natural disaster zones, the dwindling flexibility and coverage of insurance policies, and rising energy, water and maintenance costs (FSGE 2008).

The FSGE captures its stormwater runoff from the green roof, metal roof and wood decking area and routes it to the sustainable water cistern. Graywater from the home (after being disinfected using ozone) is also routed to the sustainable water cistern. This water stored in the sustainable water cistern is used for irrigation of the green roof, ground level landscape, and for toilet flushing water. This study was done in two phases. During phase one, only stormwater runoff from the green roof, metal roof and wood decking area is routed to the sustainable water cistern. Then, during phase two, the water from the graywater system is added to the sustainable water cistern. The sustainable water cistern quality is analyzed during both phases to determine if the water is acceptable for irrigation and also if it is suitable for use as toilet flushing water. The water quality of the sustainable cistern is acceptable for irrigation.

The intent of the home is to not pollute the environment, so as much nutrients as possible should be removed from the wastewater before it is discharged into the

groundwater. Thus, the FSGE design is to evaluate a new on-site sewage treatment and disposal (OSTD) system which consists of a sorption media labeled as Bold and Gold$^{TM}$ filtration media. The Bold and Gold$^{TM}$ filtration media is a mixture of tire crumb and other materials. This new OSTD system has sampling ports through the system to monitor the wastewater quality as it passes through. Also, the effluent wastewater quality is compared to that of a conventional system on the campus of the University of Central Florida.

The cost-benefit optimization model focused on designing a residential home which incorporated a green roof, cistern and graywater systems. This model had two forms, the base model and the grey linear model. The base model used current average cost of construction of materials and installation. The grey model used an interval for the cost of construction materials and green roof energy savings. Both models included a probabilistic term to describe the rainfall amount. The cost and energy operation of a typical Florida home was used as a case study for these models. Also, some of the parameters of the model were varied to determine their effect on the results. The modeling showed that the FSGE 4500 gallon cistern design was cost effective in providing irrigation water. Also, the green roof area could have been smaller to be cost effective, because the green roof cost is relatively much higher than the cost of a regular roof.

# ACKNOWLEDGMENTS

I would like to thank my advisor, Dr. Chang for all the help and advice during this process. I would also like to thank my committee members Dr. Wanielista and Dr. Randall. Especially, Dr. Wanielista for his guidance and constant help with the project. Also, the constant assistance in the nutrient measures from the Stormwater Lab students.

I would like to thank the Florida Department of Environmental Protection (FDEP) for the monetary and technical advice that made this project possible. The Florida Department of Health (FDOH) guidance was greatly appreciated during the construction of the septic system. Finally, I would like to thank Mark Baker and Nonnie Chrystal for allowing me access to their home to collect samples from the varies systems being analyzed.

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# CHAPTER 1: INTRODUCTION

## 1.1 Introduction

On-site stormwater management is an option to reduce the volume and mass of pollutants generated from the site. Also, wastewater pollutants generated for disposal using on site wastewater treatment adds to the pollution load of groundwater and may need to be reduced again using on-site methods. If no additional land is needed for the treatment, the management methods are labeled as Low Impact Development (LID). A building site that has options to add stormwater and wastewater treatment without additional land for treatment was located and thus the opportunity to use LID methods for stormwater and wastewater treatment. The site is located in Indialantic, Florida and is called Florida's Showcase Green Envirohome (FSGE).

In 2004, Hurricanes Frances and Jeanne destroyed the original structure of the FSGE displacing Mark Baker's mother Betty Baker Farley. Eleven months later Hurricane Katrina destroyed Mark's wife, Nonnie Chrystal, mother's and sister's homes in New Orleans, Louisiana. After these experiences and with Betty's blessing, Mark and Nonnie decided to build the FSGE where Betty's home once stood (FSGE 2008).

FSGE is built to meet or exceed 12 green building guidelines and obtain 8 green building certificates. The two-story 3292 $ft^2$ home is a "Near Zero-Loss Home™", "Near Zero-Energy Home™", "Near Zero-Runoff Home™", and "Near Zero-Maintenance Home™". It is spawned from the consumer-driven necessity to build a home resistant to hurricanes, tornadoes, floods, fire, mold, termites, impacts, and even earthquakes given up to 500% increase in insurance premiums in natural disaster zones, the dwindling flexibility and coverage of insurance policies, and rising energy, water and maintenance costs (FSGE 2008).

At the FSGE, green roofs, pervious pavement, and bioswales are used for stormwater management. In addition, Florida friendly plants are used in the landscaping. To provide irrigation water and water for toilet flushing the house has a sustainable water cistern. The cistern contains the stormwater runoff from 5 different green roof areas, the traditional roof area and decking, graywater from the home, AC condensate and supplemental water from an artesian well. The supplemental water from the artesian well is used to maintain a minimum volume in the cistern in times of drought or water shortage. The overflow from the cistern is routed to a 100 $ft^2$ bio-swale. Water stored in the sustainable water cistern is used for irrigating the ground level landscaping and green roof areas, toilet flushing, and laundry water. The graywater from the home is disinfected using ozone prior to being routed to the sustainable water cistern.

At FSGE a new on-site sewage treatment and disposal system (OSTD), which is a septic tank followed by a sorption filter and drainfield is also evaluated. The sorption media selected for this study is the Bold and Gold™ filtration media. The Bold and Gold™ filtration media is a mixture of tire crumb, sand and sawdust along with a top layer of sand and limestone which adds alkalinity to the filter tank. This media has been used for its nutrient removal efficiency in other pollution control applications.

## 1.2 Objectives

This is a research study to evaluate the use of on-site stormwater management from a residential home using a sustainable water cistern. Also the effectiveness of a new

OSTD using the Bold and Gold™ filter media bed is evaluated. The sustainable water cistern chemical water quality is monitored to determine if the water is an acceptable source for irrigation. Also, the sustainable water cistern bacterial counts are monitored to determine if the water is safe for use as toilet water within the home. The new OSTD system is monitored for its effluent water quality and is compared to a conventional systems water quality using varies nutrient species and bacteria.

To aid in the construction and planning of new green building homes, an optimization model is created. This model uses a cost-benefit analysis to determine the optimal design of a green home with stormwater management incorporating green roof, sustainable water cistern and graywater systems. To demonstrate the model, a typical Florida home construction cost and climate conditions are used and the results are analyzed. Also, the FSGE is inputted and results compared to the current configuration of the home.

## 1.3 Limitations

This study uses data from the FSGE, a two story home located on the east coast of central Florida. This household has a total area of 3292 $ft^2$. The sustainable water cistern has a capacity of 4500 gallons while OSTD sorption filter system has a design load of 300 gallons per day. The home was still under construction during this study. Therefore, the amount of graywater being introduced into the sustainable water cistern was limited. Also, the amount of wastewater going to the OSTD system was less than its design as only the toilets were used during the weekdays, and the kitchen sink was not used. These limitations are explained more in each chapter that addresses the systems.

## 1.4 Roadmap to Rest of Thesis

Chapter one is an introduction chapter. This chapter gives an introduction on the Florida Showcase Green Envirohome. Also, it presents the objectives and an overview of the limitations of this study. Also, a roadmap to the rest of the thesis is presented. In Chapter two, the FSGE water harvesting and stormwater systems are presented. This chapter also provides some background information on green roofs, graywater and good irrigation water quality. Then, the stormwater LID approaches and design of the FSGE is presented. This is followed by the results and discussion. Finally, conclusions and future works are presented. In Chapter three, the results of the new OSTD system performance are presented, along with background information on the Bold and Gold™ media are presented. This is followed by the approach and experimental design of the OSTS system. Results and discussion are presented next. Lastly, the conclusions, recommendations and advice for future work using the new OSTD are presented. In Chapter four presented is the green building optimization model and background information on green roof energy savings. This is followed by the model formulation and construction and climate assumptions for modeling. Next, the results of the model runs are presented and discussed. The FSGE attributes are inputted into the model and results discussed. Lastly, the conclusions and future work for the model are presented. Chapter five is the final conclusions and recommendations of the entire work.

# CHAPTER 2: FLORIDA SHOWCASE GREEN ENVIROHOME WATER HARVESTING AND SYSTEMS ANALYSIS

## 2.1 Introduction

The FSGE stormwater methods capture the stormwater runoff from the metal and green roof areas and routes it to the sustainable water cistern. The sustainable water cistern also receives the graywater from the home. With these different water sources being mixed in the sustainable water cistern, the water quality changes over time. The sources of water discharged into the sustainable water cistern (stormwater, graywater, green roof runoff, air conditioning condensate, and groundwater) are compared to each other and to recommended irrigation water quality as presented in Table 1.

Table 1: Suggested Irrigation Water Quality Compared to Various Sources

| Parameter | Irrigation Water | Graywater* | Stormwater* | Green Roof Runoff* | Groundwater* |
|---|---|---|---|---|---|
| pH | 6.5-8.4 | 7.2 | 7.5 | 7.45 | 6.5 |
| TDS (mg/L) | 175-525 | 66.5 | 80 | 161 | 300 |
| Ca (mg/L) | 20-60 | - | - | - | 43 |
| Mg (mg/L) | 10-25 | - | - | - | 3.2 |
| Total P (µg/L) | 100-400 | 22555 | 270 | 76 | 110 |
| $PO_4^-$ (µg/L-P) | 100-400 | 1338 | 130 | 46 | 60 |
| Total N (µg/L) | 1100-11300 | 6125 | - | 329 | - |
| $NO_3^-$ (µg/L-N) | 1100-11300 | 293 | 600 | 185 | <10 |

* Average values
References: (Duncan, Carrow and Huck 2000); (Jefferson, et al. 2004); (Lazarova, Hills and Birks 2003); (Pitt and Maestre 2004); (Kelly, Hardin and Wanielista 2007); and (United States Geological Survey 1992)

In this chapter presented are analyses of the water quality in the sustainable water cistern and comparisons to good quality irrigation water. Some background information for green roofs, graywater systems and irrigation water quality is presented in the following section. Then, the approach and experimental design is presented. This is followed by the results and discussion of the data collected. Finally, the conclusions and future work is presented.

## 2.2 Background

FSGE combines the use of a green roof runoff and graywater harvesting systems. These systems are currently under investigation for their many benefits to a home. These findings are presented in the following sections. Due to the main use of this collected water is for the irrigation of the lawn, data on the quality of irrigation water are also presented.

### 2.2.1 Green Roof

A green roof is a roof that is partially or completely covered with vegetation and growing media planted over a waterproofing membrane. These roofs have many positive benefits including the ability to filter pollutants out of rainwater, reduce heating and cooling costs, and increased roof lifespan. However, these benefits do come at an increased cost compared to more traditional roofing systems such as asphalt shingles.

Green roofs can greatly reduce stormwater runoff from the roof (Banting, et al. 2005). Depending on the substrate depth, typical extensive green roofs can retain 60-100% of the stormwater they receive for average rainfalls (Thompson 1998). However, retention also depends on many factors including volume and intensity of rainfall, the amount of time since the last rainfall event, and the extent of saturation of the existing substrate (Monterusso 2003).

Another study found that the rainwater retained varied during the time of the year, and a particular green roof retained an average of 69% of the rainwater during a 15-month monitoring period. Between the months of December and March the average rainfall retention was 59%. However, during the months of April to November, the average rainfall retention was 92%. Thus, the green roof retained more water during the hotter months (Liptan 2003). Wanielista, Kelly and Hardin (2006) found the yearly retention of rainfall for green roofs in the State of Florida ranged between about 33 and 50 percent dependent on the location in the State using a 4 inch depth of growth media. That retention can be increased if a cistern is used to capture the filtrate from the green roof and use if for irrigating the green roof.

A study compared a green roof and shingle roof built on the campus of York University. These two roofs were monitored for many parameters including water flows. The green roof provided significant reductions in runoff volume and peak flows as compared to the shingle roof. The runoff volume could be reduced by almost 65% while the peak flow could be reduced by almost 98% during most of the rainfall events less than 30 mm (Banting, et al. 2005). This is a significant reduction in stormwater and peak flows.

Adding a cistern to the green roof can further reduce the runoff that is discharged into the environment. Also, due to the runoff being captured and used for irrigation, the mass of nutrients being discharged into the environment is reduced (Wanielista, Kelly and Hardin 2006). As an added benefit, the captured water can be recycled to irrigate the green roof and the residential property. The capture and recycle will reduce the need of potable water to irrigate the green roof and the property. Design of cisterns and estimates for yearly reduction in rainfall discharged for meteorological zones in Florida have been developed and are in use today (Hardin 2006).

### 2.2.2 Graywater

A study conducted in Melbourne, Australia found that for an average household, 5% of the water demand was used in the kitchen, 26% in the bathrooms (excluding toilet flushing) and 15% in the laundry based on a 181 gal/d water demand. The remaining 54% of the water demand was used for irrigation and toilet flushing. Using this information, an estimated water conservation benefit for incorporating a graywater reuse system was conducted. The results of this analysis are presented in Table 2 below showing a water savings of 20 and 21 percent can be achieved when the graywater is used for irrigation or toliet flushing respectively. When the graywater is used for both irrigation and toliet flushing, a water savings of 31 percent is achieved (Christova-Boal, Eden and McFarlane 1996).

Table 2: Estimated Water Conservation Benefit

| Graywater reuse | % Water Savings |
|---|---|
| Irrigation | 21 |
| Toilet Flushing | 20 |
| Irrigation and Toilet Flushing | 31 |

A model developed by Dixon et al. (1999) incorporated a graywater and rainwater harvesting system. This model was executed for a variety of situations, varying the occupants, storage volume of the storage tank and if it was a combined system (graywater and rainwater) or singular system. It was found the water savings efficiency gains dropped after the storage volume of the tank was >100 liters. Also, it was found that adding the rainwater to the graywater did not increase the water savings significantly.

Thus, a reuse (harvesting) system using only graywater was suggested. Lastly, the more occupants in the home, the larger the storage tank had to be to gain water savings benefits (Dixon, Butler and Fewkes 1999).

A literature review conducted by Eriksson, et al. 2002 examined data collected on graywater from varies sources. Graywater characteristics were found to depend on the quality of the potable water supply, the distribution network for the potable and graywater, and the activities in the household. The compounds that are found in the graywater will vary on the lifestyles, customs, installations and types of chemicals used in the household.

Important physical parameters that should be monitored in a graywater system are temperature, turbidity, and suspended solids content. High temperatures can cause problems for the system because it favors microbial growth and precipitation of calcium carbonate ($CaCO_3$) and other inorganic salts may occur (due to decrease in solubility at high temperatures). Some graywater is known to contain some particles and colloids that can potentially clog the distribution system. Turbidity and Suspended solids measurements give some information on the presence of particles and colloids. Some sources of the solid materials in graywater are food particles from the kitchen and fibers from laundry water (Eriksson, et al. 2002).

Microbial contamination in graywater comprises a potential risk to public health. It has been found that graywater can contain at least $10^5$/100 ml of potential pathogenic micro-organisms. Research has shown fecal and total coliform increased to greater than $10^5$/100 ml when stored for 48 hr. Along with bacteria, virus contamination is of concern. However, the number of virus in the graywater is dependent on the health of the population generating the liquids. Also, the incident of disease is dependent on more than just the concentration of pathogens; it is also dependent on the health, age and exposures of people to the graywater (Dixon, Butler and Fewkes 1999).

Due to the contamination of graywater by pathogenic micro-organisms, the state of Florida has limited fecal coliform levels to non-detected colony forming units per 100 mL in graywater used for toilet flushing or irrigation of recreational areas (Eriksson, et al. 2002). To meet regulations, such as Florida's, graywater must be disinfected. March, et al. 2005 did research on finding a kinetic model for disinfection using chlorine. This study showed that a parallel first-order model shown in Equation 2.1 has four adjustable parameters that fit the chlorine residual decay of the experimental data the best (March, Gual and Ramonell 2005). $C_o$ is the initial chlorine residual while t is the time. x, $k_1$ and $k_2$ are all experimentally determined constants.

$$C(t) = C_o x e^{(-k_1 t)} + C_o (1 - x) e^{(-k_2 t)} \qquad (2.1)$$

### 2.2.3 Irrigation Water Quality Concerns

There are many parameters to consider when determining the acceptability of a water (including graywater) for irrigation. Two of the more important considerations are the total dissolved solids (TDS) and the amount of sodium (Na) in a water compared to calcium (Ca) plus magnesium (Mg), or SAR as it is more commonly known. Some other parameters that should be monitored include Alkalinity, pH, and hardness. These parameters will be discussed in more detail below.

The TDS of water is the amount of dissolved ions present in the water. High levels of dissolved ions cause plants to undergo a physiological drought due to their inability to compete with the ions for water. The TDS present in the irrigation water can either be measured directly (TDS) or indirectly (conductivity) (Bauder, Waskom and Davis 2007). An estimated TDS (in ppm) can be obtained from a conductivity measurement (in µmhos/cm) by multiplying it by 0.65 (Johnson and Zhang 2006). Table 3 shows the ranges for the classification of irrigation water based on measured conductivity or TDS values.

Table 3: Permissible Limits for Classes of Irrigation Water

| Classes of water | Concentration, total dissolved solids | |
|---|---|---|
| | Electrical conductivity µmhos* | Gravimetric ppm |
| Class 1, Excellent | 250 | 175 |
| Class 2, Good | 250-750 | 175-525 |
| Class 3, Permissible[1] | 750-2000 | 525-1400 |
| Class 4, Doubtful[2] | 2000-3000 | 1400-2100 |
| Class 5, Unsuitable[2] | >3000 | >2100 |

* Micromhos/cm at 25 degrees C.

[1] Leaching needed if used

[2] Good drainage needed and sensitive plants will have difficulty obtaining stands

The sodium adsorption ratio (SAR) is another parameter that is used to determine if water is suitable for use as irrigation water. Sodium is important because when irrigation water has a high concentration it tends to disperse the soil particles. This causes the soil to readily crust and have infiltration and permeability reduced. The calcium and magnesium tend to flocculate (hold together) soil particles; therefore the sodium concentration is compared to the calcium plus magnesium concentration in the water (Bauder, Waskom and Davis 2007). This SAR is derived using Equation 2.2.

Using this parameter, Table 4 can be used to rate the sodium hazard from low to very high.

$$SAR = \frac{Na^{+} meq/L}{\sqrt{\frac{\left(Ca^{2+} meq/L\right) + \left(Mg^{2+} meq/L\right)}{2}}} \tag{2.2}$$

Table 4: Classification of Water Sodium Hazard Based on SAR Value

| SAR Value | Sodium hazard of water | Comments |
|---|---|---|
| 1-9 | Low | Use on sodium sensitive crops must be cautioned |
| 10-17 | Medium | Amendments (such as Gypsum) and leaching needed. |
| 18-25 | High | Generally unsuitable for continuous use. |
| >26 | Very High | Generally unsuitable for use. |

The typical range for pH values for irrigation water is 6.5 to 8.4. Slightly higher pH values are usually caused by higher concentrations of bicarbonate ($HCO_3^-$) and carbonate ($CO_3^{-2}$). This causes the $Mg^{+2}$ and $Ca^{+2}$ to form insoluble minerals, thus raising the SAR. To account for this effect, a new adjusted SAR ($SAR_{adj}$) must be calculated in a lab. With slightly lower pH, the water will cause corrosion to the irrigation system which results in increased maintenance and repairs (Bauder, Waskom and Davis 2007).

Some commonly found nutrients in water are calcium, magnesium, total phosphorus, total nitrogen, total sulfur, phosphates, nitrates, and sulfates. These nutrients are used by the plants to grow. Therefore, they are guidelines for the amount of nutrients needed for plant life to grow. These requirements are specific to the plant being grown and vary in range. A nutrient guideline for irrigation water used on turf grass is presented in Table 5 (Duncan, Carrow and Huck 2000).

Table 5: Nutrient Guidelines for Turf grass

| Nutrient | Range (ppm) | | | |
|---|---|---|---|---|
| | Low | Normal | High | Very High |
| Ca | < 20 | 20-60 | 60-80 | > 80 |
| Mg | < 10 | 10-25 | 25-35 | > 35 |
| P | < 0.01 | 0.1-0.4 | 0.4-0.8 | > 0.8 |
| $PO_4^-$ | < 0.3 | 0.3-1.21 | 1.21-2.42 | > 2.42 |
| N | < 1.1 | 1.1-11.3 | 11.3-22.6 | > 22.6 |
| $NO_3^-$ | < 5 | 5-50 | 50-100 | > 100 |
| S | < 10 | 10-30 | 30-60 | > 60 |
| $SO_4^-$ | < 30 | 30-90 | 90-180 | > 180 |

The last common consideration used to determine the acceptability of water for irrigation is the concentrations of specific ions that are known to be toxic. The most common of these ions are chlorine (Cl), boron (B), and bicarbonate ($HCO_3^-$). Chlorine is a commonly encountered ion in waters that have been disinfected. Chlorine starts being toxic to plants at a level of about > 5 ppm. Bicarbonate is not toxic to plants at levels above 500 ppm; however it will deposit on the plants leaves and can contribute to excess sodium deterioration of the soil (Duncan, Carrow and Huck 2000). Boron is an essential nutrient for plants at low concentrations; however it becomes toxic at high concentrations. The toxic concentration of boron is dependent on the vegetation type, for most grasses, the tolerance range is from 2.0-10.0 mg/L (Fipps 2004).

There can be many metals present in irrigation waters such as Zinc, Copper, Iron and Manganese. However, having a high concentration of a metal can be detrimental to the natural vegetation. Some general maximum metal concentrations for some of the common metals are given below in Table 6. These show the limits when the metals begin to interfere with the growth of vegetation (Duncan, Carrow and Huck 2000).

Table 6: Metal Concentrations Above Which Can Interfere with Plant Growth

| Metal | Concentration (ppm) |
|---|---|
| Zn | 2.0 |
| Cu | 0.2 |
| Fe | 5.0 |
| Mn | 0.2 |

## 2.3 Approach

The sampling of the cistern and artisan well was conducted from Oct. 16 2008 to April 15, 2010. The sustainable water cistern samples were collected through the cleanout of the cistern. A dipper sampler was used to collect the sample from the top of the water cistern water. The well water was collected using the following process. The artesian well was opened and allowed to flow for 5 minutes. After 5 minutes of flushing out the well, the sample was collected.

These samples were then analyzed for selected water related water quality parameters. The nutrient analysis includes different nitrogen and phosphorus species. The nitrogen species of ammonia, nitrate+nitrite and total nitrogen were recorded. For the phosphorus species, the ortho-phosphate and total phosphorus were analyzed. The alkalinity of the waters was also monitored. The bacteria counts performed were total coliforms, E. Coli and enterococci. All of these analyses are done by the Stormwater Management Laboratory. Also, as the samples are being taken, a grab sample was taken to record some field parameters. These parameters are pH, conductivity, dissolved oxygen and temperature.

This sampling was done in two phases. The first phase is when the cistern water came from the green roof runoff, metal roof runoff and the supplemental artesian well water. During the second phase, the ozonized graywater was added to the sources water for the sustainable water cistern. Air conditioning condensate was not added at this time during the sampling, however it is anticipated that it will in the future.

## 2.4 Experimental Design

During the second phase, the sustainable water cistern receives the stormwater runoff from 5 different green roof areas (total of 815 $ft^2$), the stormwater runoff from a metal roof area and wood decking (2477 $ft^2$), graywater from the home, AC condensate and supplemental water from an artesian well. For the purpose of this paper, graywater is defined as all the wastewater from in the house excluding toilet plumbing fixtures, dishwashers and kitchen sinks with garbage disposals. For the FSGE, the downstairs bathroom fixtures are not routed to the sustainable water cistern. Water stored in the sustainable water cistern is used for irrigating the ground level landscaping and green roof areas, toilet flushing, and laundry water. Figure 1 shows a schematic of the graywater as it flows to ozone disinfection system prior to being added to the sustainable water cistern. This system contains a cloth filter, ozone addition and a contact time coil (which provides the contact time or disinfection). Figure 2 shows the entire water flow diagram of the FSGE.

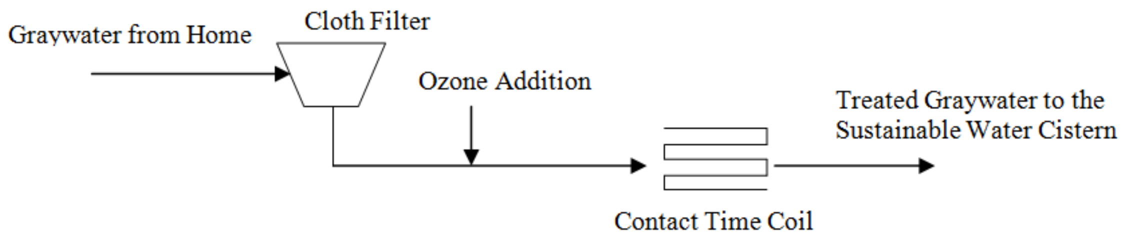



Figure 1:  Graywater System Schematic

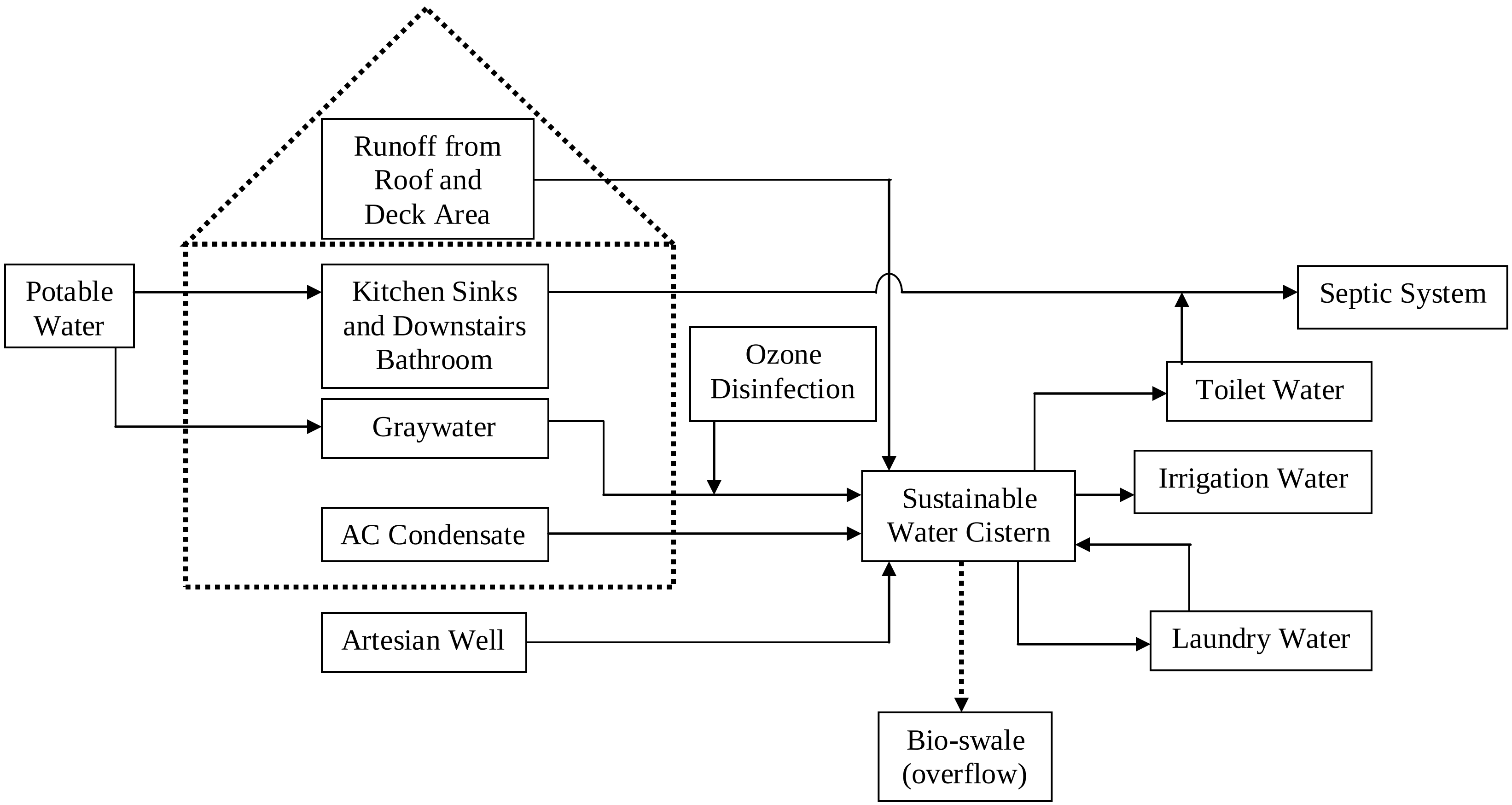



Figure 2: Water Flow Diagram for the Florida Showcase Green Envirohome

The procedures for the total nitrogen, nitrate+nitrite, ortho-phosphate and total phosphorus tests are located in APPENDIX A. Brief overviews of each of those tests are provided here. The total nitrogen was found using the persulfate digestion method. In this procedure, all the nitrogen species are converted to nitrate during the alkaline persulfate digestion. Then, the nitrate is reacted with chromotropic acid to form a yellow color. This is then measured for its absorbance and compared to the standard curve to find its value. The nitrate+nitrite are measured using the cadmium reduction method. The cadmium metal reduces nitrate in the sample to nitrite. The nitrate is then reacted with sulfanilic acid to form diazonium salts. These salts couple with the chromotropic acid to form a pink color. This is then measured for its absorbance and compared to the standard curve to find its value.

The total phosphorus is found using the acid persulfate digestion method. In this method, the organic phosphorus is converted to ortho-phosphate using heat with acid and persulfate. Then, the same procedure for finding the ortho-phosphate is used to find the total phosphorus. The ortho-phosphate is found using the PhosVer® 3 method. In this method, molybdate is added to the sample and reacts with the ortho-phosphate to form a mixed phosphate/molybdate complex. Ascorbic acid is then added to reduce the complex forming a blue color. This is then measured for its absorbance and compared to the standard curve to find its value.

To find the ammonia in the solution, an ammonia selective electrode was used. A 100 mL sample was placed in a 150 mL beaker. Then, 2 mL of ammonia ISA is added to the solution. While being gently stirred, read the potential after the probe reading has stabled. Compare this reading to the standard curve to find concentration.

Alkalinity was found by using 0.02N sulfuric acid. The procedure is as follows. A 50 mL sample initial pH is recorded along with the initial volume of 0.02N sulfuric acid. Sulfuric acid is then added to the sample until the pH of 4.3 is reached. The amount of sulfuric acid added is found by taking difference of the initial and final volumes. This is then used to find the alkalinity of sample.

The bacterial tests were conducted using IDEXX Colilert and IDEXX Enterolert testing kits. These tests use the most probable number (MPN) method to find the amount of bacteria with the sample. IDEXX Colilert test uses the following procedure. A Colilert packet is added to a 100 mL sample. Then, the sample is poured into the Quanti-Tray and sealed. Next, the sample is incubated at 35°C for 24 hours. After 24 hours, the tray is removed from the incubator. The number of yellow colored wells are counted and looked up on the MPN table. This is the cfu/100 mL of total coliforms present in your sample. Then, a 6-watt 365 nm UV florescent light is shined within 5 inches of the Quanti-Tray. The number of florescent and yellow wells are counted and looked up on the MPN table. This is the cfu/100 mL of E. Coli present in your sample. IDEXX Enterolert test uses the following procedure. An Enterolert packet is added to a 100 mL sample. Then, the sample is poured into the Quanti-Tray and sealed. Next, the sample is incubated at 41°C for 24 hours. After 24 hours, the tray is removed from the incubator. A 6-watt 365 nm UV florescent light is shined within 5 inches of the Quanti-Tray. The number of florescent wells are counted and looked up on the MPN table. This is the cfu/100 mL of enterococci present in your sample.

The field parameters are taken with field probes. For pH and temperature, the HACH PH301 probe was used. The conductivity was recorded using a HACH CDC401 probe. Finally, the HACH LDO101 probe was used to find the dissolved oxygen. A HACH 2100P portable turbidimeter was used to get the turbidity of the samples. All of these probes were calibrated 4 hours before use in the field.

## 2.5 Results and Discussion

The pre-graywater water quality data was collected from Jan. 21, 2009 through July 9, 2009 twice a month. The bacteria sampling occurred from Oct. 16 2008 to July 9, 2009 once a month. The pre-graywater data are discussed first. The sampling for the post-graywater water quality data began on Oct. 5, 2009 and continued through February 23, 2010. During this sampling period, the cistern was sampled twice a month while the artesian well was sampled once a month. Bacterial sampling occurred from Nov. 16, 2009 till April 15, 2010 once a month. All the sustainable water cistern and artesian well water raw data are available in APPENDIX B.

### 2.5.1 Pre-Graywater Data

Physical-chemical and nutrient pre-graywater data of the FSGE sustainable water cistern and artesian well water data averages, median and standard deviations are presented below in Table 7 and Table 8, respectively.

Table 7: Sustainable Water Cistern and Artesian Well Water Pre-Graywater Physical-Chemical Data (11 Samples)

| | | pH | Turbidity (NTU) | Conductivity (μS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|---|---|---|---|
| Cistern Data | Average | 7.58 | 3.04 | 3760 | 21.2 | 103 |
| | Median | 7.64 | 2.95 | 3646 | 21.2 | 106 |
| | Std. Dev | 0.26 | 1.22 | 590 | 2.2 | 22 |
| Artesian Well Data | Average | 7.69 | 10.02 | 3988 | 24.0 | 108 |
| | Median | 7.77 | 0.75 | 3981 | 24.1 | 113 |
| | Std. Dev | 0.22 | 11.55 | 242 | 1.8 | 11 |

The majority of the water in the cistern came from the artesian well water as the sampling occurred during the dry season. The pH of the cistern and well water were typically approximately the same. The average turbidity of the cistern is lower than the artesian well water. The turbidity of the artesian well water was variable. There were times when the turbidity would be low and then the next week is high. The turbidity reached a maximum value of 30.4 NTU. This sudden increase could be explained by storm events. The cisterns turbidity was rather constant over the recorded time. The average conductivity of the cistern water was lower than that of the artesian well water. The conductivity would be less in the cistern due to the runoff from the roofs diluting the artesian well water. The artesian well water temperature was higher than the cistern water. However, the temperatures of the cistern and artesian well waters tended to increase and decrease together.

Table 8: Sustainable Water Cistern and Artesian Well Water Pre-Graywater Nutrient Data (11 Samples)

| | | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| Cistern Data | Average | 0.10 | 0.31 | 0.09 | 0.16 | 0.73 |
| | Median | 0.09 | 0.29 | 0.06 | 0.11 | 0.54 |
| | Std. Dev | 0.08 | 0.22 | 0.07 | 0.11 | 0.36 |
| Artesian Well Data | Average | 0.15 | 0.26 | 1.03 | 0.08 | 0.84 |
| | Median | 0.09 | 0.22 | 1.05 | 0.07 | 0.75 |
| | Std. Dev | 0.17 | 0.19 | 0.31 | 0.05 | 0.36 |

Examining the phosphorus species, the average total phosphorus was higher in the cistern than the well water. Yet, the well water had a higher average concentration of ortho-phosphate. When examining the ortho-phosphate and total phosphorus concentrations over time, the species in the cistern and well water tended to behavior in the same manner. They would both increase and decrease over the same time period. The total nitrogen also followed a similar trend as the phosphorus species with the well water having a higher concentration typically. The average ammonia concentration was always higher in the well water compared to the cistern water. However, the cistern ammonia concentration started to increase toward the end of the background sampling period due to the introduction of a new time released fertilizer used on the green roof areas. The cistern average nitrate+nitrite value was higher than the well water average nitrate+nitrite concentration. Examining the nitrate+nitrite data over time, the well water had an initial concentration higher than the cistern water. Then, after April 21, 2009 the cistern water nitrate+nitrite concentration became higher than the well water and continued to the end of the pre-graywater sampling period.

Table 9: Sustainable Water Cistern Water Pre-Graywater Bacterial Data (26 Samples)

| Month | Average Total Coliform (cfu per 100 mL) | Average E. Coli (cfu per 100 mL) | Average Enterococci (cfu per 100 mL) |
|---|---|---|---|
| Oct | 1061.2 | 2.6 | 817.5 |
| Nov | 1048.9 | 1.4 | 1099.5 |
| Dec | 352.1 | 0.0 | 108.7 |
| Jan | 926.8 | 0.0 | 184.7 |
| Feb | 2419.6 | 0.0 | 341.1 |
| Mar | 793.1 | 0.0 | 357.7 |
| Apr | 2419.6 | 0.0 | 1308.5 |

The water samples were tested for total coliforms, E. Coli and enterococci. The monthly average of these sampling are displayed Table 9. Over the sampling time, the artesian well water never had a detectable amount of bacteria and thus is not included in Table 9. The cistern bacterial counts varied from week to week. However, the cistern E.Coli counts reached below detectable limits the majority of the sampling period. There was always a presence of total coliforms and enterococci in the cistern.

### 2.5.2 Post-Graywater Data

Table 10 and Table 11 show the average, median, and standard deviation for the nutrient and physical-chemical post-graywater data collected. It should be noted that during this sampling period, the graywater being added to the system was daily shower water and laundry water.

Table 10: Sustainable Water Cistern and Artesian Well Water Post-Graywater Physical-Chemical Data (3 Samples)

| | | pH | Turbidity (NTU) | Conductivity (μS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) | Dissolved Oxygen (mg/L) |
|---|---|---|---|---|---|---|---|
| Cistern Data | Average | 7.76 | 4.56 | 3106 | 21.6 | 90 | 9.85 |
| | Median | 7.76 | 3.10 | 3220 | 20.8 | 76 | 9.75 |
| | Std. Dev | 0.09 | 2.89 | 464 | 1.7 | 25 | 1.48 |
| Artesian Well Data | Average | 7.10 | 29.70 | 4057 | 24.5 | 93 | 2.88 |
| | Median | 7.09 | 8.06 | 4070 | 23.3 | 108 | 2.86 |
| | Std. Dev | 0.11 | 32.40 | 50 | 1.8 | 34 | 0.80 |

Unlike the pre-graywater data, the pH of the sustainable water cistern was typically the higher of the two. Also, the pH once again did not have a large variation. The turbidity was higher in the artesian well water then the cistern. The same pattern of high and low turbidities in the pre-graywater for the turbidity in the artesian well water was observed again. The conductivity of the cistern water was less that of the artesian well water. The cistern conductivity was much lower than its pre-graywater readings. This lower reading could be accounted for by the further diluting of the artesian well water by the now added graywater. The temperature and alkalinity of the cistern and artesian well water are approximately the same as seen in the pre-graywater data. There was a statistical difference at a 95% confidence between all the means of the pre-graywater and post-graywater physical-chemical data. Dissolved oxygen was monitored after the addition of the ozonation system. Examining the data, there was a high concentration within the cistern. This is what was expected since ozonating the graywater would increase the dissolved oxygen.

Table 11: Sustainable Water Cistern and Artesian Well Water Post-Graywater Nutrient Data

| | | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| Cistern Data (8 Sample) | Average | 0.07 | 0.07 | 0.53 | 0.11 | 0.71 |
| | Median | 0.07 | 0.04 | 0.34 | 0.08 | 0.65 |
| | Std. Dev | 0.04 | 0.07 | 0.52 | 0.07 | 0.27 |
| Artesian Well Data (4 Sample) | Average | 0.07 | 0.05 | 1.09 | 0.01 | 2.24 |
| | Median | 0.06 | 0.05 | 0.89 | 0.01 | 1.65 |
| | Std. Dev | 0.04 | 0.04 | 0.45 | 0.00 | 1.84 |

Examining the phosphorus species, the ortho-phosphate and total phosphorus was relatively the same in the cistern and well water. Also, the total phosphorus equaled the ortho-phosphate in the cistern, thus the main specie of phosphorus in the cistern was ortho-phosphate. This could be attributed to the ozone residual of the graywater entering the cistern. However, comparing the concentrations of total phosphorus in the post and pre-graywater data, the concentration has dropped significantly. The ammonia concentration in the cistern was once again lower than that of the artesian well water. However, the ammonia concentration was much higher than it was in the pre-graywater period. The total nitrogen and nitrate+nitrite concentrations are still relatively the same as those found in the pre-graywater data. The cistern has a higher concentration of nitrate+nitrite than the artesian well water. Once again the total nitrogen concentrations were higher in the artesian well water. There was a statistical difference at a 95% confidence between all the means of the pre-graywater and post-graywater nutrient data.

Table 12: Sustainable Water Cistern Water Post-Graywater Bacterial Data (6 Samples)

| Month | Total Coliform (cfu per 100 mL) | E. Coli (cfu per 100 mL) | Enterococci (cfu per 100 mL) |
|---|---|---|---|
| Nov | 1553.1 | 42.6 | 68.7 |
| Dec | 488.4 | 0.0 | 770.1 |
| Jan | 2419.6 | 0.0 | 1203.3 |
| Feb | 2419.6 | 0.0 | 1732.9 |
| Mar | 920.8 | 0.0 | 1413.6 |
| Apr | 2419.6 | 0.0 | 18.6 |

These samples were tested for total coliforms, E. Coli and enterococci. The results of these sampling are displayed Table 12. Over the sampling time, the artesian well water never had a detectable amount of bacteria and thus is not included in Table 12. The cistern bacterial counts varied from month to month. However, the cistern E. Coli counts reached below detectable limits the majority of the sampling period. There was always a presence of total coliforms and enterococci in the cistern.

### 2.5.3 Irrigation Water Quality Considerations

Table 13 compares the average values of the pre and post graywater sustainable water cistern quality with the good quality irrigation water as shown in the introduction of this chapter (see Table 1). The pre-graywater sustainable cistern water was within the recommended range except the nitrogen species. The nitrate was far below the recommendation while the total nitrogen was only 0.4 mg/L less than the recommended concentration. The post-graywater sustainable water cistern quality was within the recommended pH range. All the phosphorus in the sustainable water cistern was converted to ortho-phosphate (due to the ozonation). There was a reduced concentration of the phosphorus species. Like the pre-graywater, the nitrogen species were below the recommendation. However, the concentrations of the nitrogen species were almost identical to the pre-graywater quality.

Table 13: Comparison of Good Quality Irrigation Water with Pre and Post Graywater Sustainable Water Cistern

| Parameter | Irrigation Water | Pre-Graywater Water | Post-Graywater Water |
|---|---|---|---|
| pH | 6.5-8.4 | 7.58 | 7.76 |
| Total P (mg/L) | 0.1-0.4 | 0.31 | 0.07 |
| $PO_4^-$ (mg/L-P) | 0.1-0.4 | 0.1 | 0.07 |
| Total N (mg/L) | 1.1-11.3 | 0.73 | 0.71 |
| $NO_3^-$ (mg/L-N) | 1.1-11.3 | 0.16 | 0.11 |

## 2.6 Conclusions and Future Work

The pH, conductivity, temperature and alkalinity of the pre-graywater sustainable water cistern and artesian well water were approximately the same. The turbidity was the major difference with the sustainable water cistern having a stable value and the artesian well water being highly unstable. The pre-graywater sustainable water cistern nutrient concentrations tended to behave (increasing and decreasing) the same as the artesian well water. This is due to the majority of the sustainable water cistern coming from the artesian well as it was the dry season. The trend ended toward the end of the sampling period as a time released fertilizer was applied to the green roofs and was carried into the sustainable water cistern. During the testing, the E. Coli reached below detectable limits the majority of the time while there was always a presence of total coliforms and enterococci.

The pH, temperature and alkalinity of the post-graywater sustainable water cistern and artesian well water were approximately the same. The conductivity in the cistern was consistently lower than the artesian well water due to the dilution of the cistern water with graywater. Also, the highly variable turbidity for the artesian well water and stable values of the cistern was observed again. The post-graywater sustainable water cistern total phosphorus and ortho-phosphate concentrations were the same. Thus, the addition of ozone transformed all the phosphorus species to ortho-phosphate. The total nitrogen and nitrate+nitrite stayed relatively the same. Also, the ammonia concentration was much greater in the post-graywater compared to the pre-graywater sustainable water cistern quality. Once again, the E. Coli reached below detectable limits the majority of the time while there was always a presence of total coliforms and enterococci.

The pre and post graywater sustainable cistern water quality was compared to recommended parameters for a good irrigation water quality. The pre-graywater sustainable water cistern quality was more within the recommended range of good irrigation quality values than the post-graywater sustainable water cistern quality. However both are highly acceptable based on the parameters of the study. The pre-graywater sustainable water cistern quality was within the pH and phosphorous species recommended range while the post-graywater sustainable water cistern was only within the pH recommended range.

Some future work that needs to be done is the continued monitoring of the sustainable water cistern when the bathroom sinks are routed to the sustainable water cistern and as the home becomes occupied (as the home is still under construction at this time). This will increase the quantity of graywater into the sustainable water cistern and thus change the chemical makeup of the water. Also, an analysis of the sustainable water cistern quality should be carried out for each season. This is to track the changes in quality due to the main source of the water changing. During the wet season, the rainwater will be a main source of water as opposed to the dry seasons where the graywater and artesian well water will be the main sources. Lastly, fecal coliform needs to be monitored as the regulations for the use of graywater as toilet water is regulated by fecal coliform.

# CHAPTER 3: BOLD AND GOLD$^{TM}$ WASTEWATER FILTERING MEDIA ANALYSIS

## 3.1 Introduction

This chapter focuses on the information for the on-site sewage treatment and disposal (OSTD) system, which is a septic tank followed by a sorption filter and drainfield at the FSGE. When the water stored in the sustainable water cistern is harvested in the house for toilet flushing, the nutrient concentrations in the water has slightly higher concentrations compared to the potable water which is typically used in a conventional home. Thus, the black water leaving the home will have higher concentrations of nutrients compared to a conventional home's black water (black water is the wastewater from toilets only).

The FSGE design is to evaluate a new OSTD system. Keeping in concert with the green and non-polluting theme for FSGE, nutrients in the wastewater should be removed before discharge to the environment and sorption filtration has that possibility. The sorption media selected for this study is the Bold and Gold$^{TM}$ filtration media. The Bold and Gold$^{TM}$ filtration media is a mixture of tire crumb, sand and sawdust. This media has been used for its nutrient removal efficiency in many studies.

In this chapter presented are analyses of the water quality of the wastewater as it passes through the Bold and Gold$^{TM}$ filtration media. Also, this is compared to a conventional septic system. Some background on the Bold and Gold$^{TM}$ filtration media is presented in the following section. Then, the approach and experimental design is presented. This is followed by the results and discussion of the data collected. Finally, the conclusions and future work is presented.

## 3.2 Background

Bold and Gold™ is a tire crumb based media used for nutrient removal. The composition of the media depends on the application. The mixes can consist of expanded clay, sand, tire crumb, limestone, and saw dust. Some of the applications for the media include green roofs, upflow stormwater filters, and septic systems. The following are some of the studies the Bold and Gold™ media were used.

The Bold and Gold™ media was reported as a pollution control and growth media for green roofs. During this project, expanded clay, compost, and tire crumb were used as the pollution control and growing media for the plants of the green roof. Then, the nutrient removal and other parameters were monitored to see which provided the best media for the green roofs. It was shown that the Bold and Gold™ media significantly reduced the ortho-phosphate and phosphorus concentrations. Also, it showed a slight reduction in the nitrate-nitrite concentration, even thought it was not statistically significant (Hardin 2006).

Bold and Gold™ media was used in a chamber upflow filter and skimmer (CUFS) in a detention pond for nutrient reduction. The CUFS was operational when there was a seven inch head differential between the pond and the top of the filter which occurred usually after a storm event that filled the pond to the discharge elevation. The samples were taken within 24 hours of the rainfall event. Samples were taken from the top of the detention pond near the pond outlet and the outlet of the CUFS. The results of this study showed the CUFS significantly reduced the concentrations of turbidity, ortho-phosphate, total phosphorus, and total suspended solids (Ryan 2008). Also low concentrations in the influent were further reduced.

A study conducted by Timir Shah studied the removal efficiency of nutrients in a septic system using a mix of sand, tire crumb, and sawdust (STS); or sand tire crumb and paper (STP). The study was conducted using columns with the media packed into them. Total nitrogen and phosphorus were two of the nutrients monitored in the study (Shah 2007).

Table 14: Total Nitrogen Data (Shah 2007)

| **Total Nitrogen** | | | |
|---|---|---|---|
| Date | Influent | STS - 4.5 (mg/L) | STP - 4.5 (mg/L) |
| 19-Oct | 96.39 | 6.24 | 5.12 |
| 26-Oct | 35.60 | 6.36 | 6.96 |
| 10-Nov | 1135.06 | 5.26 | 6.50 |
| 17-Nov | 488.25 | 4.21 | 5.71 |
| 30-Nov | 688.82 | 5.22 | 5.44 |
| 2-Feb | 678 | 6.93 | 1.058 |
| 26-Feb | 126.16 | 12.106 | 15.917 |
| 7-Mar | 67.493 | 10.289 | 0.948 |
| Average Conc. (mg/L) | 414.47 | 7.08 | 5.96 |
| % Removal | | 98.29 | 98.56 |

Table 14 shows the total nitrogen data collected during the study. Total nitrogen data showed that both columns had an average removal efficiency of approximately 98%. The STS efficiencies ranged from 82% to 99.5%. The STP efficiencies ranged from 80% to 99.8% (Shah 2007). These high removals were achieved even with high effluent concentrations. This shows a septic system of this design can take high effluent nitrogen concentrations and reduce them to low concentrations.

Table 15:  Total Phosphorus Data (Shah 2007)

| **Total Phosphorus** | | | |
|---|---|---|---|
| Date | Influent | STS - 4.5 (mg/L) | STP - 4.5 (mg/L) |
| 19-Oct | 6.79 | 0.15 | 0.21 |
| 26-Oct | 4.15 | 0.06 | 0.08 |
| 10-Nov | 704.54 | 0.23 | 0.19 |
| 17-Nov | 194.81 | 0.09 | 0.15 |
| 30-Nov | 550.45 | 0.18 | 0.21 |
| 2-Feb | 36.09 | 0.09 | 0.19 |
| 26-Feb | 3.19 | 0.08 | 0.07 |
| 7-Mar | 2.13 | 0.14 | 0.07 |
| Average Conc. (mg/L) | 187.77 | 0.13 | 0.15 |
| % Removal | | 99.93 | 99.92 |

Table 15 shows the total phosphorous data collected during the study.  Total Phosphorus had an average removal efficiency of 99.9%.  The STS efficiencies ranged from 93% to 99.9% while the STP efficiencies ranged from 96% to 99.9% (Shah 2007). These removal efficiencies did not vary with high effluent concentrations.  This shows how a septic system of this design can handle high effluent phosphorus concentrations and reduce them to low concentrations.

## 3.3 Approach

The wastewater quality before and after passing through the Bold and Gold$^{TM}$ filter media is used as the measure of performance.  The sampling for the nutrient and bacteria analysis of the Bold and Gold$^{TM}$ filter media is conducted once a month.  The nutrient analysis includes many different parameters listed as follows.  Typical parameters analyzed by laboratory methods are total suspended solids (TSS), alkalinity, $BOD_5$ and $CBOD_5$.in addition to the nitrogen species, ammonia, nitrate+nitrite, nitrite, organic nitrogen, and total nitrogen and the phosphorus species, ortho-phosphate, organic phosphorus and total phosphorus. Fecal coliforms and E. Coli are the bacterial analysis being done. All these nutrient and bacterial analysis are done by Environmental Research and Design (ERD), a NELAC certified laboratory. Also, as the time of sampling, the parameters recorded in the field are pH, conductivity, dissolved oxygen and temperature. These measurements are taken by field probes. These probes are calibrated within 4 hours prior to the sampling event in the field.

This data collection is done in two phases. During the first phase, the influent samples are grab samples collected only from wastewater coming from the toilets. This sampling period is from November 2009 till the end of March 2010. During the second phase, the influent sample is collected from a trough installed in the influent line of the septic tank. This trough collects the wastewater as it enters the septic tank over time to get a composite sample (3 Liters). This sampling period is from April 2010 till the end of May 2010. Currently the home is under construction so all the samples collected are primarily only wastewater from the toilets.

## 3.4 Experimental Design

Figure 3 shows the current setup of the FSGE septic system with the conventional and Bold and Gold$^{TM}$ filter media. The conventional drain field and the filter media each receive half of the wastewater from the home, or 300 gallons per day of wastewater of the total 600 gallons per day of wastewater expected from the home. The flow is measured by using a Polylok dipper tray which counts the number of times the tray empties. The tray empties when 1.5 gallons of water has been retained. The Bold and Gold™ filter media is followed by a conventional drain field.

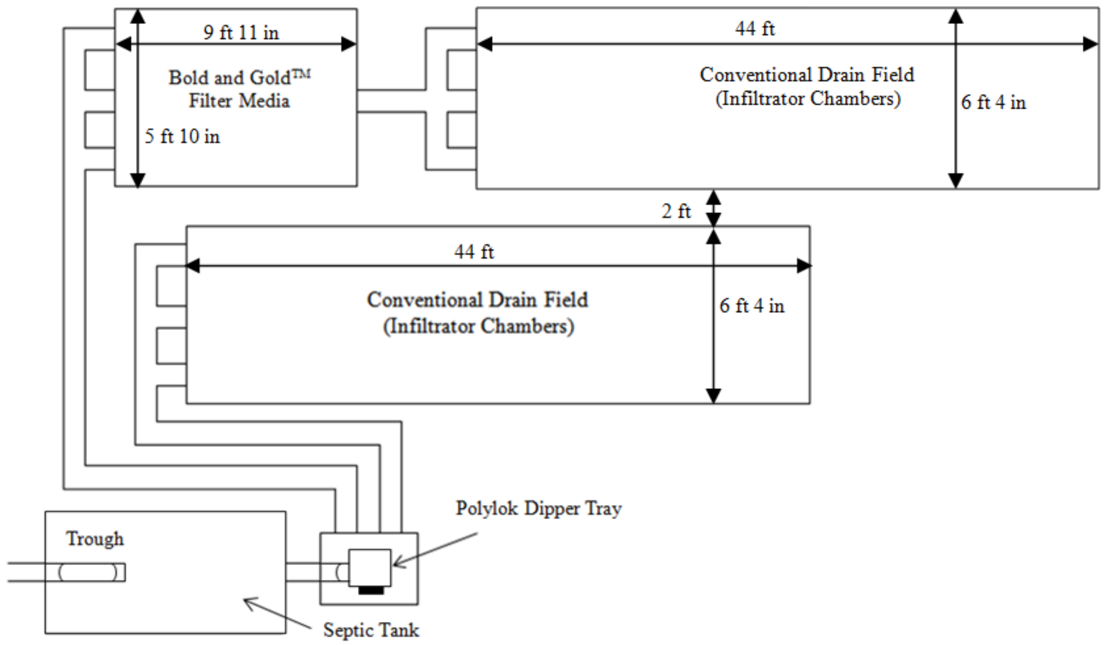



Figure 3: FSGE Septic System with Bold and Gold™ Filter Media and Drain Field

A trough is installed inside the septic tank to collect a composite influent sample. The trough is made from 4 inch PVC pipe that was cut to allow the collection of influent while letting excess water to overflow out. A screw cap was installed at the end of the trough. This allows the wastewater to flow through until a sample is collected. When a composite sample is to be collected, the cap is screwed on and the wastewater is captured for 24 hours. After this time, a composite sample is collected. Then, the cap is screwed off and the wastewater is allowed to flow through again. Figure 4 below shows a picture of the installed trough.

Figure 4:  Installed Septic Tank Trough

Figure 5 shows the Bold and Gold filter media configuration.  The wastewater from the septic tank is infiltrated into the Bold and Gold$^{TM}$ filter media using infiltrator chambers.  The water is directed to the front of the Bold and Gold$^{TM}$ filter media by an impervious membrane.  The Bold and Gold$^{TM}$ mixture used for this filter media was 24% tire crumb, 6% sawdust and 70% sand by volume.  The Bold and Gold$^{TM}$ filter media is contained within a 9.9 ft. by 5.8 ft. tray.  The baffle walls are positioned to minimize the short circuiting of the bed and increase the retention time.  A P.T.I. pipe bundle is placed at the end to keep the Bold and Gold$^{TM}$ filter media from leaving the system. Lastly, a layer of 20% limestone and 80% sand mixture by volume was placed on top the Bold and Gold$^{TM}$ to add alkalinity to the wastewater before entering treatment system.

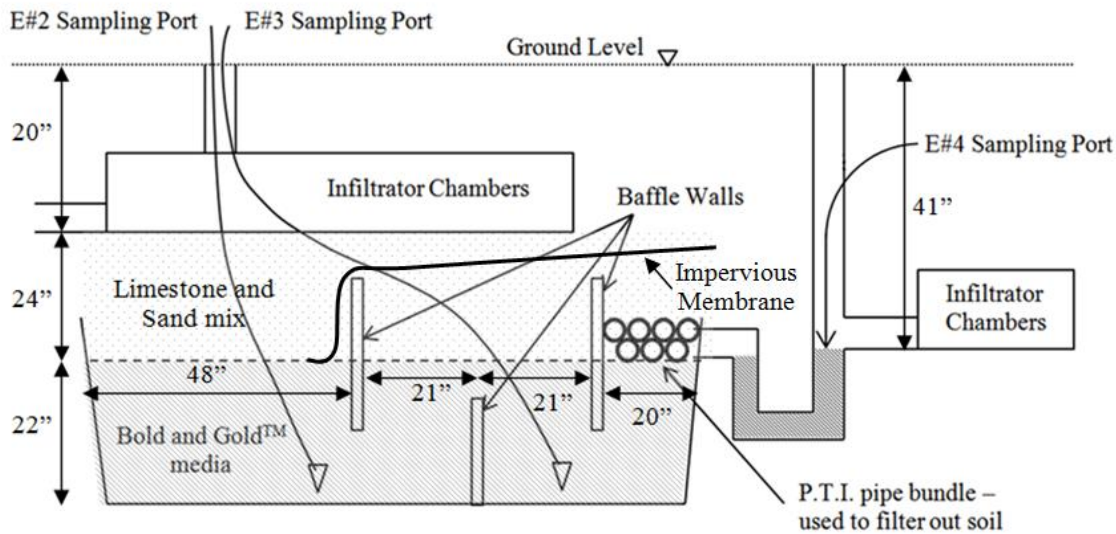



Figure 5: Bold and Gold$^{TM}$ Filter Media Bed Schematic

In Figure 5, the current sampling points of E#2, E#3 and E#4 within the Bold and Gold$^{TM}$ filter media are shown. The E#2 and E#3 sampling are taken from A-cups within the Bold and Gold$^{TM}$ media. The A-cup is a PVC cup that has a filter cloth and sampling tube ran up to the surface of the ground. A suction pump is used to collect the samples in the A-cup. Figure 6 shows a diagram of the A-cup. The E#4 sample is taken from the constantly wet portion of the effluent pipe from the Bold and Gold$^{TM}$ media. These sampling points were selected to document the water quality changes as the wastewater flows through the Bold and Gold$^{TM}$ filter media.

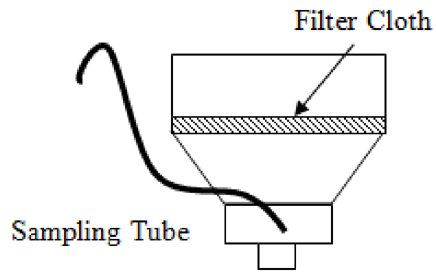



Figure 6: A-Cup Diagram

To make sure the OSTD system works properly, the following guidelines should be followed (Clearstream Wastewater Systems Inc. 2003):

1. Any sewage system should not have inorganic materials (plastics, cigarette butts, throwaway diapers, baby wipes advertised as disposable, etc.), that the bacteria cannot consume, discharged into the system.

2. Large amounts of harsh chemicals, oils, grease, high sudsing detergents, discharge from water softeners, disinfectants or any other chemical or substance that can kill bacteria should not be discharged into the system.

3. Excessive use of water, over the design flow, or organic overloading in excess of design parameters will cause the system not to perform at its fullest capabilities.

4. The proper operation of this or any other sewage treatment system depends upon the proper organic loading and the healthy life of the micro-organisms inside the system.

Also, some minimum maintenance must be done on the system. This includes pumping sludge from the pre-treatment tank every 5 to 7 years. This is done by dropping the pump hose through the access opening on the top of the tank all the way through to the bottom of the tank. Pump out the whole tank volume and then immediately re-fill the tank with water to the bottom of the inlet “tee” to prevent the pre-treatment tank from being forced out of the ground by the hydraulic pressure from the ground water it displaces.

The samples are collected using a suction pump and are preserved according to the tests that are being conducted. A 60 mL sample used for analysis of the total phosphorus, total nitrogen and ammonia is preserved by adding $H_2SO_4$ to reduce the pH below 2 and refrigerating. A 60 mL sample used for analysis of the nitrate+nitrite, nitrite, and ortho-phosphate is preserved by filtering the samples using 45 µm filter and refrigerating. Another 60 mL sample for analysis of the organic nitrogen and organic phosphorus is preserved by filtering the samples using 45 µm filter, adding $H_2SO_4$ to drop the pH below 2, and refrigerating. All other tests are run from a refrigerated 2 liter sample collected.

The field parameters are taken with field probes. For pH and temperature, the HACH PH301 probe was used. The conductivity was recorded using a HACH CDC401 probe. Finally, the HACH LDO101 probe was used to find the dissolved oxygen. A HACH 2100P portable turbidimeter was used to get the turbidity of the samples. All of these probes were calibrated 4 hours before use in the field.

## 3.5 Results and Discussion

The influent sample data are presented first, divided into the grab and composite influent samples. Next, the water quality of the wastewater is tracked as it flows through the Bold and Gold™ media filter. Lastly, the overall performance of the system is presented and the effluent samples are compared to a conventional systems effluent water quality. The raw data are located in APPENDIX C.

### 3.5.1 Influent Water Quality Analysis

The grab wastewater sampling occurred from December 2009 to March 2010. The composite wastewater sampling occurred from April 2010 to June 2011. There were a total of four samples collected, once a month, for the grab samples. There were a total of two composite samples taken, once a month, for the composite samples. The results from the field probes and ERD laboratories are presented in the following tables.

Table 16: Grab and Composite Influent Samples Physical-Chemical Data

| | | pH | Dissolved Oxygen (mg/L) | Conductivity (µS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|---|---|---|---|
| Grab Samples (4 sample) | Average | 6.47 | 5.54 | 3750 | 22.2 | 310 |
| | Median | 6.48 | 5.52 | 3720 | 21.6 | 230 |
| | Std. Dev | 0.12 | 0.14 | 210 | 2.2 | 172 |
| Composite Samples (2 sample) | Average | 7.89 | 0.43 | 4970 | 26.1 | 222 |

Examining Table 16, the grab samples pH, dissolved oxygen, conductivity and temperature were close to each other as noted in a lower standard deviation of the grab samples. The low dissolved oxygen reading of the composite sample shows that there was bacterial activity within the collection period. The pH and conductivity of the composite samples were greater than what was observed in the grab samples.

Table 17: Grab and Composite Influent Samples TSS, $BOD_5$ and $CBOD_5$ Data

| | | TSS (mg/L) | $BOD_5$ (mg/L) | $CBOD_5$ (mg/L) |
|---|---|---|---|---|
| Grab Samples (4 sample) | Average | 284.1 | 619.3 | 546.5 |
| | Median | 64.3 | 531.0 | 454.5 |
| | Std. Dev | 400.5 | 291.9 | 326.4 |
| Composite Samples (2 sample) | Average | 114 | 350.8 | 306.3 |

Table 17 displays the TSS, $BOD_5$ and $CBOD_5$ data for the influent samples during the collection period. The composite sample average values were within one standard deviation of the grab samples. However, they were all less than those observed in the grab samples. Thus, this could be more evidence that a less concentrated waste was available with the composite sample. The median TSS for the grab samples was relatively low possibly due to the majority of the sample being urine. The average TSS was high however because one of the grab samples TSS was much higher than what it was normally and most likely reflects additional loadings.

Table 18: Grab and Composite Influent Samples Nitrogen Species Data

| | | $NH_3$ (mg/L) | Organic Nitrogen (mg/L) | TKN (mg/L) | Nitrate+Nitrite (mg/L) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| Grab Samples (4 sample) | Average | 76.037 | 351.919 | 427.956 | 0.800 | 492.353 |
| | Median | 47.740 | 268.888 | 349.270 | 0.715 | 276.043 |
| | Std. Dev | 75.503 | 249.977 | 230.303 | 0.685 | 458.214 |
| Composite Samples (2 sample) | Average | 221.699 | 188.037 | 409.735 | 0.942 | 190.984 |

Table 19: Grab and Composite Influent Samples Phosphorus Species Data

| | | Soluble Reactive Phosphorus (mg/L) | Organic Phosphorus (mg/L) | Total Phosphorus (mg/L) |
|---|---|---|---|---|
| Grab Samples (4 sample) | Average | 13.174 | 2.414 | 17.407 |
| | Median | 9.014 | 1.839 | 12.250 |
| | Std. Dev | 8.914 | 1.915 | 12.028 |
| Composite Samples (2 sample) | Average | 7.816 | 3.667 | 13.879 |

The grab and composite nitrogen species samples are presented in Table 18. The only composite sample parameter that did not fall within one standard deviation of the grab sample was the ammonia indicating relatively consistent readings. Examining Table 18, the ammonia and nitrate+nitrite were greater than the average of the grab samples while organic nitrogen, total kjeldahl nitrogen and total nitrogen were less than the grab samples averages.

Table 19 displays the phosphorus species analysis of the grab and composite samples. The phosphorus species composite samples all fall within the first standard deviation of the grab samples.

Table 20: Influent Bold and Gold™ Bacterial Data

| | Fecal Coliform (cfu per 100 mL) | E. Coli (cfu per 100 mL) |
|---|---|---|
| Grab Samples | | |
| 11/16/2009 | 5000 | 4200 |
| 12/30/2009 | < 1 | < 1 |
| 1/26/2010 | < 1 | < 1 |
| 2/10/2010 | 551 | 496 |
| 3/11/2010 | < 1 | < 1 |
| Composite Samples | | |
| 4/15/2010 | 52000000 | 38400000 |
| 5/18/2010 | 14000000 | 13200000 |

Table 20 presents the results of the bacterial analysis. During the grab sample period, the bacterial counts were very low. This could be due to the ozone residual killing the bacteria during transport from the sustainable water cistern water used as the toilet water or the grab sample was only urine and thus relatively free of bacteria. However, when the composite samples were taken, the bacterial counts went into the millions. This high concentration of bacteria is more of the norm expected for influent samples.

The Environmental Technology Verification (ETV) protocols for suggested average influent requirements are (National Science Foundation 2007):

- $CBOD_5$: 100 – 450 mg/L
- TSS: 100 – 500 mg/L
- TKN: 25 – 70 mg/L
- Total P: 3 – 20 mg/L
- Alkalinity: greater than 60 mg/L
- Temperature: 10º C – 30º C

The grab samples averages all fell within these suggested ranges except for the $CBOD_5$ and TKN. When examining the composite samples, the averages fell within the range except the TKN. In both cases, the high value of the TKN could be attributed to the influent water consisting of only toilet water, thus having higher values of organic nitrogen.

### 3.5.2 Bold and Gold™ Filter Media Analysis

The wastewater quality is tracked through the Bold and Gold™ filter media bed using the sampling ports E#2, E#3 and E#4. E#2 is located at the influent side of the Bold and Gold™ filter media bed while E#3 is located towards the effluent side. E#4 is taken from the constantly wet effluent pipe of the Bold and Gold ™ filter media bed. The sampling period occurred from December 2009 to June 2010. The results from the field probes and ERD laboratories are presented in the following tables.

Table 21: Bold and Gold™ Filter Media Physical-Chemical Data (6 samples)

| | | pH | Dissolved Oxygen (mg/L) | Conductivity (µS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|---|---|---|---|
| E#2 | Average | 7.14 | 2.54 | 2410 | 23.3 | 286 |
| | Median | 7.10 | 2.69 | 2400 | 24.0 | 249 |
| | Std. Dev | 0.11 | 0.42 | 130 | 2.4 | 138 |
| E#3 | Average | 7.07 | 3.33 | 2430 | 23.7 | 277 |
| | Median | 7.03 | 2.88 | 2510 | 24.2 | 217 |
| | Std. Dev | 0.12 | 1.28 | 190 | 2.6 | 167 |
| E#4 | Average | 7.08 | 2.43 | 2410 | 23.7 | 292 |
| | Median | 7.06 | 2.52 | 2480 | 23.8 | 271 |
| | Std. Dev | 0.10 | 0.22 | 190 | 2.2 | 165 |

Table 21 presents the physical-chemical data of the wastewater as it passed through the Bold and Gold™ filter media. The pH and conductivity remained almost constant as it passed through the Bold and Gold™ media. The dissolved oxygen increased as the wastewater passed through the Bold and Gold™ media and then decreased when it reached the effluent pipe. The alkalinity decreased as it passed through the Bold and Gold™ media and then increased after reaching the effluent pipe.

Table 22: Bold and GoldTM Filter Media TSS, $BOD_5$ and $CBOD_5$ Data (6 samples)

| | | TSS (mg/L) | $BOD_5$ (mg/L) | $CBOD_5$ (mg/L) |
|---|---|---|---|---|
| E#2 | Average | 45.5 | 59.8 | 39.1 |
| | Median | 30.5 | 73.3 | 30.3 |
| | Std. Dev | 30.2 | 49.4 | 39.8 |
| E#3 | Average | 14.8 | 50.1 | 45.7 |
| | Median | 15.0 | 55.8 | 48.7 |
| | Std. Dev | 6.3 | 35.1 | 36.2 |
| E#4 | Average | 26.4 | 30.1 | 24.2 |
| | Median | 20.0 | 25.3 | 22.9 |
| | Std. Dev | 18.6 | 19.7 | 15.0 |

As shown in Table 22, changes in TSS, $BOD_5$ and $CBOD_5$ are recorded but do not appear to be significant as the wastewater passes through the Bold and Gold™ filter media. In fact, the TSS increased from E#3 to E#4. This may be due to some of the loose materials washing through the Bold and Gold™ filter media and should continue to be monitored.

Table 23: Bold and GoldTM Filter Media Nitrogen Species Data (6 samples)

| | | $NH_3$ (mg/L) | Organic Nitrogen (mg/L) | TKN (mg/L) | Nitrate+Nitrite (mg/L) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| E#2 | Average | 12.447 | 9.480 | 21.927 | 9.120 | 22.812 |
| | Median | 6.402 | 9.558 | 14.898 | 3.177 | 21.899 |
| | Std. Dev | 19.421 | 7.874 | 25.711 | 11.912 | 15.011 |
| E#3 | Average | 1.498 | 4.035 | 5.533 | 0.029 | 4.536 |
| | Median | 1.107 | 2.118 | 4.124 | 0.010 | 2.824 |
| | Std. Dev | 1.479 | 4.031 | 4.814 | 0.049 | 4.170 |
| E#4 | Average | 2.724 | 4.621 | 7.344 | 0.130 | 6.260 |
| | Median | 2.557 | 3.745 | 6.810 | 0.006 | 5.874 |
| | Std. Dev | 2.025 | 2.078 | 3.165 | 0.304 | 3.078 |

Table 24: Bold and GoldTM Filter Media Phosphorus Species Data (6 samples)

| | | Soluble Reactive Phosphorus (mg/L) | Organic Phosphorus (mg/L) | Total Phosphorus (mg/L) |
|---|---|---|---|---|
| E#2 | Average | 0.617 | 0.054 | 0.795 |
| | Median | 0.044 | 0.063 | 0.104 |
| | Std. Dev | 1.418 | 0.035 | 1.618 |
| E#3 | Average | 0.027 | 0.044 | 0.098 |
| | Median | 0.023 | 0.047 | 0.084 |
| | Std. Dev | 0.024 | 0.023 | 0.050 |
| E#4 | Average | 0.010 | 0.046 | 0.090 |
| | Median | 0.011 | 0.049 | 0.094 |
| | Std. Dev | 0.004 | 0.042 | 0.035 |

The nitrogen species and phosphorus species data are presented in Table 23 and Table 24, respectively. Overall, all the nitrogen and phosphorus species were reduced from the front end of the Bold and Gold$^{TM}$ filter media bed to the effluent pipe. However, all of the nitrogen species increased in concentration from the end of the Bold and Gold$^{TM}$ filter media bed to the constantly wet effluent pipe. Of the phosphorus species, only the organic phosphorus followed this same trend.

The bacteria counts for the wastewater as it travels through the Bold and Gold$^{TM}$ filter media bed were all low with the majority being below detection limit at <1. This again may be influenced primarily by sterile urine. As full time operation of the home occurs, differences should be noted as the mix of wastewater will have more bacteria.

### 3.5.3 Overall Performance

Examining the wastewater quality into the septic tank and compared to the effluent from the Bold and Gold$^{TM}$ filter media, removal efficiencies can be calculated for some of the common water quality parameters. Figure 7 shows the removal efficiency of the Bold and Gold$^{TM}$ filter media from E#1 to E#4.

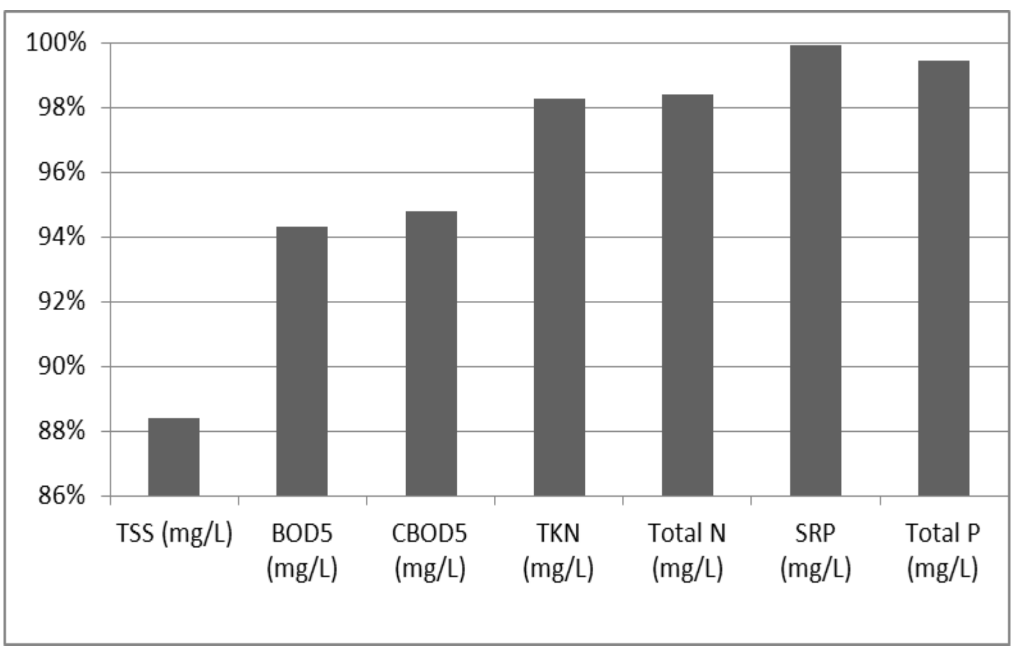



Figure 7: Removal Efficiency of the Influent Samples through the Bold and Gold$^{TM}$ Filter Media.

The TSS removal was approximately 88%. The $BOD_5$ and $CBOD_5$ removal efficiencies were both approximately 94% and 95%, respectively. The TKN and total nitrogen removals were 98%. Lastly, the soluble reactive phosphorus and total phosphorus removals also reached high levels at 99.9% and 99%, respectively. The nutrient removals were incredibly high thus making this a highly efficient system for nutrient reduction.

Table 25: Comparison of Bold and Gold$^{TM}$ Filter Media and UCF Control Conventional System Effluent.

| | Bold and Gold$^{TM}$ Effluent (Dec. 2009-May 2010) | | Conventional System (UCF Control System) | |
|---|---|---|---|---|
| | Average | Std. Dev. | Average | Std. Dev. |
| Alkalinity (mg/L) | 292 | ± 165 | 54 | ± 44 |
| TSS (mg/L) | 26.4 | ± 18.6 | 1.96 | ± 1.05 |
| $BOD_5$ (mg/L) | 30.1 | ± 19.7 | 1.23 | ± 0.68 |
| $CBOD_5$ (mg/L) | 24.2 | ± 15.0 | 0.90 | ± 0.4 |
| Ammonia-N (mg/L) | 2.72 | ± 2.03 | 0.04 | ± 0.02 |
| $NO_X$-N (mg/L) | 0.130 | ± 0.304 | 41.973 | ± 0.089 |
| Nitrite-N (mg/L) | 0.020 | ± 0.044 | 0.003 | ± 0.004 |
| Nitrate-N (mg/L) | 0.110 | ± 0.260 | 41.970 | ± 6.076 |
| Org. N (mg/L) | 4.62 | ± 2.08 | 6.08 | ± 3.71 |
| TKN (mg/L) | 7.34 | ± 3.17 | 6.11 | ± 1.22 |
| TN (mg/L) | 6.26 | ± 3.08 | 48.09 | ± 3.77 |
| SRP (mg/L) | 0.010 | ± 0.004 | 4.577 | ± 0.571 |
| Org. P (mg/L) | 0.046 | ± 0.042 | 0.347 | ± 0.237 |
| TP (mg/L) | 0.090 | ± 0.035 | 4.924 | ± 0.804 |

Table 25 shows the effluent values of the Bold and Gold$^{TM}$ filter media (E#4) compared to the effluent values of the UCF control conventional system on campus. The Bold and Gold$^{TM}$ filter media reduced the total nitrogen and total phosphorus values far below that of the conventional system. Thus, the Bold and Gold$^{TM}$ filter media significantly reducing the nutrient pollutants being released into the environment. However, the conventional system reduced value of $BOD_5$ and $CBOD_5$ in the effluent more than the Bold and Gold$^{TM}$ filter media. Thus, at FSGE, the value of the conventional drain field following the B&G filter media is evident.

## 3.6 Conclusions and Future Work

There is evidence of bacterial activity within the composite sample with the reduction of the average dissolved oxygen, $BOD_5$ and $CBOD_5$ compared to the grab samples. Once FSGE is in full operation with commonly generated wastewater, the results should be more evident. Also, samples should be collected within the Polylok dipper tray and used to determine the effect of the septic tank within the wastewater system.

As the wastewater traveled through the Bold and Gold$^{TM}$, the nitrogen and phosphorus species were reduced. However, all of the nitrogen species and organic phosphorus increased from the Bold and Gold$^{TM}$ filter media bed as it entered the constantly wet effluent pipe. This could be because of short circuiting, thus it is recommended that this point of sampling be eliminated in the future. The pH and conductivity of the samples were almost constant as the wastewater traveled through the Bold and Gold$^{TM}$ filter media bed.

The overall removal efficiencies of the Bold and Gold$^{TM}$ filter media were over 98% for the total nitrogen and total phosphorus. Also, it removed over 94% of the $BOD_5$ and $CBOD_5$. Lastly, the 88% of the TSS was removed. These are encouraging results for removal efficiencies for the new OSTD considering it is taking only black water from the home.

When the effluent wastewater quality was compared to a conventional system wastewater effluent quality, the Bold and Gold$^{TM}$ filter media system had much lower concentrations of total nitrogen and total phosphorus. Thus, the Bold and Gold$^{TM}$ filter media was superior at removing nutrient pollutants entering the environment. However, the TSS, $BOD_5$ and $CBOD_5$ effluent concentrations were higher in the Bold and Gold$^{TM}$ filter media effluent.

Further analysis of the Bold and Gold$^{TM}$ filter media bed under normal wastewater loads (i.e. bathroom wastewater, kitchen sink wastewater, etc.) needs to be done. This is to examine how the system will react under a lower nutrient load as the influent black wastewater will be diluted by these other sources. Also, this will produce a more constant flow of wastewater relative to that being produced currently. Lastly, the life expectancy of the Bold and Gold$^{TM}$ filter media bed needs to be determined.

# CHAPTER 4: GREEN BUILDING OPTIMIZATION MODEL

## 4.1 Introduction

Implementing energy saving and water conservation strategies typically increase the capital cost of a home. However, the added benefits of these strategies over time may offset part of the increase in capital cost for the home. Thus, a cost-benefit-risk analysis should be completed to determine the viability and variability of the use of a water conservation and/or energy saving strategy for a home.

A cost-benefit-risk model is ideal to use when anticipating constructing a more efficient new green home, incorporating a green roof and a combined gray water/stormwater harvesting system. The aim of the model is to find the maximum amount of green roof area on a home possible without the home exceeding the cost of a conventional home when the cost-benefit relationship of the above strategies is taken into account simultaneously. This is done by developing two models. The first model is known as the base model and is a stochastic linear programming model. The second model is known as the grey model and is a stochastic grey linear programming model.

Background information on the green roof energy savings is presented in the following section as background information on the graywater harvesting system and green roof was presented in chapter 2. This is followed by the two models formulation. To demonstrate the utility of these models, a typical Florida home with an asphalt shingle or metal roof is used as a “control” and the FSGE current construction is also compared to the model results. The control homes and FSGE attributes are described following the two models formulation. Within this section, an analysis of the monthly rainfall amount for the home is presented. The results and discussions of the control home model runs and the FSGE run is given. Lastly, the conclusions and future work are written.

## 4.2 Background

Green roofs have been studied for their effect on building energy costs. The green roof can help in cooling a building during the summer due to the evapotranspiration effect from plants and the evaporation of moisture in the soil. Also, during the winter months, the greater insulation property of the green roof prevents the heat from escaping in a building.

Del Barrio (1998) found that green roofs act like an insulator and not a cooling device during the summer months. This is done by reducing the heat flux through the roof. Some of the properties of the green roof that affect its performance as an insulator include soil density, thickness, and moisture content. However, no analysis of the effects of a green roof during the winter months was done due to inadequacy of the soil modeling approach for this purpose (Del Barrio 1998).

In a study done by Onmura et al. (2001), a rooftop lawn garden was shown to reduce the heat flux into the room underneath the garden by 50%. It also showed surface temperature reduced from 60°C to 30°C during the day. This led to the conclusion that the evaporation component is important to reducing the heat flux (Onmura, Matsumoto and Hokoi 2001).

Liu and Baskaran (2003) did a study comparing a green roof to a bituminous roof assembly (reference roof) in Ottawa, Canada. The green roof outperformed the reference roof during the summer months. The green roof reduced the space cooling of the building by 75% compared to the reference roof. Also, the roof temperature rarely reached over 30°C while the reference roof reached temperatures of 70°C. This study also found that the green roof was more efficient at reducing heat gain than heat loss. Therefore, would be more efficient in warmer climates (Liu and Baskaran 2003).

However, green roofs energy saving has not been studied for residential home, rather commercial application (multi-story and strip mall buildings). Thus, there is no data on the energy savings a green roof provides. Therefore, the energy savings from the green roof will be one of the variables manipulated to see its effect on the model.

## 4.3 Base Model Formulation

Since the green roof needs a long term irrigation system and the stormwater is being harvested in the model, the model is developed with a chance constraint to incorporate the variability of the rainfall that provides the major portion of the irrigation water for the green roof. What results is the formulation of a linear stochastic programming model to address the cost-benefit-rick concern. This model is known as the base model in this paper.

### 4.3.1 Base Model Solution Procedure

The optimization model can be formulated by maximizing the green roof area, thereby maximizing energy savings. The objective function is shown in Equation 4.1 in which $A_g$ ($m^2$) is the area of green roof required in the context of optimization.

$$Max \quad Z = A_g \tag{4.1}$$

The added cost of the green roof and cistern capacity must be offset by the benefits obtained through incorporating these systems. This cost-benefit constraint is defined by Equation 4.2. AF is the amortization factor for the capital costs. The capital cost of the green roof materials and installation is expressed as the green roof area $A_g$ ($m^2$) times the cost of the green roof per unit area $C_g$ ($/$m^2$). The capital cost of traditional roof materials and installation is calculated by multiplying the area of the horizontal traditional roof area $A_t$ ($m^2$) times the cost of traditional roof per unit area $C_t$ ($/$m^2$) and the sloped roof factor $S_t$. $S_t$ is added to account for the extra area of roof due to the conventional roof area being sloped. The capital cost of cistern materials and installation is found by taking the required volume of the cistern $V_c$ ($m^3$) times the cost of cistern per unit volume $C_c$ ($/$m^3$). To find the added cost of the new system compared to the traditional roof, the traditional roof cost must be subtracted from the total cost of the new system. Thus, the original cost of traditional roof is found by multiplying the cost of the traditional roof per unit area $C_t$ ($/$m^2$) by the total area of the original traditional roof $A_r$ ($m^2$) and the sloped roof factor $S_t$. The annual benefit due to the green roof is an energy savings expressed as $B_g$ ($/$m^2$/yr) times the area of the green roof. The benefit of water savings gained by reusing the stormwater and gray water for flushing toilets $Vt_m$ ($m^3$) and irrigating the ground level landscape $Vi_m$ ($m^3$) is found by times these values by $B_w$ ($/$m^3$) which is the same as the potable water price.

$$AF(C_g A_g + C_t S_t A_t + C_c V_c - C_t S_t A_r) \le [B_g A_g + B_w \sum_{m=1}^{12} (Vi_m + Vt_m)] \quad (4.2)$$

When the entire roof is covered by the green roof, a specific energy savings is assumed. This percentage of energy savings is assumed to be directly proportional to the percentage of roof covered by green roof. This leads to the formulation of Equation 4.3 where $E_h$ is the energy demand of the home (KWh), $C_e$ is the cost of energy ($/KWh) and ES is the energy savings (decimal percentage).

$$B_g = \frac{(E_h)(C_e)(ES)}{A_r} \tag{4.3}$$

The model considers the mass balance of water entering and leaving the cistern. Figure 8 shows the mass balance around the cistern associated with all the flows entering and exiting the cistern. The water inflows to the cistern are the gray water from the home, the stormwater runoff from the roof and the supplemented potable water. The water is then used to flush the toilets in the home or for irrigation of the land and green roof, thus reducing the potable water demand for these purposes.

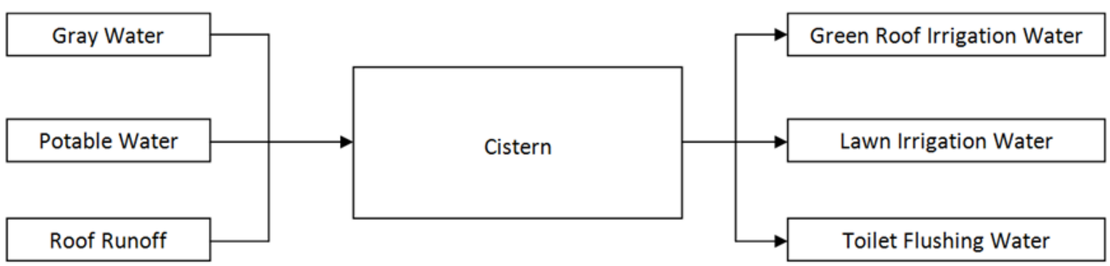



Figure 8: Water Mass Balance around the Cistern

This mass balance around the cistern on a monthly scale is used in development of the mass balance constraints Equations 4.4. The amount of water stored in the cistern at the end of the month m is expressed as $S_m$ ($m^3$). Stormwater runoff from the green roof and traditional roof area is represented by $Vr_m$ ($m^3$). The gray water from the home is depicted by $Vh_m$ ($m^3$). The water in the cistern used for irrigating the green roof, toilet flushing, and irrigation of the backyard on a monthly basis are expressed as $Vg_m$ ($m^3$),

$Vt_m$ ($m^3$), and $Vl_m$ ($m^3$), respectively. The potable water being supplied to the cistern to make up the difference for watering of the lawn is represented as $Vp_m$ ($m^3$).

$$S_m = S_{m-1} + Vr_m + Vh_m + Vp_m - Vg_m - Vl_m - Vt_m \qquad \forall m \tag{4.4}$$

The volume of stormwater runoff entering the cistern is dictated by the area of green roof, traditional roof and rainfall amount. This volume of runoff is found using Equation 4.5. This expression is the chance constraint. It states that the probability of the volume of runoff $Vr_m$ that should be greater than or equal to the volume of actual runoff is larger than the cutoff value with respect to the level of reliability β. The values of $R_g$ and $R_{t,}$ in Equation 4.5 are runoff coefficients for the green roof and conventional roof, respectively. P (m) is the rainfall amount in a specified time period, which is a random variable in this model and can be characterized by the goodness of fit tests.

$$\Pr\{Vr_m \geq [(A_g)(R_g) + (A_t)(R_t)](P)\} \geq \beta \qquad \forall m \tag{4.5}$$

The expression above can be simplified by rewritten it to be Equations 4.6. This equation states that the volume of runoff is equal to the rainfall amount at a level of reliability, β, times the area of the roof and there corresponding runoff coefficients. $P_\beta$ (m) is defined as the rainfall amount that will be equal to or greater than the actual rainfall amount at a level of reliability β. This allows Equation 4.5 to be incorporated into the linear model as a deterministic equivalent constraint in Equation 4.6.

$$Vr_m \geq [(A_g)(R_g) + (A_t)(R_t)](P_\beta) \qquad \forall m \tag{4.6}$$

The gray water leaving for the cistern ($Vh_m$) and reentering as toilet water ($Vt_m$) are expressed below in Equations 4.7 and 4.8, respectively. Gray water and toilet flushing water are related to the number of residents of the home. The volume of gray water can be found by taking 70% of the average water usage per capita W ($m^3$/capita) times the number of residents, n. This is to account for the 30% in water savings from the gray water harvesting system. Then, the 30% of the typical potable water usage can recycled from the cistern as toilet flushing water based on our experience.

$$Vh_m = n(W)(0.7) \qquad \forall m \tag{4.7}$$

$$Vt_m = n(W)(0.3) \qquad \forall m \tag{4.8}$$

The irrigation requirement of the green roof is shown in Equation 4.9 while the irrigation requirement of the lawn is shown in Equation 4.10. The green roof irrigation requirement is found by taking the area of the green roof and times it by the volume of irrigation water required per unit area, $I_m$ ($m^3/m^2$). Likewise, the irrigation volume of the lawn is found by taking the area of the lawn, $A_l$ ($m^3$) times the volume of irrigation water required per unit area, $I_m$ ($m^3/m^2$).

$$Vg_m = (A_g)(I_m) \qquad \forall m \tag{4.9}$$

$$Vl_m = (A_l)(I_m) \qquad \forall m \tag{4.10}$$

The amount of harvested water being reused for irrigation of the land is found using Equation 4.11. The amount of harvested water reused for irrigation of the ground level landscape $Vi_m$ ($m^3$) is found by taking the required water for irrigating the lawn minus the potable water used to supplement the cistern that offsets the essential benefit.

$$Vi_m = Vl_m - Vp_m \qquad \forall m \tag{4.11}$$

The size of the cistern is determined by the following constraints. The cistern volume must be greater than any of the storage values at the end of each month as shown in Equation 4.12. The cistern must also have the capacity to capture the runoff from the roof each month, thus capturing all the monthly rain water. This constraint is defined below in Equation 4.13.

$$V_c \geq S_m \qquad \forall m \tag{4.12}$$

$$V_c \geq Vr_m \qquad \forall m \tag{4.13}$$

The summation of the traditional and green roof area cannot exceed the total roof area. Thus, Equation 4.14 must hold true. The final parameter is to define all the nonzero constraints. These are listed below in 4.15.

$$A_r = A_g + A_t \tag{4.14}$$

$$A_g, A_t, V_c, V_p, S_m \geq 0 \tag{4.15}$$

## **4.4 Grey Model Formulation**

When it comes to the cost of the construction materials, there is an uncertainty associated with the cost of the selected material. For example, cooper and aluminum metal roof systems are commonly used. However, these roofs have different capital costs associated with them. Also, the region has an impact on the cost of the materials. Thus, the cost of the roofing materials and cistern are included in the model as grey numbers or interval numbers. The energy saving provided by the green roof is inputted into the model as grey numbers. This is due to the uncertainty associated with the lack of research into the energy savings potential of the green roof.

Due to the roof systems costs and green roof energy savings being grey numbers and being inputted into the model as a range, the optimal solution will also be a range. Thus, there will be an upper and lower bound to the optimal solution. The base model is then developed into two models, one to find the upper and the other to find the lower bound green roof area. Then, they are combined to make one model that will yield the optimum upper and lower bounds simultaneously. This combined model is a grey linear stochastic programming model. This model is known as the grey model in this paper.

### 4.4.1 Upper Bound Model Solution Procedure

First, the optimization of the upper bound model is presented. In the cost-benefit constraint, the grey numbers have been replaced with a plus or minus superscript. The minus sign was placed on the cost terms to denote using the lower bound of the cost. The benefit due to the green roof has a plus superscript and thus means using the upper bound of the energy savings. These inputs will provide the maximum area of green roof to be found (see APPENDIX D for grey linear programming paper). The decision variables ($A_g$, $A_t$, $V_c$, and $V_i$) all share the plus superscript to denote they belong to the upper bound optimization. This use of the plus superscript for decision variables affected by the grey numbers is then used throughout the model. Thus, Equations 4.1, 4.2, 4.3, 4.4, 4.6, 4.9, 4.11, 4.12, 4.13, 4.14 and 4.15 are replaced with Equations 4.16, 4.17, 4.18, 4.19, 4.20, 4.21, 4.22, 4.23, 4.24, 4.25, and 4.26, respectively.

$$Max \quad Z = A_g^{\ +} \tag{4.16}$$

$$AF(C_g^{\ -}A_g^{\ +} + C_t^{\ -}S_tA_t^{\ +} + C_c^{\ -}V_c^{\ +} - C_t^{\ -}S_tA_r) \le [B_g^{\ +}A_g^{\ +} + B_w\sum_{m=1}^{12}(Vi_m^{\ +} + Vt_m)] \tag{4.17}$$

$$B_g^{\ +} = \frac{(E_h)(C_e)(ES^+)}{A_r} \tag{4.18}$$

$$S_m^{\ +} = S_{m-1}^{\ +} + Vr_m^{\ +} + Vh_m + Vp_m^{\ +} - Vg_m^{\ +} - Vl_m - Vt_m \qquad \forall m \tag{4.19}$$

$$Vr_m^{\ +} \geq [(A_g^{\ +})(R_g) + (A_t^{\ +})(R_t)](P_\beta) \qquad \forall m \tag{4.20}$$

$$Vg_m^{\ +} = (A_g^{\ +})(I_m) \qquad \forall m \tag{4.21}$$

$$Vi_m^{\ +} = Vl_m - Vp_m^{\ +} \qquad \forall m \tag{4.22}$$

$$V_c^{\ +} \geq S_m^{\ +} \qquad \forall m \tag{4.23}$$

$$V_c^{\ +} \geq Vr_m^{\ +} \qquad \forall m \tag{4.24}$$

$$A_r = A_g^{\ +} + A_t^{\ +} \tag{4.25}$$

$$A_g^{\ +}, A_t^{\ +}, V_c^{\ +}, V_p^{\ +}, S_m^{\ +} \geq 0 \tag{4.26}$$

### 4.4.2 Lower Bound Model Solution Procedure

The lower bound model formulation entails switching the upper bound values used in the upper bound model with the lower bound values and vice versa for the lower bound values. Thus, Equations 4.1, 4.2, 4.3, 4.4, 4.6, 4.9, 4.11, 4.12, 4.13, 4.14 and 4.15 are replaced with Equations 4.27, 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, 4.34, 4.35, 4.36, and 4.37, respectively.

$$Max \quad Z = A_g^{\ -} \tag{4.27}$$

$$AF(C_g^{\ +}A_g^{\ -} + C_t^{\ +}S_tA_t^{\ -} + C_c^{\ +}V_c^{\ -} - C_t^{\ +}S_tA_r) \leq [B_g^{\ -}A_g^{\ -} + B_w\sum_{m=1}^{12}(Vi_m^{\ -} + Vt_m)] \tag{4.28}$$

$$B_g^{\ -} = \frac{(E_h)(C_e)(ES^-)}{A_r} \tag{4.29}$$

$$S_m^{\ -} = S_{m-1}^{\ -} + Vr_m^{\ -} + Vh_m + Vp_m^{\ -} - Vg_m^{\ -} - Vl_m - Vt_m \qquad \forall m \tag{4.30}$$

$$Vr_m^{\ -} \geq [(A_g^{\ -})(R_g) + (A_t^{\ -})(R_t)](P_\beta) \qquad \forall m \tag{4.31}$$

$$Vg_m^- = (A_g^-)(I_m) \qquad \forall m \tag{4.32}$$

$$Vi_m^- = Vl_m - Vp_m^- \qquad \forall m \tag{4.33}$$

$$V_c^- \geq S_m^- \qquad \forall m \tag{4.34}$$

$$V_c^- \geq Vr_m^- \qquad \forall m \tag{4.35}$$

$$A_r = A_g^- + A_t^- \tag{4.36}$$

$$A_g^-, A_t^-, V_c^-, V_p^-, S_m^- \geq 0 \tag{4.37}$$

### 4.4.3 Combined Grey Model Solution Procedure

The upper and lower bound models can be combined into one model that yields the optimal range of green roof area for the residential home. This is done in reference to the grey programming paper located in APPENDIX D. First, the two objective equations have to be formed into a single objective equation. This is shown as Equation 4.38.

$$Max \quad Z = A_g^+ + A_g^- \tag{4.38}$$

Next, Equations 4.27, 4.28, 4.29, 4.30, 4.31, 4.32, 4.33, 4.34, 4.35, 4.36, and 4.37 are added to the constraints listed in the upper bound model formulation. Finally, a new constraint must be added to ensure that the upper bound will always be larger than the lower bound. This is shown in Equation 4.39 below.

$$A_g^+ \geq A_g^- \tag{4.39}$$

## 4.5 Case Study Inputs

The case study homes are located in the coastal city of Indialantic, Florida. A study period of 50 years is used since that is a good low end estimate of a green roof life expectancy. The control home and FSGE attributes are explained in more detail below. This is followed by the different roof systems attributes and finally the monthly rainfall data analysis.

### 4.5.1 Control Home and FSGE Attributes

Table 26 lists the attributes of the home being modeled in this study. The home has a total roof area of 223 $m^2$ (2400 $ft^2$) and is occupied by three inhabitants. The traditional roof area has a roof pitch of 3/12. 18000 KWh of energy per year is assumed to be the energy demand of this home and 0.36 $m^3$/day (95 gal/day) per capita water consumption will be assumed (Borisova and Carriker 2009). The home currently has a septic system on site. The current cost for electricity in this area is $0.13/KWh (Florida Power and Lights 2009) and the cost for potable water is $4.23/1000 gallons (City of Melbourne 2009).

Table 26: Modeled Home Attributes

| | |
|---|---|
| Roof Area | 223 $m^3$ |
| Roof Pitch | 3/12 |
| Inhabitants | 3 People |
| Water Usage per Capita | 0.36 $m^3$/day |
| Energy usage | 18000 KWH per year |

The home has a 674.5 $m^2$ (1/3 acre) of lawn area that must be irrigated. Currently, there is irrigation watering restrictions in the water management district this home resides. The regulations are between the months of March to November, the lawn may only be watered up to of ¾ inch (0.019 m) two days a week. During November to

March, the lawn may only be watered up to ¾ inch (0.019 m) one day a week (St. Johns Water Management District 2009).

The FSGE shares all the attributes of the control home other than the roof area is 307 $m^2$ (3300 $ft^2$). The home incorporates decking with metal 231.3 $m^2$ (2477 $ft^2$) and green roof 75.7 $m^2$ (815 $ft^2$). Also, the home has a cistern of 17.0 $m^3$ (4500 gallons). Since the home is already constructed, the model is used to verify the home as it is currently built.

### 4.5.2 Roof Systems Attributes

This study compares shingle and metal roof systems with the green roof. Table 27 displays the grey numbers of the model upper and lower bounds as well as the average values. The average values are used in the base model. An explanation of the different roof systems used and there attributes as they pertain to the model follows.

Table 27: Modeled Grey Numbers

| Object | Lower Bound | Average | Upper Bound |
|---|---|---|---|
| Shingle Roof ($/$m^2$) | 11 | 32 | 43 |
| Metal Roof ($/$m^2$) | 32 | 86 | 129 |
| Green Roof ($/$m^2$) | 161 | 215 | 269 |
| Cistern ($/$m^3$) | 198 | 264 | 330 |
| Energy Savings (%) | 5 | 8 | 10 |

Shingle roof vary in cost from one job to another considering the roof slope and shape of the roof. Also, the type of shingle, whether organic or fiber glass, effects the cost. Therefore, a range of $11-43/$m^2$ ($1-4/$ft^2$) was used (CostHelper 2008). Since the lifetime of a typical roof is approximately 15-20 years, the model had to incorporate replacing the roof twice (year 17 and 34) during the analysis. Finally, a runoff coefficient of 0.9 is used for the shingle roof.

Metal roofs are more durable and could survive the entire 50 years of the study time. However, this roof systems cost more than shingle roofs. Since, like shingles, they vary in type and style a range of \$32-129/m$^2$ (\$3-12/ft$^2$) is assumed for its cost (CostHelper 2008). A runoff coefficient of 0.95 is assumed for the metal roof.

The construction cost for green roofs are also widely variable. The variability is due to the selection of media, plants and configuration of the green roof as they affect the overall cost of the green roof. Also, climate has an influence on the cost as this dictates the vegetation on the roof. For this study a sampling of the local market of green roofs cost found a range of \$161-269/m$^2$ (\$15-25/ft$^2$) was a good estimate. The amount of rainfall the green roof retains during rainfall events is also variable. However, an assumed value of 40 % of the annual rainfall retained has been reported in the literature (Wanielista, Kelly and Hardin 2006). Thus, a runoff coefficient of 0.6 is used. The energy savings, since not extensively studied for residential homes, was ranged from 5-10%. This came from a personal communication from the Florida Solar Energy Center with reference to how much the roof contributes to the total home energy savings. The cistern cost depends on the material and the capacity required. Thus, it has a wide range of cost which, after sampling the local market, was found to be \$198-330/m$^3$ (\$5.61-9.35/ft$^3$) (\$0.75-1.25/gallon).

### 4.5.3 Monthly Rainfall Data Analysis

The monthly rainfall data used in this model came from a National Oceanic and Atmospheric Administration (NOAA) rainfall gage located in Melbourne, Florida. This is the closest rainfall gage to Indialantic, Florida. The collection of data covers the years of 1938-2006. Some basic statistics of the rainfall data are presented in Table 28 and a histogram of the rainfall data on a monthly basis is shown in Figure 9. To account for the monthly variability of the rainfall amount, a chance constraint was placed into the model. The chance constraint is the rainfall amount that will at least occur each month at a selected risk level. Thus, to find this rainfall amount, the distribution of each month's rainfall data most closely follows must be found.

Table 28: Basic Statistics of the Monthly Rainfall Data in Meters

| Statistic | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Average | 0.06 | 0.07 | 0.08 | 0.05 | 0.09 | 0.16 | 0.15 | 0.15 | 0.20 | 0.13 | 0.07 | 0.05 |
| Median | 0.04 | 0.06 | 0.06 | 0.05 | 0.08 | 0.16 | 0.14 | 0.15 | 0.18 | 0.12 | 0.05 | 0.04 |
| Std Dev. | 0.04 | 0.05 | 0.06 | 0.04 | 0.06 | 0.09 | 0.07 | 0.08 | 0.10 | 0.09 | 0.06 | 0.05 |

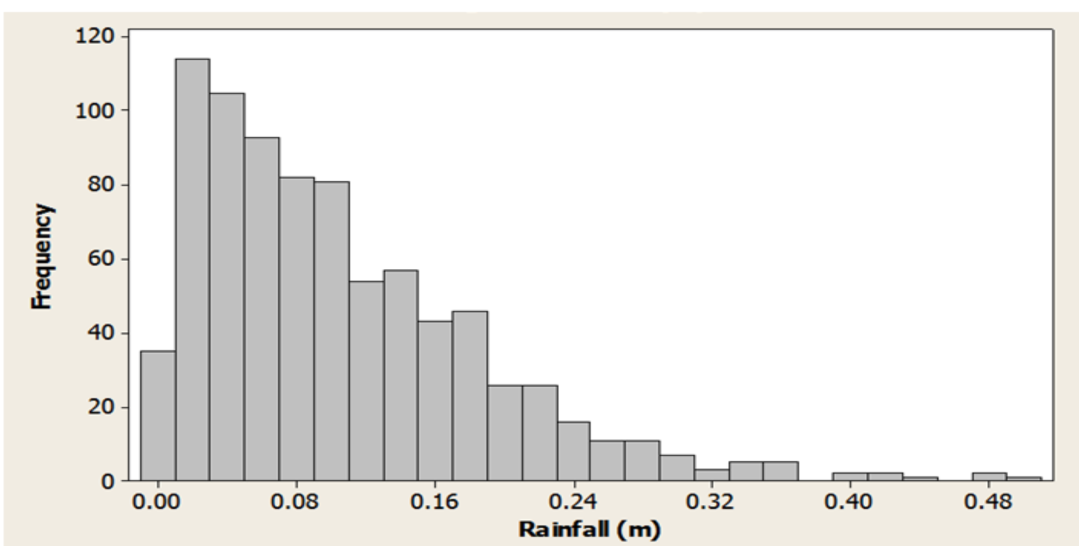



Figure 9: Histogram of the Monthly Rainfall Amounts from 1938-2006

The monthly probability density functions (pdf) were identified based on the rainfall data using MiniTab software package as a tool. Research finding shows that the monthly rainfall data most closely followed either the Weibull or gamma pdf. The results of the analysis are displayed in Table 29. The monthly rainfall data passed the Anderson-Darling (Anderson and Darling 1954) and Kolmogorov-Smirnov (Massey and J. 1951) tests at a significance of 95%.

Table 29: Results of pdf Analysis of the Monthly Rainfall Data

| Month | Distribution | Shape Factor | Scale Factor |
|---|---|---|---|
| January | Weibull | 1.31277 | 0.06157 |
| February | Weibull | 1.35863 | 0.07243 |
| March | Weibull | 1.3175 | 0.08724 |
| April | Weibull | 1.16267 | 0.0575 |
| May | Weibull | 1.49728 | 0.10197 |
| June | Weibull | 1.90576 | 0.18188 |
| July | Gamma | 3.80561 | 0.03821 |
| August | Gamma | 3.67604 | 0.0411 |
| September | Gamma | 4.05234 | 0.04937 |
| October | Weibull | 1.51352 | 0.14376 |
| November | Gamma | 1.62222 | 0.04365 |
| December | Gamma | 1.69466 | 0.03256 |

The two parameters that describe the Weibull distribution are the shape (α) and scale (β) parameters. The Weibull probability density function is displayed in Equation 4.40. These two parameters are also found in the gamma distribution. The gamma probability function is shown in Equation 4.41. The values for each month's parameters are also listed in table 2 with the goodness of fit tests located in APPENDIX E.

$$Weibull \quad pdf(y) = \frac{\alpha}{\beta} y^{\alpha-1} \exp^{-y^{\alpha}/\beta} \tag{4.40}$$

$$Gamma \quad pdf(y) = \frac{y^{\alpha-1} \exp^{-y/\beta}}{\beta^{\alpha} \Gamma(\alpha)} \tag{4.41}$$

## 4.6 Results and Discussion of Models

The results of the two models are displayed separately following sections. The models were run with varied reliability levels of 99%, 95%, 90%, 80%, 70% and 60% to see the effect it had on the results. Also, the base model energy savings values were varied from 2% to 48% to determine the effect energy savings had on the model.

### 4.6.1 Base Model Results and Discussion

The results of the base model runs are presented in Table 30. The first observation is the green roof covered a portion of the roof and is therefore economical. However, to be economical, only a portion of the roof should be covered. Therefore, only a portion of the total roof was covered with the green roof. This is due primarily to the huge cost difference between the green roof and the two traditional roofing systems analyzed. Also, there was enough harvested water to supply the toilet water for the home in all the reliability levels.

Table 30: Base Model Varied Reliability Level Results

| Model Roof System | Reliability (%) | $A_g$ ($m^2$) | $A_t$ ($m^2$) | $V_i$ ($m^3$) | $V_p$ ($m^3$) | $V_c$ ($m^3$) |
|---|---|---|---|---|---|---|
| Shingle | 99 | 37.6 | 185.4 | 121.9 | 997.8 | 7.9 |
| | 95 | 34.0 | 188.8 | 154.9 | 964.9 | 13.1 |
| | 90 | 32.4 | 190.6 | 180.3 | 939.4 | 16.8 |
| | 80 | 30.3 | 192.7 | 220.0 | 899.7 | 22.1 |
| | 70 | 28.9 | 194.1 | 255.3 | 864.4 | 26.6 |
| | 60 | 27.8 | 195.2 | 290.2 | 829.6 | 31.0 |
| Metal | 99 | 42.9 | 180.1 | 114.1 | 1005.6 | 8.2 |
| | 95 | 38.9 | 184.1 | 149.3 | 970.4 | 13.7 |
| | 90 | 36.7 | 186.3 | 176.4 | 943.3 | 17.5 |
| | 80 | 34.2 | 188.8 | 218.5 | 901.2 | 23.1 |
| | 70 | 32.5 | 190.5 | 255.8 | 863.9 | 27.8 |
| | 60 | 31.1 | 191.9 | 292.6 | 827.1 | 32.3 |

The shingle roof has a smaller area of green roof compared to that of the metal roof area over all the levels of reliability selected. This is mainly attributed to the lower cost of shingle roofing per unit area. Since the original cost of the system was smaller, the added cost of the system had to be smaller. However, due to the smaller area of green roof, the shingle roof had more water available for irrigation. Thus, the added benefit of using less potable water compared to the metal roof could become a trade-off factor in the context of optimization.

As the reliability level is increased, the area of green roof increased. This occurred because of Equation 4.13. As the reliability level decreased, the more rain water was expected. Therefore, the cistern volume also had to increase to deal with the greater rainfall amount. The added benefit of water for land irrigation could not overcome this increased cost. Hence, the reduction of the green roof area was the only alternative.

However, the difference of green roof area from a reliability level of 60 to a reliability level of 99 is only 11.8 $m^2$ (127 $ft^2$) for the metal roof and 9.8 $m^2$ (105 $ft^2$) for the asphalt shingle roof. This equates to a change in total roof area of approximately 5.3% and 4.4% for the metal and asphalt shingle roofs respectively. This is not a significant amount of roof area increase.

To determine the sensitivity of the energy savings in the optimization steps, the estimated energy savings was therefore varied from 2% to 48%. The range of energy savings was drawn from a previous study in regard to the upper and lower limits of possible energy savings for a commercial building due to varying roof material affecting the insulation properties of the roof (Niachou, et al. 2001). The reliability analysis was done on the shingle and metal roofs at a reliability level of 95%. The results are displayed in Figure 10.

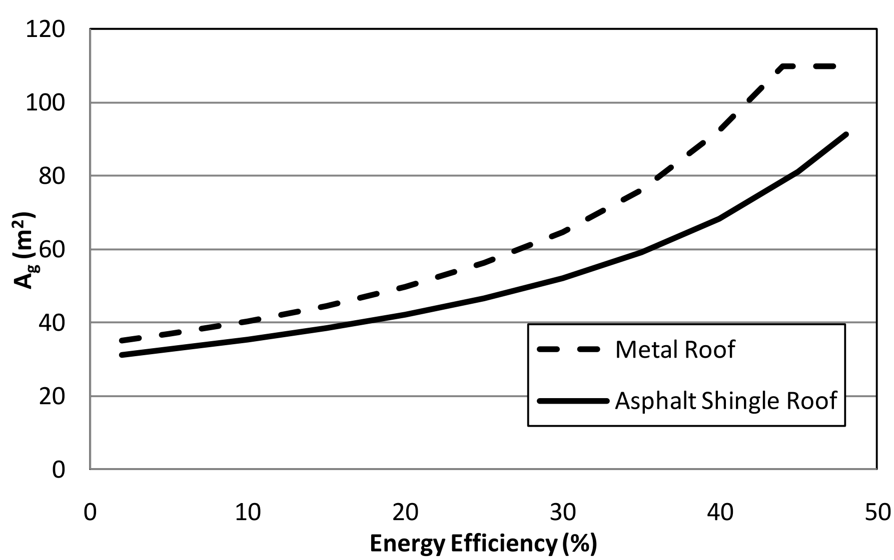



Figure 10: Base Model Varied Energy Savings at a Reliability Level of 95%

As the energy savings from the green roof was increased, the maximum area of green roof also increased for both cases of shingle and metal roofs. While varying the energy savings provided by the green roof, the irrigation requirement of the green roof became the limiting constraint for the metal roof. The maximum amount of green roof area was found to be 109.7 $m^2$ (1181 $ft^2$) for the metal roof. This limiting constraint was not reached with the asphalt shingle roof. Again, this is due to the cost difference between the two roofing materials.

The maximum amount of green roof area for the metal roof model was reached at an energy savings 44%. This is a large drop in energy usage and might not be attainable by the use of a green roof alone. Better insulation materials around the building envelop may be a supplemental measure to collectively achieve the goal.

The metal and shingle roof models increase in green roof area started off with an almost linear trend. Then, the green roof area began to increase exponentially at the end. Thus, the greater the energy savings the greater increase in green roof area achievable.

### 4.6.2 Grey Model Results and Discussion

Table 31 displays the results of the grey model varied reliability level for the shingle and metal roof runs. The total benefit of the integrated systems were not enough to make the entire roof a green roof as seen previously in the base model. Again, this is due primarily to the huge cost difference between the green roof and the two conventional roofing systems analyzed. Also, the harvested water supplied the toilet flushing water for the home. The shingle roof had smaller areas of green roof compared to that of the metal roof area over all the model runs as observed and explained in the base model results.

Table 31: Grey Model Varied Reliability Level Results

| Model Roof System | Reliability (%) | $A_g$ ($m^2$) | | $A_t$ ($m^2$) | | $V_i$ ($m^3$) | | $V_c$ ($m^3$) | |
|---|---|---|---|---|---|---|---|---|---|
| | | Min | Max | Min | Max | Min | Max | Min | Max |
| Shingle | 99 | 36.2 | 64.2 | 186.8 | 158.8 | 184.4 | 183.2 | 7.9 | 7.6 |
| | 95 | 30.5 | 62.1 | 192.5 | 160.9 | 212.0 | 209.3 | 13.2 | 12.6 |
| | 90 | 27.1 | 61.4 | 195.9 | 161.6 | 234.7 | 230.6 | 16.9 | 16.0 |
| | 80 | 22.7 | 61.3 | 200.3 | 161.7 | 271.7 | 264.9 | 22.4 | 21.0 |
| | 70 | 19.4 | 61.8 | 203.6 | 161.2 | 305.5 | 295.9 | 27.0 | 25.3 |
| | 60 | 16.4 | 62.6 | 206.6 | 160.4 | 339.5 | 326.6 | 31.5 | 29.3 |
| Metal | 99 | 49.2 | 70.7 | 173.8 | 152.3 | 185.0 | 184.0 | 8.1 | 7.8 |
| | 95 | 41.2 | 68.2 | 181.8 | 154.8 | 213.6 | 210.9 | 13.6 | 13.0 |
| | 90 | 36.3 | 67.5 | 186.7 | 155.5 | 237.4 | 233.0 | 17.5 | 16.5 |
| | 80 | 29.9 | 67.4 | 193.1 | 155.6 | 276.1 | 268.4 | 23.2 | 21.7 |
| | 70 | 25.0 | 68.0 | 198.0 | 155.0 | 311.7 | 300.3 | 28.2 | 26.1 |
| | 60 | 20.6 | 68.9 | 202.4 | 154.1 | 347.7 | 332.0 | 32.9 | 30.2 |

Due to the smaller area of green roof, the shingle roof had more water available for irrigation. Thus, the added benefit of using less potable water compared to the metal roof could become a trade-off factor in the context of optimization. This is due to the runoff being greater off the conventional roofs compared to the green roof. When examining the maximum and minimum for each reliability level, the volume of water used for irrigation varied slightly. The range of the relative percent differences ranged from 1% - 5%.

The volume of the cistern increased as the reliability level increased for each conventional roof. This is due to the increase in runoff from the roof with the reliability decrease. The difference in required volume was not great for the minimum and maximum cases for each reliability level. The range of the relative percent difference of the volume differences was 4% - 9%.

Figure 11 and Figure 12 show plots for the green roof area versus the risk level for both the asphalt shingles and metal roofs. The gap between the maximum and minimum values for both conventional roofs analyzed increased as the reliability level decreased. The asphalt shingle green roof minimum to maximum difference from a reliability level of 99% to 60% was 28.0 $m^2$ to 46.2 $m^2$. The metal green roof minimum to maximum difference from a reliability level of 99% to 60% was 21.5 $m^2$ to 48.3 $m^2$.

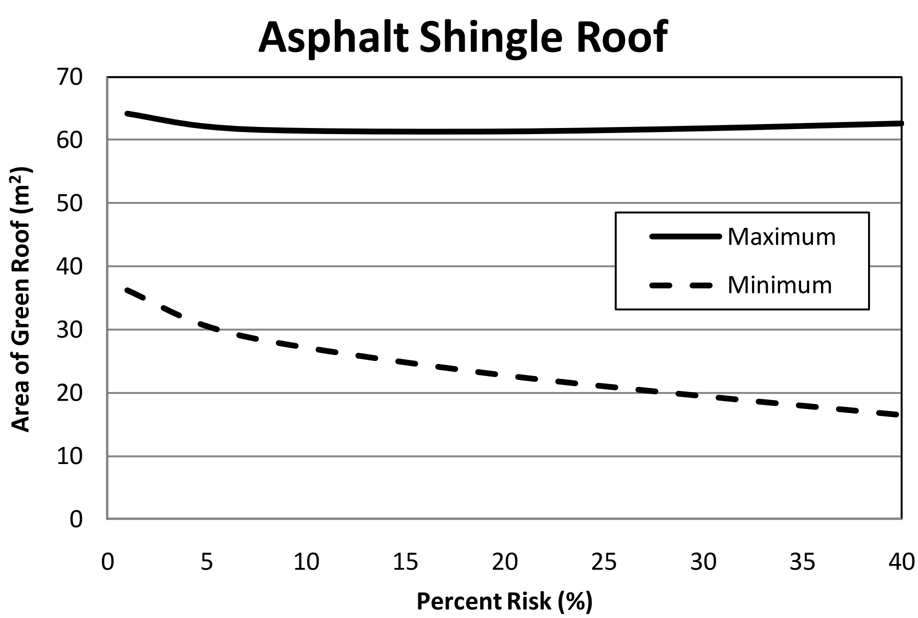



Figure 11: Area of Green Roof versus Risk for Asphalt Shingle Roof

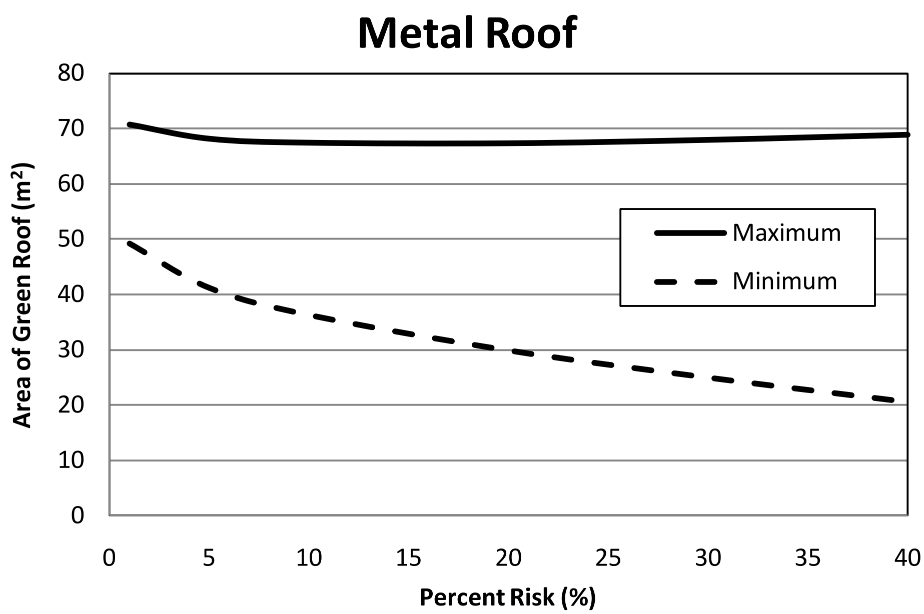



Figure 12: Area of Green Roof versus Risk for Metal Roof

The maximum area of the green roof for each of the roof systems varied very little between reliability levels. The relative percent difference for the maximum area of the green roof was 5% for the asphalt shingle and metal roof. The decreased reliability level increased the rainfall expected. Thus, the cistern volume had to increase to deal with the new runoff volume being routed to it. This increased cost of the cistern was not overcome by the benefits gained from the system. Hence, the linear trend of the area of the green roof.

The area of green roof decreased for the minimal case as the reliability level was decreased. As with the maximum case, the cistern also increased as the runoff was increased. With the higher unit cost of the cistern, the benefits were overcome by this added cost. Hence, the reduction of the green roof area was the only alternative to reduce the cost of the total system. The relative percent difference between the values of the minimum green roof area was 75% and 82% for the asphalt shingle and metal roofs, respectively.

### 4.6.3 FSGE Model Results and Discussion

As seen in the previous two models, the total benefits of the integrated systems were not enough to make the entire roof a green roof. Also, the harvested water supplied the toilet flushing water for the home. The FSGE currently has 75.7 $m^2$ (815 $ft^2$) of green roof and 231.3 $m^2$ (2477 $ft^2$) of decking and metal roof. The current cistern has a capacity of 4500 gallons (17.0 $m^3$). The grey model results are shown in Table 32. The actual green roof area versus the model results was never reached. This means, the green roof currently installed is oversized from an optimization standpoint. However, the cistern capacity was found to fall within the 99%-95% reliability level.

Table 32: FSGE Grey Model Results

| Reliability (%) | $A_g$ ($m^2$) | | $A_t$ ($m^2$) | | $V_i$ ($m^3$) | | $V_c$ ($m^3$) | |
|---|---|---|---|---|---|---|---|---|
| | Min | Max | Min | Max | Min | Max | Min | Max |
| 99 | 42.7 | 67.3 | 264.3 | 239.7 | 196.6 | 195.4 | 11.6 | 11.2 |
| 95 | 31.2 | 63.8 | 275.8 | 243.2 | 237.2 | 234.0 | 19.4 | 18.6 |
| 90 | 24.3 | 62.8 | 282.7 | 244.2 | 271.0 | 265.6 | 24.9 | 23.7 |
| 80 | 15.2 | 62.6 | 291.8 | 244.4 | 326.1 | 316.3 | 33.0 | 31.1 |
| 70 | 8.3 | 63.4 | 298.7 | 243.6 | 376.7 | 362.1 | 40.0 | 37.4 |
| 60 | 2.0 | 64.7 | 305.0 | 242.3 | 427.9 | 407.5 | 46.8 | 43.3 |

## 4.7 Conclusions and Future Work

This model has shown how the synergistic operation of water conservation and energy savings features affect the optimal design of a residential home and produces the added benefit of these systems to outweigh the added cost. This can be shown when a typical Florida home was put into a practice. The modeling outputs in our study proved that a green roof and graywater harvesting system can be incorporated into a typical process of green home design.

First, there were some common observations for both the base and grey models. It was shown that the maximum allowable area of green roof was greater in the metal roof home than an asphalt shingle roof home. As the reliability was decreased, the area of green roof decreased generally. This was due to the increased size, thus cost of the cistern.

The major findings of the base model are discussed below. The difference of green roof area when the reliability was varied from 99% to 60% was only 11.8 $m^2$ (127 $ft^2$) for the metal roof and 9.8 $m^2$ (105 $ft^2$) for the asphalt shingle roof. This equates to a change in total roof area of approximately 5.3% and 4.4% for the metal and asphalt shingle roofs respectively. When the base model's energy savings was varied from 2% to 48%, the irrigation of the green roof became the limiting constraint for the metal roof. The maximum amount of green roof area was found to be 109.7 $m^2$ (1181 $ft^2$) for the metal roof. Also, these options came with the assumption that the green roof can achieve an energy consumption reduction of 44% which might not be achievable by a green roof alone. The trend of the varied energy savings started off almost linear and then increased exponentially. Thus, the greater the green roof area the greater the energy savings achieved.

The major findings of the grey model are discussed below. The difference of the volume of the cistern and irrigation water for the upper and lower bounds of each reliability level did vary greatly. They relative percent difference only reached a high point of 9%. The gap between the upper and lower bound values increased as the reliability levels decreased. The upper bound for the green roof area stayed almost linear for the shingle and metal roofs. The area of the green roof lower bound decreased as the reliability level decreased. This constant maximum area and decreasing lower bound were results of the high cost of the cistern. The relative percent difference between the values of the minimum green roof area was 75% and 82% for the asphalt shingle and metal roofs, respectively.

Finally, the FSGE was inputted into the grey model. The area of the green roof recommended by the model was found to be smaller than the current area of green roof. Therefore, the green roof was oversized from the prospective of optimization. However, the cistern was within the 99%-95% reliability range for the maximum and minimum levels.

A future improvement to this model is to include a parameter for the increase in the value of the property due to the inclusion of a green roof. This is due to the green roof improving the aesthetics of the property. Also, a study on the energy savings of the green roof must be done. Then, it can be incorporated into this model to better understand the energy savings associated with it. Lastly, if more sources of water can be found (i.e. artesian well water), then the area of green roof can be increased beyond the limit imposed by the rainwater.

# CHAPTER 5: CONCLUSIONS AND RECOMENDATIONS

## 5.1 Summary

This study centered on the stormwater, wastewater and graywater operation of Florida Showcase Green Envirohome (FSGE). This home incorporated many green building technologies. This study focused on the water harvesting systems and a sorption filter in an on-site sewage treatment and disposal (OSTD) system. Also, a green building optimization model was developed.

The sustained cistern water quality was monitored for when the only influent was the stormwater runoff from the green roof, metal roof and decking. This water was supplemented by the artesian well water to ensure a minimum water level equal to irrigation demand was maintained within the sustainable water cistern. The sustainable water cistern was sampled twice a month during this period.

Then, graywater from the daily use of a shower and laundry water was added to the other sources entering into the sustainable water cistern. This graywater is disinfected using ozone prior to its addition into the sustainable water cistern. This sustainable water cistern is then sampled twice a week to compare changes in water quality.

The new sorption filter OSTD system utilizes the Bold and Gold™ filter media within the system. The wastewaters from the home were first collected by taking a grab sample that were only from toilet water and were low in bacteria concentrations. The wastewater was primarily urine. Then, a trough was installed in the influent end of the septic tank and composite samples were collected from there. There are two sampling ports installed into the Bold and Gold$^{TM}$ filter media bed and one in the constantly wet effluent pipe. Nutrient samples were taken once a month.

The optimization model focused on designing a residential home which incorporated a green roof, cistern and graywater systems. This model had two forms, the base and the grey linear model. The base model used average cost of construction while the grey used an interval for the cost of construction and green roof energy savings. Both models included a probabilistic term to describe the rainfall amount. As more risk was assumed in the model, the more rainwater was expected. A typical Florida home and the FSGE was used as a case study for these models.

## 5.2 Conclusions

This study involved the analysis of the sustainable water cistern water quality, a new OSTD system utilizing Bold and Gold$^{TM}$ sorption filter media and the development of a green building optimization model. The sustainable water cistern was analyzed first. The water quality of the cistern when stormwater runoff from the metal, wood decking and green roof was entering the sustainable water cistern was compared to the water quality when graywater was added to the sources entering the sustainable water cistern. The sustainable water cistern quality was relatively the same with the addition of the graywater. However, the only phosphorus species present in the cistern was ortho-phosphate when graywater was added to the sustainable water cistern. Also, the ammonia concentration was higher in the cistern when the graywater was introduced. The bacteria counts in the cistern did not drop when graywater as added as was expected since the graywater was ozonized before introduction into the sustainable water cistern.

It was also found that the sustainable water cistern quality before the addition of graywater had a higher nutrient level for the irrigation water.

Preliminary sampling of the OSTD system utilizing Bold and Gold$^{TM}$ filter media was analyzed. Samples were taken as the influent into the septic tank and as the wastewater traveled through the Bold and Gold$^{TM}$ filter media bed. The sorption filter OSTD system was very effective at removing nutrients (over 98%) such as total nitrogen and total phosphorus. However, when the sorption filter OSTD system's effluent was compared to a conventional system effluent located on the UCF campus, the concentrations of TSS, $BOD_5$ and $CBOD_5$ were lower in the conventional system but the conventional system had higher nutrient levels. . Nevertheless, the sorption filter is followed by a conventional drain field. Thus, the OSTD system utilizing the Bold and Gold$^{TM}$ filter media reduced the nutrient pollutants being released into the environment.

Lastly, the green building optimization model was created. This model focused on designing a home which incorporated a green roof, cistern and graywater systems. This model had two forms, the base and the grey linear model. As more risk was assumed in the model, the more rainwater was expected. A typical Florida home and FSGE was used as a case study for these models.

Both models demonstrated how the synergistic operations of water conservation and energy saving features affect the optimal design of a residential home. Some common observations found from both models are that to be economical, the entire roof should not be covered by a green roof. Due to the greater cost of the cistern which was designed to catch the worst month's stormwater runoff, the area of green roof cover was reduced as reliability was reduced. With the base model, the change in green roof area was less than 6% when the reliability level was varied and thus not having a huge effect on the green roof area. Also, it was found the irrigation requirement of the green roof was the limiting constraint for when the energy savings cost of the home was varied. For the grey model, it was found that the interval gap of the green roof area grew wider as the reliability level was decreased. However, the upper bound was almost linear for all the reliability levels. Thus, only the lower bound was affected by the reliability level change. Finally, the FSGE current green roof was found to be larger than the area of green roof recommended from the model. However, the cistern was within the 99%-95% reliability range for the maximum and minimum levels.

## 5.3 Recommendations

The sustainable water cistern water quality was suitable for irrigation of the lawn. However, an SAR would be useful and it is recommended that sampling should be done to identify these values. Fecal coliforms were not measured in this work, and it is recommended that future work include fecal coliforms due to the regulation being written in fecal coliforms. Since the sustainable water cistern had a presence of total coliforms and enterococci during the entire sampling time, better disinfected may be required before the water use as graywater. Therefore, as one option, the graywater should be collected separately from the stormwater runoff and use that water for toilet flushing. As another option, the entire sustainable cistern volume can be ozonated. Then the water will be disinfected before its use as toilet water.

The OSTD sorption filter system operated very well with respect to the nutrient removal. However, the TSS, $BOD_5$ and $CBOD_5$ effluent was higher when compared to the conventional systems effluent after the drain field. Thus, the Bold and Gold™ filter media should be followed by the conventional drain field or other distributors to allow for the extra removal of the $BOD_5$ and $CBOD_5$. The FSGE OSTD system has a conventional drain field following the sorption media. An additional sampling of the polylok is suggested as the influent to the sorption filter. Also, the sampling from the conventional field at the FSGE should be done when the home is occupied.

The inclusion of a parameter for the increase in the value of the property due to the inclusion of a green roof should be added. This is due to the green roof improving the aesthetics of the property. Also, a study on the energy savings of the green roof must be done. Then, it can be incorporated into this model to better understand the energy savings associated with it. Lastly, if more sources of water can be found (i.e. artesian well water), then the area of green roof can be increased beyond the limit imposed by the rainwater.

# APPENDIX A: NUTRIENT TEST PROCEDURES

(Obtained from www.hach.com)

# Total Nitrogen Test Procedure

# Nitrogen, Total

**Method 10071** — **Persulfate Digestion Method**

**Test 'N Tube™ Vials** — **LR (0.5 to 25.0 mg/L N)**

**Scope and Application:** For water and wastewater.

## Test Preparation

**Before starting the test:**

Digestion is required for determining total nitrogen.

This test is technique-sensitive. Invert the vials as described here to avoid low results: Hold the vial in a vertical position with the cap pointing up. Turn the vial upside-down. Wait for all of the solution to flow down to the cap. Pause. Return the vial to an upright position. Wait for all the solution to flow to the bottom of the vial. This process equals one inversion.

If the test overranges, repeat the digestion and measurement with diluted sample. The digestion must be repeated for accurate results.

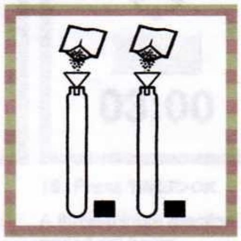
Use the deionized water provided in the reagent set or Organic-free Water to prepare the standards and perform the procedure.

| Collect the following items: | Quantity |
|---|---|
| Test 'N Tube™ LR Total Nitrogen Reagent Set | 1 |
| DRB 200 Reactor | 1 |
| Funnel, micro | 1 |
| Pipet, TenSette®, 1.0 to 10.0 mL plus tips | 1 |
| Test Tube Cooling Rack | 1–3 |

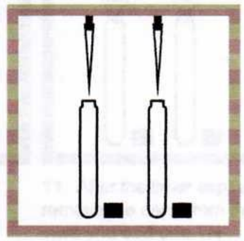
***Note:** Reorder information for consumables and replacement items is on page 7.*

## Test 'N Tube — Method 10071

**1.** Turn on the DRB 200 Reactor and heat to 105 °C.



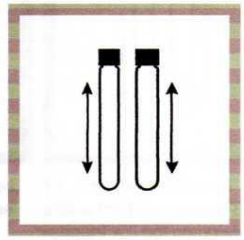
**2.** Using a funnel, add the contents of one Total Nitrogen Persulfate Reagent Powder Pillow to each of two Total Nitrogen Hydroxide Digestion Reagent vials. Wipe off any reagent that may get on the lid or the tube threads.



**3.** **Prepared Sample:** Add 2 mL of sample to one vial.

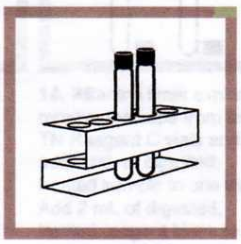
**Blank Preparation:** Add 2 mL of the deionized water included in the kit to a second vial.

***Note:*** *Use only water that is free of all nitrogen-containing species as a substitute for the provided deionized water.*



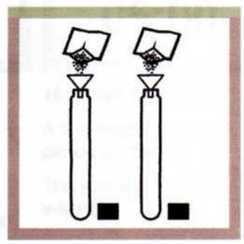
**4.** Cap both vials. Shake vigorously for at least 30 seconds to mix. The persulfate reagent may not dissolve completely after shaking. This will not affect accuracy.

**5.** Insert the vials in the reactor. Heat for exactly 30 minutes.

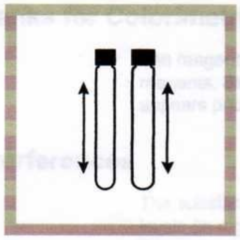


**6.** Using finger cots, immediately remove the hot vials from the reactor. Cool the vials to room temperature.


**7.** Select the test.



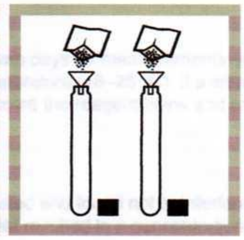
**8.** Remove the caps from the digested vials and add the contents of one Total Nitrogen (TN) Reagent A Powder Pillow to each vial.



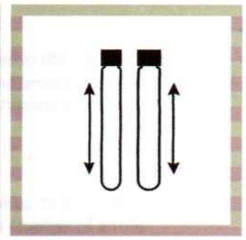
**9.** Cap the tubes and shake for 15 seconds.


**10.** Press **TIMER>OK**.

A three-minute reaction period will begin.



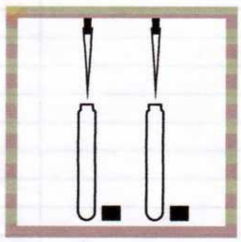
**11.** After the timer expires, remove the caps from the vials and add one TN Reagent B Powder Pillow to each vial.



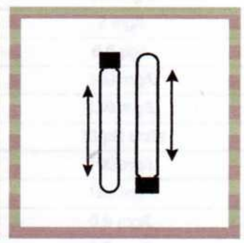
**12.** Cap the tubes and shake for 15 seconds. The reagent will not completely dissolve. This will not affect accuracy. The solution will begin to turn yellow.


**13.** Press **TIMER>OK**.

A two-minute reaction period will begin.



**14.** After the timer expires, remove the caps from two TN Reagent C vials and add 2 mL of digested, treated sample to one vial. Add 2 mL of digested, treated reagent blank to the second TN Reagent C vial.



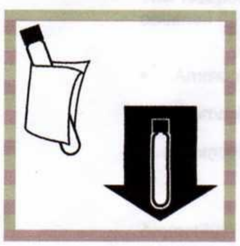
**15.** Cap the vials and invert ten times to mix. Use slow, deliberate inversions for complete recovery.

The tubes will be warm to the touch.


**16.** Press **TIMER>OK**.

A five-minute reaction period will begin.

The yellow color will intensify.

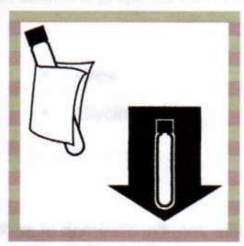


**17.** Wipe the reagent blank and insert it into the 16-mm round cell holder.


**18.** Press **ZERO**.

The display will show:

0.0 mg/L N



**19.** Wipe the reagent vial and insert it into the 16-mm round cell holder.

Results are in mg/L N.

## Nitrate+Nitrite Test Procedure

# Nitrate

**Method 8192** | **Cadmium Reduction Method**

**Powder Pillows** | **LR (0.01 to 0.50 mg/L $NO_3^-$–N)**

**Scope and Application:** For water, wastewater, and seawater

## Test Preparation

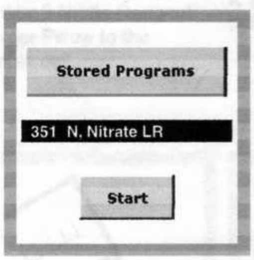
**Before starting the test:**

| |
|---|
| For more accurate results, determine a reagent blank value for each new lot of reagent. Follow the procedure using deionized water in place of the sample. Subtract the reagent blank value from the final results or perform a reagent blank adjust. |
| A deposit of unoxidized metal will remain after the NitraVer® 6 dissolves. The deposit will not affect results. |
| Shaking time and technique influence color development. Analyze a standard solution several times and adjust the shaking time to obtain the correct result. Use this time for analyzing samples. |
| Rinse the sample cell and mixing cylinder immediately after use to remove all cadmium particles. |
| Properly dispose of the used sample. Prepared samples contain cadmium and must be disposed of according to Federal, State, and local hazardous waste regulations. Refer to the current MSDS for safe handling and disposal information. |

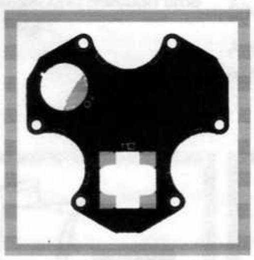
| Collect the following items: | Quantity |
|---|---|
| NitraVer® 6 Nitrate Reagent powder pillow | 1 |
| NitraVer® 3 Nitrite Reagent powder pillow | 1 |
| Cylinder, graduated, mixing, 25-mL | 1 |
| Sample Cells, 1-inch square, 10-mL | 2 |

*Note: Reorder information for consumables and replacement items is on page 5.*

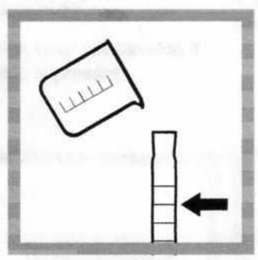
## Powder Pillows — Method 8192




1. Select the test.



2. Insert the Multi-cell Adapter with the 1-inch square cell holder facing the user.

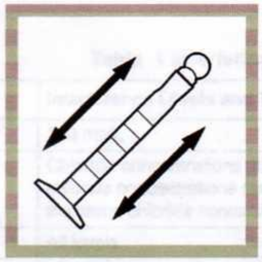


3. Fill a 25-mL graduated mixing cylinder with 15 mL of sample.

4. Add the contents of one NitraVer 6 Reagent Powder Pillow to the cylinder. Stopper.


**5.** Press **TIMER>OK**.

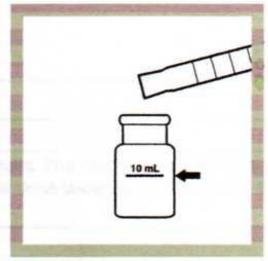
A 3-minute reaction time will begin.



**6.** Shake the cylinder vigorously during the three-minute timer.


**7.** When the timer expires, press **TIMER>OK** again.

A 2-minute reaction period will begin.

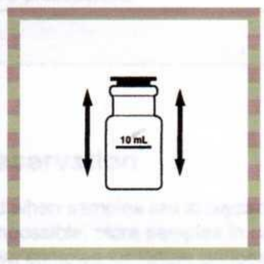



**8.** When the timer expires, carefully pour 10 mL of the sample into a clean square sample cell. Do not transfer any cadmium particles to the sample cell.


**9. Prepared Sample:** Add the contents of one NitriVer 3 Nitrite Reagent Powder Pillow to the sample cell.


**10.** Press **TIMER>OK**.

A 30-second reaction time will begin.

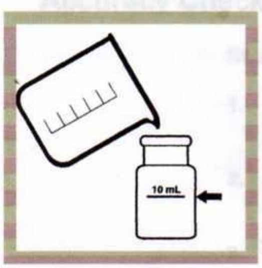



**11.** Shake the sample cell gently during the 30-second timer.

A pink color will develop if nitrate is present.


**12.** Press **TIMER>OK**.

A 15-minute reaction period will begin.




**13. Blank Preparation:** When the timer expires, fill a second square sample cell with 10 mL of original sample.

**14.** Insert the blank into the cell holder with the fill line facing the user.


**15.** Press **ZERO**.
The display will show:

0.00 mg/L $NO_3^-$–N

**16.** Insert the prepared sample into the cell holder with the fill line facing the user.

Results are in mg/L $NO_3^-$–N.

<u>**Total Phosphorus Test Procedure**</u>

# Phosphorus, Total, Digestion

**★Method 8190** **Acid Persulfate Digestion Method[1]**

**Powder Pillows**

**Scope and Application:** For water, wastewater, and seawater; USEPA Accepted for wastewater analyses

[1] Adapted from *Standard Methods for the Examination of Water and Wastewater* 4500-P B & E

## Test Preparation

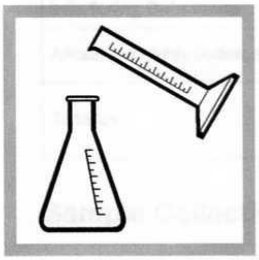
**Before starting the test:**

| |
|---|
| Rinse all glassware with 1:1 Hydrochloric Acid Solution (Cat. No. 884-49). Rinse again with deionized water. |
| The results of the reactive phosphorus test after the digestion will include the organic phosphate plus the orthophosphate and the acid-hydrolyzable (condensed) phosphate. The organic phosphate concentration is determined by subtracting results of an acid hydrolyzable phosphorus test from this result. Make sure that both results are in the same units, either mg/L $PO_4^{3-}$ or mg/L P before subtracting. |

| Collect the following items: | Quantity |
|---|---|
| Potassium Persulfate Powder Pillows | 1 pillow |
| Sodium Hydroxide Solution, 5.0 N | 2 mL |
| Sulfuric Acid Solution, 5.25 N | 2 mL |
| Water, deionized | 4 liters |
| Cylinder, graduated, 25-mL | 1 |
| Flask, Erlenmeyer, 125-mL | 1 |
| Hot Plate, 4-inch diameter, 120 VAC | 1 |
| Hot Plate, 4-inch diameter, 240 VAC | 1 |

***Note:** Reorder information for consumables and replacement items is on page 4.*

## Powder Pillows — Method 8190



1. Use a graduated cylinder to measure 25 mL of sample. Pour the sample into a 125-mL Erlenmeyer flask.

2. Add the contents of one Potassium Persulfate Powder Pillow. Swirl to mix.

3. Use a 1-mL calibrated dropper to add 2.0 mL of 5.25 N Sulfuric Acid Solution to the flask.


4. Place the flask on a hot plate. Boil gently for 30 minutes.
Do not boil dry.

Concentrate the sample to less than 20 mL for best recovery. After concentration, maintain the volume near 20 mL by adding small amounts of deionized water. Do not exceed 20 mL.

5. Cool the sample to room temperature.

6. Use a 1-mL calibrated dropper to add 2.0 mL of 5.0 N Sodium Hydroxide Solution to the flask. Swirl to mix.

7. Pour the sample into a 25-mL graduated cylinder. Adjust the volume to 25 mL with deionized water rinsings from the flask.


8. Proceed with a reactive phosphorus test of the expected total phosphorus concentration range. Extend the color development time to 10 minutes for the Ascorbic Acid method.

**Ortho-phosphate Test Procedure**

# Phosphorus, Reactive (Orthophosphate)

★**Method 8048**

**Test 'N Tube™ Vials**

**PhosVer® 3 Method**

**(0.06 to 5.00 mg/L $PO_4^{3-}$ or 0.02 to 1.60 mg/L P)**

**Scope and Application:** For water, wastewater, and seawater; USEPA accepted for reporting wastewater analysis[1]

[1] Procedure is equivalent to USEPA Method 365.2 and Standard Method 4500-P E for wastewater.

## Tips and Techniques

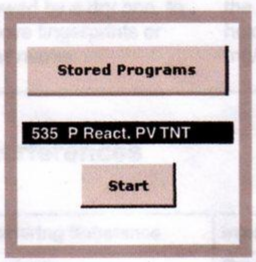
**Before starting the test:**

| |
|---|
| For more accurate results, determine a reagent blank value for each new lot of reagent. Follow the procedure using deionized water instead of the sample. Subtract the reagent blank value from the final results or perform a reagent blank adjust. |

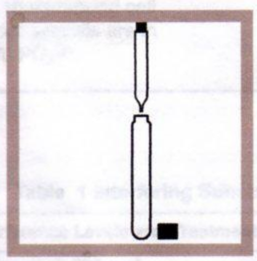
| **Collect the following items:** | **Quantity** |
|---|---|
| PhosVer® 3 Reagent Powder Pillow | 1 |
| Reactive Phosphorus Test 'N Tube Vial | 1 |
| Micro funnel | 1 |
| Pipet, TenSette®, 1–10 mL | 1 |
| Pipet TIps for TenSette Pipet | 1 |
| Test Tube Rack | varies |

***Note:*** *Reorder information for consumables and replacement items is on page 5.*

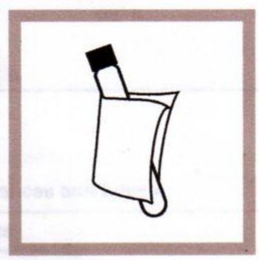
## Test 'N Tube — Method 8048



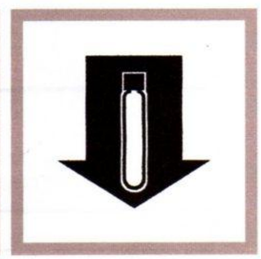

1. Select the test.



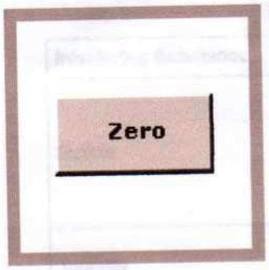
2. Use a TenSette® Pipet to add 5.0 mL of sample to a Reactive Phosphorus Test 'N Tube Dilution Vial. Cap and mix.



3. Wipe the outside of the vial with a damp towel, followed by a dry one, to remove fingerprints or other marks.

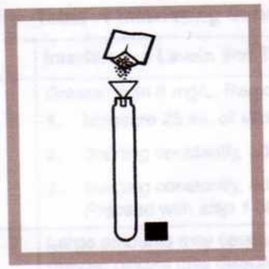


4. Insert the vial into the 16-mm round cell holder.

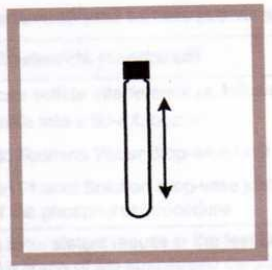



**5.** Press **Zero**.

The display will show: 0.00 mg/L $PO_4^{3-}$



**6.** Using a funnel, add the contents of one PhosVer 3 Phosphate Powder Pillow to the vial.



**7.** Immediately cap the vial tightly and shake for at least 20 seconds. The powder will not dissolve completely.


**8.** Press **TIMER>OK**.

A two-minute reaction period will begin. Read samples between two and eight minutes after adding the PhosVer 3 reagent.

**9.** Wipe the outside of the vial with a damp towel, followed by a dry one, to remove fingerprints or other marks.

**10.** When the timer expires, insert the vial into the 16 mm round cell holder. Results are in mg/L $PO_4^{3-}$.

## Interferences

**Table 1 Interfering Substances and Levels**

| Interfering Substance | Interference Levels and Treatments |
|---|---|
| Aluminum | Greater than 200 mg/L |
| Arsenate | All levels |
| Chromium | Greater than 100 mg/L |
| Copper | Greater than 10 mg/L |
| Iron | Greater than 100 mg/L |
| Nickel | Greater than 300 mg/L |
| Silica | Greater than 50 mg/L |
| Silicate | Greater than 10 mg/L |

# APPENDIX B: SUSTAINABLE WATER CISTERN AND ARTESIAN WELL WATER RAW DATA

## **Pre-Graywater Data**

Table 33: Pre-Graywater Sustainable Water Cistern Nutrient Data

| Date | Ortho-Phosphate (mg/L $PO_4^{3-}$) | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| 1/21/2009 | 0.33 | 0.11 | 0.34 | - | 0.20 | 1.14 |
| 1/26/2009 | - | - | 0.06 | 0.06 | 0.25 | 0.50* |
| 2/12/2009 | 0.29 | 0.09 | 0.34 | 0.04 | 0.07 | 0.54 |
| 2/26/2009 | 0.44 | 0.14 | - | 0.04 | - | - |
| 3/12/2009 | 0.42 | 0.13 | - | 0.06 | - | - |
| 3/25/2009 | 0.86 | 0.28 | 0.82 | - | 0.07 | 0.50* |
| 4/6/2009 | - | - | 0.13 | - | 0.01* | 0.50* |
| 4/21/2009 | 0.22 | 0.07 | 0.37 | - | 0.37 | 0.75 |
| 6/18/2009 | 0.06* | 0.02* | - | 0.15 | 0.09 | 0.50* |
| 7/2/2009 | 0.06* | 0.02* | 0.24 | 0.24 | 0.11 | 0.57 |
| 7/9/2009 | 0.14 | 0.04 | 0.14 | 0.07 | 0.25 | 1.60 |
| Averages | 0.31 | 0.10 | 0.31 | 0.09 | 0.16 | 0.73 |
| Median | 0.29 | 0.09 | 0.29 | 0.06 | 0.11 | 0.54 |
| Std. Dev | 0.24 | 0.08 | 0.22 | 0.07 | 0.11 | 0.36 |

*: indicate lower detection limit reached.

Table 34: Pre-Graywater Artesian Well Water Nutrient Data

| Date | Ortho-Phosphate (mg/L $PO_4^{3-}$) | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| 1/21/2009 | 0.28 | 0.09 | 0.40 | 1.57 | 0.13 | 1.27 |
| 1/26/2009 | - | - | 0.05 | 1.05 | 0.14 | 1.61 |
| 2/12/2009 | 0.83 | 0.27 | 0.40 | 0.68 | 0.15 | 0.54 |
| 2/26/2009 | 0.67 | 0.21 | - | 1.09 | - | - |
| 3/12/2009 | 0.52 | 0.17 | - | 0.75 | - | - |
| 3/25/2009 | 1.62 | 0.52 | 0.12 | - | 0.11 | 0.50* |
| 4/6/2009 | - | - | 0.06 | 0.84 | 0.01* | 0.61 |
| 4/21/2009 | 0.06 | 0.02 | 0.62 | - | 0.01* | 0.75 |
| 6/18/2009 | 0.06* | 0.02* | - | 0.65 | 0.02 | 0.50* |
| 7/2/2009 | 0.06* | 0.02* | 0.31 | 1.44 | 0.07 | 0.78 |
| 7/9/2009 | 0.12 | 0.04 | 0.12 | 1.24 | 0.04 | 0.99 |
| Averages | 0.47 | 0.15 | 0.26 | 1.03 | 0.08 | 0.84 |
| Median | 0.28 | 0.09 | 0.22 | 1.05 | 0.07 | 0.75 |
| Std. Dev | 0.49 | 0.16 | 0.19 | 0.31 | 0.05 | 0.36 |

*: indicate lower detection limit reached.

Table 35: Pre-Graywater Sustainable Water Cistern Field Data

| Date | pH | Turbidity (NTU) | Conductivity (µS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|---|---|---|
| 1/21/2009 | 7.87 | 2.95 | 3633 | 18.1 | 124 |
| 1/26/2009 | 7.76 | 3.76 | 3990 | 20.5 | 118 |
| 2/12/2009 | 7.64 | 1.6 | 2803 | 19.3 | 128 |
| 2/26/2009 | 7.35 | 4.45 | 3556 | 19.6 | 119 |
| 3/12/2009 | 7.72 | 2.95 | 5040 | 21.9 | 123 |
| 3/25/2009 | 7.71 | 1.68 | 3925 | 22.2 | 77 |
| 4/6/2009 | 7.34 | 2.59 | 3478 | 24.4 | 94 |
| 4/21/2009 | 8.08 | 5.83 | 3658 | 23.5 | - |
| 6/18/2009 | 7.23 | 1.66 | - | - | 75 |
| 7/2/2009 | 7.34 | 3.01 | - | - | 80 |
| 7/9/2009 | 7.36 | 3.01 | - | - | 90 |

| | | | | | |
|---|---|---|---|---|---|
| Averages | 7.58 | 3.04 | 3760 | 21.2 | 103 |
| Median | 7.64 | 2.95 | 3646 | 21.2 | 106 |
| Std. Dev | 0.26 | 1.22 | 590 | 2.0 | 22 |

Table 36: Pre-Graywater Artesian Well Water Field Data

| Date | pH | Turbidity (NTU) | Conductivity (µS/m) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) |
|---|---|---|---|---|---|
| 1/21/2009 | 7.82 | 0.36 | 3785 | 20.1 | 118 |
| 1/26/2009 | 7.80 | 0.61 | 3982 | 24.0 | 114 |
| 2/12/2009 | 7.95 | 0.27 | 4015 | 23.1 | 119 |
| 2/26/2009 | 7.57 | 0.32 | 4126 | 23.1 | 113 |
| 3/12/2009 | 7.77 | 30.4 | 3980 | 25.9 | 118 |
| 3/25/2009 | 7.93 | 0.75 | 3581 | 24.2 | 82 |
| 4/6/2009 | 7.47 | 0.63 | 4479 | 25.9 | 98 |
| 4/21/2009 | 7.99 | 29.6 | 3954 | 25.6 | - |
| 6/18/2009 | 7.48 | 11.7 | - | - | 97 |
| 7/2/2009 | 7.43 | 17.8 | - | - | 113 |
| 7/9/2009 | 7.39 | 17.8 | - | - | 104 |
| Averages | 7.69 | 10.02 | 3988 | 24.0 | 108 |
| Median | 7.77 | 0.75 | 3981 | 24.1 | 113 |
| Std. Dev | 0.22 | 11.55 | 242 | 1.8 | 11 |

Table 37: Pre-Graywater Sustainable Water Cistern Bacteria Data

<table>
<tr><th></th><th colspan="2">Total Coliform (cfu per 100 mL)</th><th colspan="2">E. Coli (cfu per 100 mL)</th><th colspan="2">Enterococci (cfu per 100 mL)</th></tr>
<tr><td>6/9/2008</td><td colspan="2">-</td><td colspan="2">269.4</td><td colspan="2">18.95</td></tr>
<tr><td>6/24/2008</td><td colspan="2">-</td><td colspan="2">157.3</td><td colspan="2">9.7</td></tr>
<tr><td>7/7/2008</td><td colspan="2">-</td><td colspan="2">141.4</td><td colspan="2">8.3</td></tr>
<tr><td>7/21/2008</td><td colspan="2">-</td><td colspan="2">167.8</td><td colspan="2">8.9</td></tr>
<tr><td>9/11/2008</td><td colspan="2">308.2</td><td colspan="2">17.8</td><td colspan="2">41.9</td></tr>
<tr><td>9/20/2008</td><td>46.3*</td><td>133.6*</td><td>16.0*</td><td>4.1*</td><td>48.2*</td><td>117.4*</td></tr>
<tr><td>9/25/2008</td><td>169.1*</td><td>343.0*</td><td>62.0*</td><td>85.5*</td><td>629.4*</td><td>601.5*</td></tr>
<tr><td>10/2/2008</td><td colspan="2">343.0</td><td colspan="2">16.0</td><td colspan="2">48.2</td></tr>
<tr><td>10/9/2008</td><td colspan="2">11.0</td><td colspan="2">0.0</td><td colspan="2">63.0</td></tr>
<tr><td>10/16/2008</td><td colspan="2">2419.6</td><td colspan="2">1.0</td><td colspan="2">2419.6</td></tr>
<tr><td>10/22/2008</td><td>2419.6*</td><td>665.3*</td><td>0.0*</td><td>1.0*</td><td>1203.3*</td><td>1413.6*</td></tr>
<tr><td>10/30/2008</td><td>920.8*</td><td>648.8*</td><td>0.0*</td><td>0.0*</td><td>113.9*</td><td>461.1*</td></tr>
<tr><td>11/6/2008</td><td>2419.6*</td><td>648.8*</td><td>0.0*</td><td>0.0*</td><td>1203.3*</td><td>2419.6*</td></tr>
<tr><td>11/13/2008</td><td>164.4*</td><td>2419.6*</td><td>0.0*</td><td>0.0*</td><td>362.3*</td><td>2419.6*</td></tr>
<tr><td>11/20/2008</td><td colspan="2">141.4</td><td colspan="2">0.0</td><td colspan="2">48.2</td></tr>
<tr><td>11/27/2008</td><td colspan="2">499.6</td><td colspan="2">8.6</td><td colspan="2">144.0</td></tr>
<tr><td>12/4/2008</td><td colspan="2">343.0</td><td colspan="2">0.0</td><td colspan="2">113.9</td></tr>
<tr><td>12/11/2008</td><td colspan="2">111.9</td><td colspan="2">0.0</td><td colspan="2">43.2</td></tr>
<tr><td>12/18/2008</td><td colspan="2">601.5</td><td colspan="2">0.0</td><td colspan="2">169.1</td></tr>
<tr><td>1/2/2009</td><td colspan="2">920.8</td><td colspan="2">0.0</td><td colspan="2">629.4</td></tr>
<tr><td>1/7/2009</td><td colspan="2">40.3</td><td colspan="2">0.0</td><td colspan="2">24.1</td></tr>
<tr><td>1/14/2009</td><td colspan="2">133.6</td><td colspan="2">0.0</td><td colspan="2">48.2</td></tr>
<tr><td>1/21/2009</td><td colspan="2">1119.9</td><td colspan="2">0.0</td><td colspan="2">178.2</td></tr>
<tr><td>1/26/2009</td><td colspan="2">2419.6</td><td colspan="2">0.0</td><td colspan="2">43.5</td></tr>
<tr><td>2/12/2009</td><td colspan="2">2419.6</td><td colspan="2">0.0</td><td colspan="2">224.7</td></tr>
<tr><td>2/26/2009</td><td colspan="2">2419.6</td><td colspan="2">0.0</td><td colspan="2">457.5</td></tr>
<tr><td>3/12/2009</td><td colspan="2">665.3</td><td colspan="2">0.0</td><td colspan="2">113.9</td></tr>
<tr><td>3/25/2009</td><td colspan="2">920.8</td><td colspan="2">0.0</td><td colspan="2">601.5</td></tr>
<tr><td>4/6/2009</td><td colspan="2">2419.6</td><td colspan="2">0.0</td><td colspan="2">1203.3</td></tr>
<tr><td>4/21/2009</td><td colspan="2">2419.6</td><td colspan="2">0.0</td><td colspan="2">1413.6</td></tr>
</table>

* duplicate samples

## Post-Graywater Data

Table 38: Post-Graywater Sustainable Water Cistern Nutrient Data

| Date | Ortho-Phosphate (mg/L $PO_4^{3-}$) | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| 10/5/2009 | 0.20 | 0.06 | 0.20 | 0.59 | 0.04 | 0.87 |
| 10/26/2009 | 0.06* | 0.02* | 0.11 | 0.34 | 0.03 | 0.36 |
| 11/16/2009 | 0.32 | 0.10 | 0.00 | 1.69 | 0.05 | 0.48 |
| 12/9/2009 | 0.30 | 0.10 | 0.00 | 0.00 | 0.09 | 0.56 |
| 1/20/2010 | 0.23 | 0.07 | 0.13 | 0.09 | 0.24 | 0.74 |
| 1/26/2010 | 0.06* | 0.02* | 0.00 | - | 0.15 | 0.54 |
| 2/10/2010 | 0.07 | 0.02 | 0.00 | 0.34 | 0.17 | 1.27 |
| 2/23/2010 | 0.45 | 0.14 | 0.08 | 0.66 | 0.07 | 0.82 |
| | | | | | | |
| Averages | 0.21 | 0.07 | 0.07 | 0.53 | 0.11 | 0.71 |
| Median | 0.22 | 0.07 | 0.04 | 0.34 | 0.08 | 0.65 |
| Std. Dev | 0.13 | 0.04 | 0.07 | 0.52 | 0.07 | 0.27 |

*: indicate lower detection limit reached.

Table 39: Post-Graywater Artesian Well Water Nutrient Data

| Date | Ortho-Phosphate (mg/L $PO_4^{3-}$) | Ortho-Phosphate (mg/L P) | Total Phosphorus (mg/L) | Ammonia (mg/L) | Nitrate+Nitrite (mg/L $NO_3^-$-N) | Total Nitrogen (mg/L) |
|---|---|---|---|---|---|---|
| 10/5/2009 | 0.20 | 0.06 | 0.09 | 1.71 | 0.01* | 4.74 |
| 12/9/2009 | 0.06* | 0.02* | 0.02 | 0.66 | 0.01* | 1.65 |
| 1/26/2010 | 0.17 | 0.05 | 0.00 | - | 0.01* | 0.34 |
| 2/23/2010 | 0.41 | 0.13 | 0.08 | 0.89 | 0.01* | 0.26 |
| Averages | 0.21 | 0.07 | 0.05 | 1.09 | 0.01 | 1.75 |
| Median | 0.19 | 0.06 | 0.05 | 0.89 | 0.01 | 1.00 |
| Std. Dev | 0.13 | 0.04 | 0.04 | 0.45 | 0.00 | 1.81 |

*: indicate lower detection limit reached.

Table 40: Post-Graywater Sustainable Water Cistern Field Data

| Date | pH | Turbidity (NTU) | Conductivity (µS/cm) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) | Dissolved Oxygen (mg/L ) |
|---|---|---|---|---|---|---|
| 1/21/2009 | 7.87 | 1.98 | 2490 | 23.9 | 76 | 8.09 |
| 1/26/2009 | 7.76 | 3.1 | 3610 | 20.8 | 118 | 11.71 |
| 2/12/2009 | 7.64 | 8.6 | 3220 | 20.0 | 75 | 9.75 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Averages | 7.76 | 4.56 | 3106 | 21.6 | 90 | 9.85 |
| Median | 7.76 | 3.10 | 3220 | 20.8 | 76 | 9.75 |
| Std. Dev | 0.09 | 2.89 | 464 | 1.7 | 25 | 1.48 |

Table 41: Post-Graywater Artesian Well Water Field Data

| Date | pH | Turbidity (NTU) | Conductivity (μS/cm) | Temperature (°C) | Alkalinity (mg/L $CaCO_3$) | Dissolved Oxygen (mg/L ) |
|---|---|---|---|---|---|---|
| 1/21/2009 | 7.25 | 75.5 | 4110 | 26.8 | 45 | 1.91 |
| 1/26/2009 | 6.97 | 8.06 | 3990 | 23.3 | 125 | 3.86 |
| 2/12/2009 | 7.09 | 5.54 | 4070 | 22.9 | 108 | 2.86 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Averages | 7.10 | 29.70 | 4057 | 24.5 | 93 | 2.88 |
| Median | 7.09 | 8.06 | 4070 | 23.3 | 108 | 2.86 |
| Std. Dev | 0.11 | 32.40 | 50 | 1.8 | 34 | 0.80 |

Table 42: Post-Graywater Sustainable Water Cistern Bacteria Data

| | Total Coliform (cfu per 100 mL) | E. Coli (cfu per 100 mL) | Enterococci (cfu per 100 mL) |
|---|---|---|---|
| 11/16/2009 | 1553.1 | 42.6 | 68.7 |
| 12/9/2009 | 488.4 | 0 | 770.1 |
| 1/26/2010 | 2419.6 | 0 | 1203.3 |
| 2/10/2010 | 2419.6 | 0 | 1732.9 |
| 3/11/2010 | 920.8 | 0 | 1413.6 |
| 4/15/2010 | 2419.6 | 0 | 18.6 |
| Averages | 1703.5 | 7.1 | 867.9 |
| Median | 1986.4 | 0.0 | 986.7 |
| Std. Dev | 780.0 | 15.9 | 649.1 |

# APPENDIX C: BOLD AND GOLD$^{TM}$ RAW DATA

Table 43: Nutrient Raw Data for the Bold and Gold™ Filter Media

| Date Collected | Sample Description | Alkalinity (mg/L) | TSS (mg/L) | $BOD_5$ (mg/L) | $CBOD_5$ (mg/L) | $NH_3$ (mg/L) | $NO_x$-N (mg/L) | Nitrite (mg/L) | Org. N (mg/L) | Total N (mg/L) | SRP (mg/L) | Org. P (mg/L) | Total P (mg/L) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 12/9/2009 | E #1 | 567 | 85.5 | 314.0 | 197.0 | 6.763 | 1.716 | 0.011 | 367.246 | 375.725 | 6.355 | 1.612 | 7.967 |
| | E #2 | 524 | 25.0 | 102.0 | 79.5 | 0.620 | 0.013 | 0.004 | 10.858 | 11.491 | 0.017 | 0.091 | 0.108 |
| | E #3 | 528 | 21.0 | 55.6 | 55.2 | 0.983 | 0.010 | 0.004 | 10.601 | 11.594 | 0.002 | 0.062 | 0.064 |
| | E #4 | 515 | 54.1 | 32.7 | 29.9 | 0.254 | 0.006 | 0.002 | 7.379 | 7.639 | 0.011 | 0.108 | 0.119 |
| 1/20/2010 | E #1 | 212 | 31.0 | 1101.0 | 1080.0 | 64.464 | 0.055 | 0.091 | 747.275 | 1271.161 | 10.950 | 5.562 | 16.533 |
| | E #2 | 346 | 99.0 | 108.0 | 20.0 | 10.060 | 5.325 | 1.038 | 8.257 | 15.945 | 0.000 | 0.055 | 0.090 |
| | E #3 | 277 | 22.0 | 106.0 | 105.0 | 2.783 | 0.010 | 0.003 | 2.960 | 3.097 | 0.011 | 0.071 | 0.090 |
| | E #4 | 348 | 43.0 | 59.9 | 46.0 | 2.609 | 0.005 | 0.003 | 3.425 | 3.612 | 0.009 | 0.059 | 0.080 |
| 2/23/2010 | E #1 | 220 | 43.0 | 524.0 | 420.0 | 31.016 | 1.199 | 0.912 | 170.529 | 176.361 | 7.078 | 0.416 | 7.804 |
| | E #2 | 193 | 64.0 | 1.4 | 1.2 | 9.349 | 21.857 | 0.369 | 16.230 | 39.150 | 0.008 | 0.085 | 0.099 |
| | E #3 | 148 | 15.0 | 56.0 | 42.8 | 1.230 | 0.015 | 0.006 | 1.275 | 1.556 | 0.070 | 0.018 | 0.098 |
| | E #4 | 92 | 27.0 | 45.9 | 34.6 | 2.505 | 0.009 | 0.003 | 2.723 | 3.029 | 0.002 | 0.038 | 0.129 |
| 3/31/2010 | E #1 | 240 | 977.0 | 538.0 | 489.0 | 201.906 | 0.231 | 0.081 | 122.625 | 146.165 | 28.314 | 2.066 | 37.322 |
| | E #2 | 166 | 33.0 | 1.1 | 0.0 | 0.068 | 1.028 | 0.039 | 1.291 | 3.136 | 0.095 | 0.012 | 0.290 |
| | E #3 | 156 | 5.0 | 22.8 | 14.0 | 0.088 | 0.006 | 0.000 | 1.146 | 2.551 | 0.029 | 0.060 | 0.196 |
| | E #4 | 173 | 12.0 | 13.8 | 9.0 | 1.309 | 0.005 | 0.003 | 3.036 | 10.378 | 0.012 | 0.070 | 0.108 |
| 4/29/2010 | E #1 | 227 | 140.0 | 630 | 561 | 425.836 | 0.127 | 0.062 | 354.535 | 356.911 | 13.876 | 6.788 | 24.206 |
| | E #2 | 180 | 28.0 | 52.5 | 40.5 | 51.132 | 0.013 | 0.000 | 19.949 | 39.299 | 3.510 | 0.071 | 4.094 |
| | E #3 | 126 | 11.0 | 56.5 | 54.5 | 0.142 | 0.004 | 0.000 | 0.872 | 0.893 | 0.034 | 0.033 | 0.078 |
| | E #4 | 193 | 13.0 | 17.9 | 15.8 | 3.521 | 0.004 | 0.000 | 4.065 | 4.108 | 0.014 | 0.001 | 0.037 |
| 6/2/2010 | E #1 | 216 | 88 | 71.5 | 51.5 | 17.561 | 1.756 | 0.264 | 21.538 | 25.057 | 1.755 | 0.545 | 3.551 |
| | E #2 | 304 | 24 | 94.0 | 93.5 | 3.455 | 26.484 | 0.980 | 0.293 | 27.852 | 0.071 | 0.011 | 0.091 |
| | E #3 | 429 | 15 | 3.5 | 2.6 | 3.761 | 0.129 | 0.009 | 7.354 | 7.527 | 0.016 | 0.022 | 0.062 |
| | E #4 | 430 | 9 | 10.5 | 10.0 | 6.144 | 0.751 | 0.110 | 7.095 | 8.793 | 0.010 | 0.002 | 0.068 |

Table 44: Bacteria Raw Data for the Bold and Gold™ Filter Media

| Date Collected | Sample Description | Fecal Coliform (cfu/100mL) | E. Coli (cfu/100mL) | Comments |
|---|---|---|---|---|
| 11/16/2009 | E #1 | 5000 | 4200 | Sampling of Toilet discharge only |
| | E #2 | <1 | <1 | |
| | E #3 | <1 | <1 | |
| | E #4 | <1 | <1 | |
| 12/30/2009 | E #1 | <1 | <1 | Sampling of Toilet discharge only |
| | E #2 | <1 | <1 | |
| | E #3 | <1 | <1 | |
| | E #4 | <1 | <1 | |
| 1/26/2010 | E #1 | <1 | <1 | Sampling of Toilet discharge only |
| | E #2 | 8 | 4 | |
| | E #3 | <1 | <1 | |
| | E #4 | <1 | <1 | |
| 2/10/2010 | E #1 | 551 | 496 | Sampling of Toilet discharge only |
| | E #2 | <1 | <1 | |
| | E #3 | <1 | <1 | |
| | E #4 | <1 | <1 | |
| 3/11/2010 | E #1 | <1 | <1 | Sampling of Toilet discharge only |
| | E #2 | <1 | <1 | |
| | E #3 | <1 | <1 | |
| | E #4 | <1 | <1 | |
| 4/15/2010 | E #1 | 52000000 | 38400000 | Sampling of discharge from Toilet and other fixtures |
| | E #2 | 4900 | 81 | |
| | E #3 | 35 | <1 | |
| | E #4 | 293 | 263 | |
| 5/18/2010 | E #1 | 14000000 | 13200000 | Sampling of discharge from Toilet and other fixtures |
| | E #2 | 4 | <1 | |
| | E #3 | <1 | <1 | |
| | E #4 | 8 | 4 | |

Table 45: Field Raw Data for the Bold and Gold™ Filter Media

| Date Collected | Sample Description | pH | Conductivity (µS/cm) | Dissolved Oxygen (mg/L) | Temperature (°C) | Comments |
|---|---|---|---|---|---|---|
| 12/9/2009 | E #1 | 6.62 | 3.50 | 5.73 | 25.6 | Sampling of Toilet discharge only |
| | E #2 | 7.08 | 2.45 | 1.98 | 25.2 | |
| | E #3 | 6.98 | 2.46 | 2.22 | 25.6 | |
| | E #4 | 7.09 | 2.48 | 2.06 | 24.9 | |
| 1/26/2010 | E #1 | 6.30 | 4.08 | 5.37 | 20.4 | Sampling of Toilet discharge only |
| | E #2 | 7.11 | 2.30 | 2.89 | 20.5 | |
| | E #3 | 7.07 | 2.62 | 5.14 | 20.8 | |
| | E #4 | 6.95 | 2.48 | 2.69 | 22.5 | |
| 2/23/2010 | E #1 | 6.54 | 3.68 | 5.46 | 20.1 | Sampling of Toilet discharge only |
| | E #2 | 7.05 | 2.35 | 3.02 | 20.1 | |
| | E #3 | 7.03 | 2.56 | 4.86 | 19.9 | |
| | E #4 | 7.02 | 2.36 | 2.56 | 20.1 | |
| 3/31/2010 | E #1 | 6.42 | 3.75 | 5.58 | 22.8 | Sampling of Toilet discharge only |
| | E #2 | 7.03 | 2.25 | 2.75 | 22.7 | |
| | E #3 | 6.99 | 2.59 | 3.54 | 22.8 | |
| | E #4 | 7.02 | 2.55 | 2.54 | 22.6 | |
| 4/29/2010 | E #1 | 8.02 | 5.31 | 0.32 | 25.9 | Sampling of discharge from Toilet and other fixtures |
| | E #2 | 7.36 | 2.50 | 1.96 | 25.5 | |
| | E #3 | 7.34 | 2.20 | 2.02 | 26.4 | |
| | E #4 | 7.28 | 2.58 | 2.20 | 26.0 | |
| 6/2/2010 | E #1 | 7.75 | 4.63 | 0.54 | 26.3 | Sampling of discharge from Toilet and other fixtures |
| | E #2 | 7.21 | 2.63 | 2.63 | 26.0 | |
| | E #3 | 7.02 | 2.14 | 2.22 | 26.4 | |
| | E #4 | 7.10 | 2.02 | 2.50 | 26.3 | |

# APPENDIX D: GREY LINEAR PROGRAM PAPER

A Grey Linear Programming (GLP) model can be given in the following standard format:

$$\text{Max } f^{\pm} = C^{T\pm} X^{\pm} \tag{1}$$

Subject to:

$$A^{\pm} X^{\pm} \leq B^{\pm} \tag{2}$$

$$x_j^{\pm} \geq 0,\ x_j^{\pm}\ \varepsilon\ X^{\pm},\ \forall j = 1,...,n \tag{3}$$

where:

$$C^{T\pm} = [c_1^{\pm}, c_2^{\pm}, ..., c_n^{\pm}],$$

$$X^{T\pm} = [x_1^{\pm}, x_2^{\pm}, ..., x_n^{\pm}],$$

$$B^{T\pm} = [b_1^{\pm}, b_2^{\pm}, ..., b_m^{\pm}],$$

$$A^{\pm} = \{a_{ij}^{\pm}\}, \qquad \forall \text{i} = 1,..., \text{m}, \text{ j} = 1,..., \text{n}.$$

For the grey numbers $c_j^{\pm}, a_{ij}^{\pm},\ and\ b_i^{\pm}$, we have:

$$c_j^{\pm} = [c_j^{-}, c_j^{+}], \qquad \forall \text{j} \tag{4}$$

$$a_{ij}^{\pm} = [a_{ij}^{-}, a_{ij}^{+}], \qquad \forall \text{ij} \tag{5}$$

$$b_i^{\pm} = [b_i^{-}, b_i^{+}], \qquad \forall \text{j} \tag{6}$$

Since some grey parameters exist in the objective function and constraints, the optimal solution of model equations (1) to (3) will be:

$$f^{*\pm} = [f^{*-}, f^{*+}] \tag{7}$$

$$X^{*\pm} = [x_1^{*\pm}, x_2^{*\pm}, ..., x_n^{*\pm}] \tag{8}$$

$$x_j^{*\pm} = [x_j^{*-}, x_j^{*+}], \qquad \forall \text{j} \tag{9}$$

**Method of Solution**

Model equation (1) to (3) can be converted from a grey problem (uncertain) to a white problem (certain) in the following way:

$$\text{Max } f_m^{\pm} = C_m^{T\,\pm} X_m^{\pm} \tag{10}$$

$$\text{Subject to: } A_m^{\pm} X_m^{\pm} \le B_m^{\pm} \tag{11}$$

$$x_{j\,m}^{\pm} \ge 0, x_{j\,m}^{\pm} \in x_m^{\pm}, j = 1,...,n \tag{12}$$

$$C_m^{T\,\pm} = \left[c_{1\,m}^{\pm}, c_{2\,m}^{\pm},..., c_{n\,m}^{\pm}\right],$$

$$X_m^{T\,\pm} = \left[x_{1\,m}^{\pm}, x_{2\,m}^{\pm},..., x_{n\,m}^{\pm}\right],$$

$$B_m^{T\,\pm} = \left[b_{1\,m}^{\pm}, b_{2\,m}^{\pm},..., b_{n\,m}^{\pm}\right],$$

$$A_m^{\pm} = \left\{a_{ij\,m}^{\pm}\right\}, \qquad \forall \text{i} = 1,..., \text{m}, \text{j} = 1,..., \text{n}.$$

$c_{j\,m}, a_{ij\,m},$ *and* $b_{i\,m}$ are the whitening values of $c_{j\,m}^{\pm}, a_{ij\,m}^{\pm},$ *and* $b_{i\,m}^{\pm}$, respectively. Therefore a set of whitening solution $f_m^{*\,\pm}$ and $x_m^{*\,\pm}$, which are included in the optimal grey solutions $f_m^{*\,\pm}$ and $x_m^{*\,\pm}$, can be derived by solving the model defined in equations (10) to (12).

For n grey coefficients $c_j^{\pm}\,(j = 1,2,...,n)$ in the objective function, if $k_1$ of them are positive, and $k_2$ coefficients are negative, $c_j^{\pm} \le 0\ (j = 1,2,...,k_2)$, where $k_1 + k_2 = n$ (the model does not include the situation where the two bounds of $c_j^{\pm}$ have different signs). Thus, we can develop the following expressions for the upper and lower bounds of $f^{\pm}$:

$$f^{+} = c_1^{+} x_1^{+} + c_2^{+} x_2^{+} + ... + c_{k_1}^{+} x_{k_1}^{+} + c_{k_1+1}^{+} x_{k_1+1}^{-} + ... + c_n^{+} x_n^{-} \tag{13}$$

$$f^{-} = c_1^{-} x_1^{-} + c_2^{-} x_2^{-} + ... + c_{k_1}^{-} x_{k_1}^{-} + c_{k_1+1}^{-} x_{k_1+1}^{+} + ... + c_n^{-} x_n^{+} \tag{14}$$

Based on equation (13), relevant constraints can be given as:

$$a_{i1}^{-}x_1^{+} + a_{i2}^{-}x_2^{+} + .... + a_{ik_1}^{-}x_{k_1}^{+} + a_{ik_1+1}^{+}x_{k_1+1}^{-} + ... + a_{in}^{+}x_n^{-} \leq b_i^{+} \quad (15)$$

Similarly, based on equation (14), relevant constraints are:

$$a_{i1}^{+}x_1^{-} + a_{i2}^{+}x_2^{-} + .... + a_{ik_1}^{+}x_{k_1}^{-} + a_{ik_1+1}^{-}x_{k_1+1}^{+} + ... + a_{in}^{-}x_n^{+} \leq b_i^{-} \quad (16)$$

For whitening solutions $x_{jm}^{*\pm}$, we have $x_{jm}^{*\pm}\, \varepsilon\, x^{*\pm}$. Therefore:

$$x_j^{+} \geq x_{jm}^{*\pm}, \qquad j = 1,2,...,k_1 \quad (17)$$

$$x_j^{-} \leq x_{jm}^{*\pm}, \qquad j = k_1+1, k_1+2,...,n \quad (18)$$

$$x_j^{-} \leq x_{jm}^{*\pm}, \qquad j = 1,2,...,k_1 \quad (19)$$

$$x_j^{+} \geq x_{jm}^{*\pm}, \qquad j = k_1+1, k_1+2,...,n \quad (20)$$

Thus, the model defined by equation (1) to (3) can be divided into two sub models:

$$Max\ f^{+} \quad (21)$$

Subject to: (3), (15), (17), and (18) (22)

$$Max\ f^{-} \quad (23)$$

Subject to: (3), (16), (19), and (20) (22)

The model defined by equations (21)-(22)and (23)-(24) are linear programming models with a single objection function, Therefore, $f^{*+}$, $x_j^{*+}\ (j = 1,2,...,k_1)$ and $x_j^{*-}\ (j = k_1+1, k_1+2,...,n)$ can be solved by model equations (21)-(22), and $f^{*-}$, $x_j^{*+}(j = k_1+1, k_1+2,...,n)$ and $x_j^{*-}\ (j = 1,2,...,k_1)$ can be solved by model equations (23)-(24). Thus, the solutions of the GLP model equations (1) to (3) are:

$$f^{*\pm} = \left[f^{*-},\ f^{*+}\right], \quad (25)$$

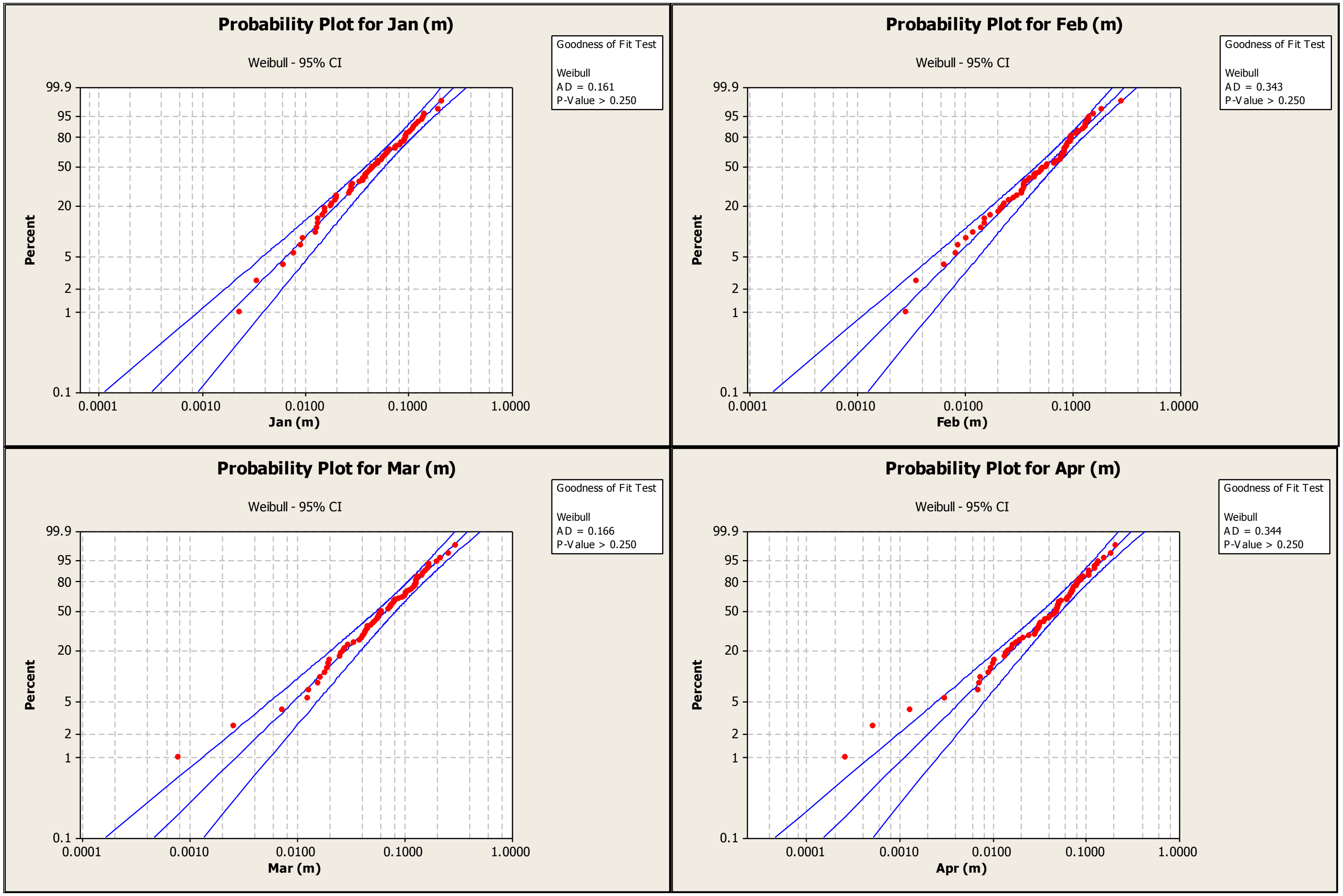
$$x_j^{*\pm} = \left[x_j^{*-},\ x_j^{*+}\right], \qquad \forall j \quad (26)$$

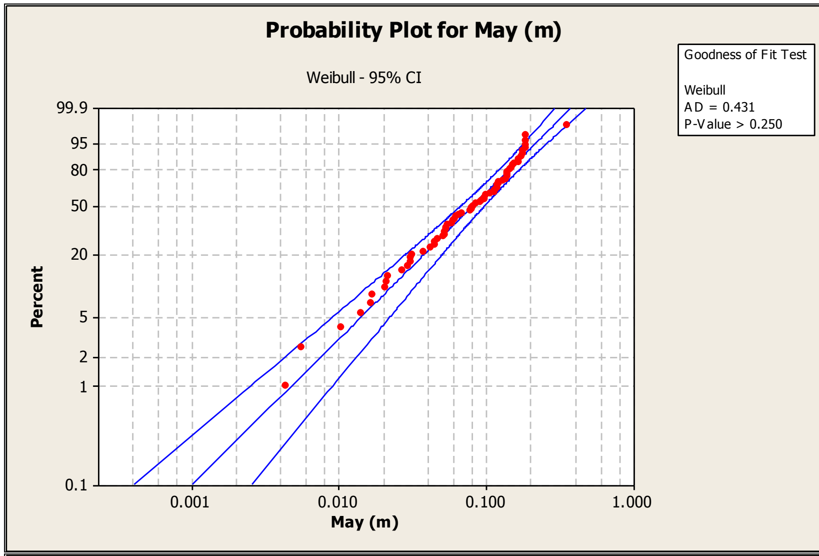
where $f^{*\pm}$ and $x_j^{*\pm}$ are all grey numbers.

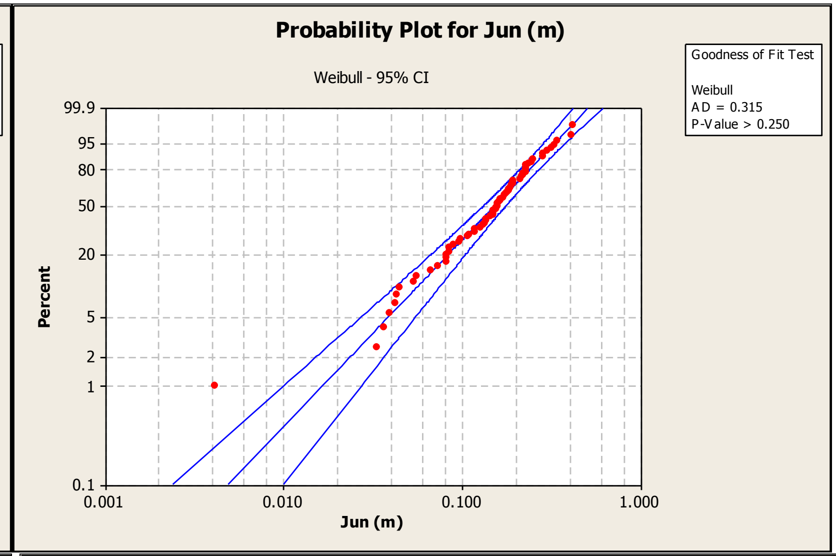
Solutions of the GLP model include decision variables ( $x_j^{*\pm}$, $\forall$ j) and the relevant objective value ( $f^{*\pm}$). The decision variable solutions are expressed as $x_j^{*\pm} = [x_j^{*-}, x_j^{*+}]$, $\forall$ j, which means that the maximum possible value of $x_j^{*\pm}$ is $x_j^{*+}$ (upper limit), and the minimum is $x_j^{*-}$ (lower limit). The solutions can be directly applied to decision making, with the values being adjusted within the grey intervals in the final decision scheme.

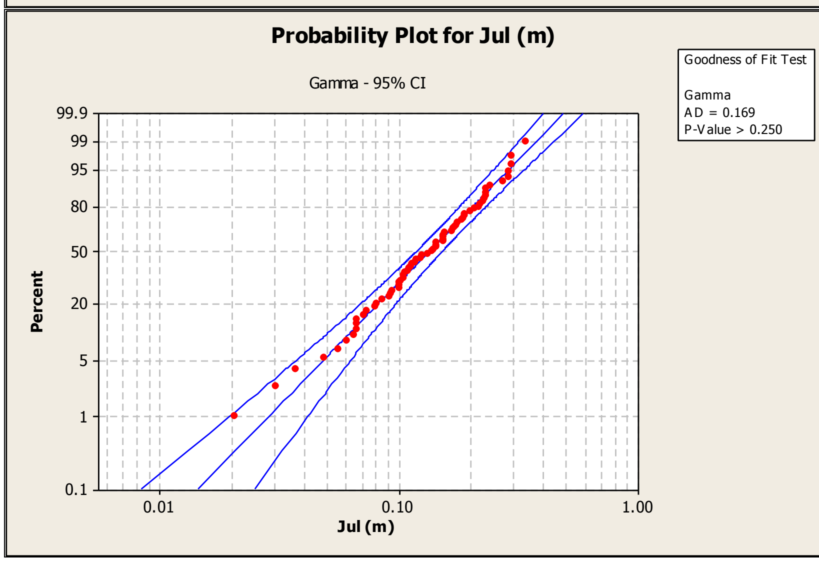
The solution of the objective function is important for assessing decision efficiencies. It is expressed as $f^{*\pm} = [f^{*-}, f^{*+}]$, which means that the maximum objective value is $f^{*+}$ (upper limit), and the minimum is $f^{*-}$ (lower limit). The upper and lower limits of the objective function value correspond to different distributions of decision variables. The adjustment of decision variables within their grey intervals will lead to the variation of objective function value within its corresponding grey interval.

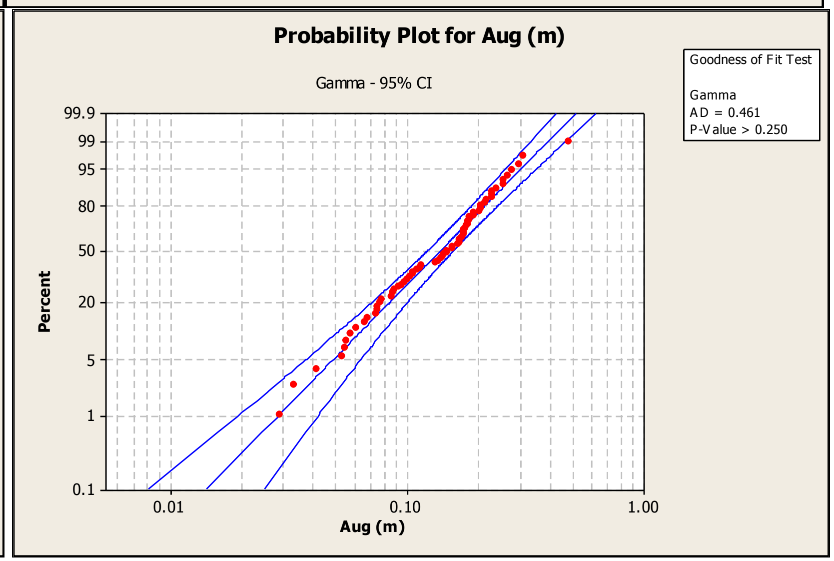
# APPENDIX E: MONTHLY RAINFALL DATA GOODNESS OF FIT TESTS

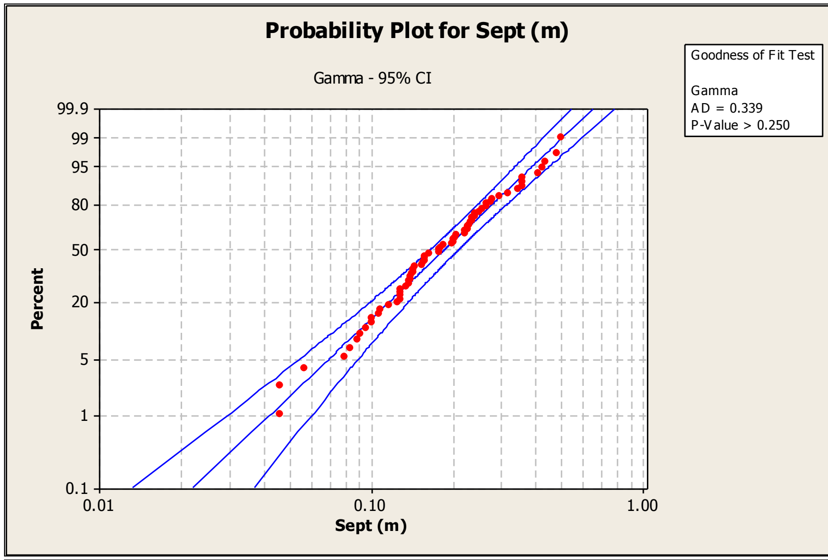

Probability Plot for Jan (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.161
P-Value > 0.250
Percent
Jan (m)
Probability Plot for Feb (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.343
P-Value > 0.250
Percent
Feb (m)
Probability Plot for Mar (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.166
P-Value > 0.250
Percent
Mar (m)
Probability Plot for Apr (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.344
P-Value > 0.250
Percent
Apr (m)

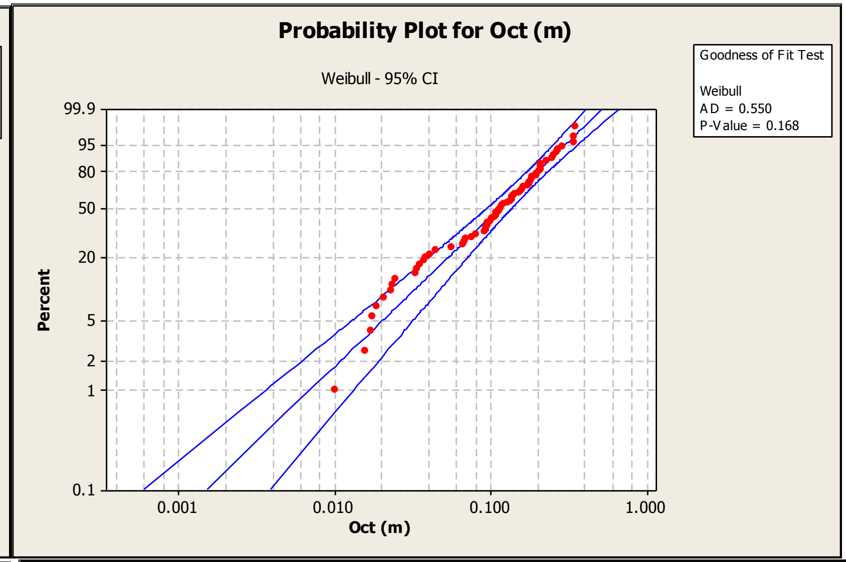

Probability Plot for May (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.431
P-Value > 0.250
Percent
99.9
95
80
50
20
5
2
1
0.1
0.001
0.010
0.100
1.000
May (m)

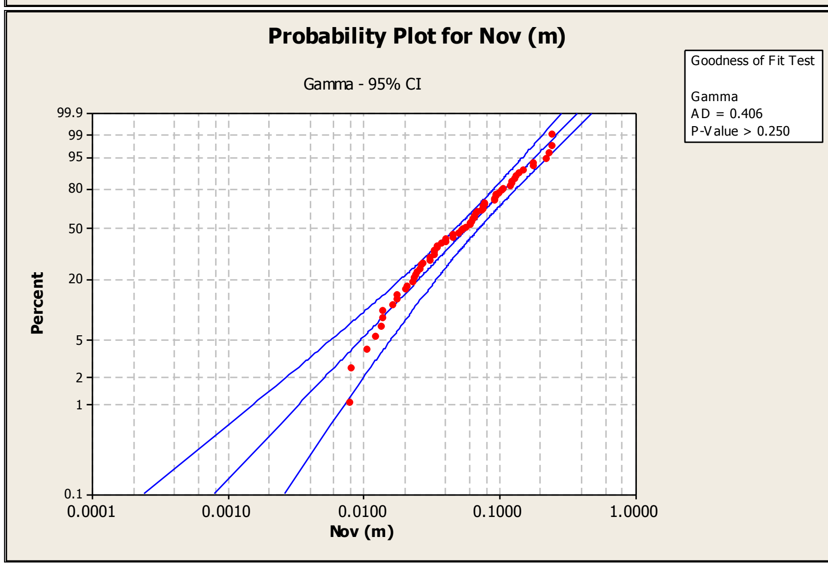

Probability Plot for Jun (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.315
P-Value > 0.250
Percent
99.9
95
80
50
20
5
2
1
0.1
0.001
0.010
0.100
1.000
Jun (m)

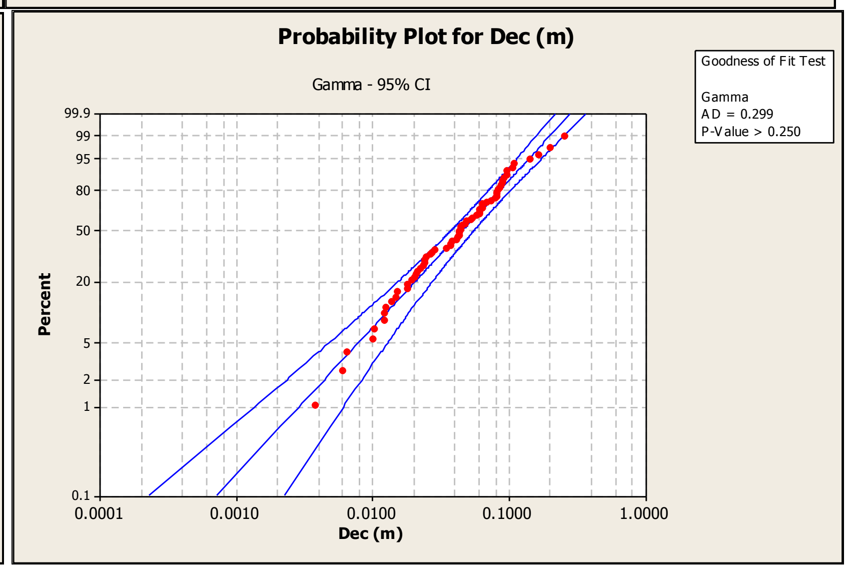

Probability Plot for Jul (m)
Gamma - 95% CI
Goodness of Fit Test
Gamma
AD = 0.169
P-Value > 0.250
Percent
99.9
99
95
80
50
20
5
1
0.1
0.01
0.10
1.00
Jul (m)


Probability Plot for Aug (m)
Gamma - 95% CI
Goodness of Fit Test
Gamma
AD = 0.461
P-Value > 0.250
Percent
99.9
99
95
80
50
20
5
1
0.1
0.01
0.10
1.00
Aug (m)


Probability Plot for Sept (m)
Gamma - 95% CI
Goodness of Fit Test
Gamma
AD = 0.339
P-Value > 0.250
Percent
Sept (m)
99.9
99
95
80
50
20
5
1
0.1
0.01
0.10
1.00


Probability Plot for Oct (m)
Weibull - 95% CI
Goodness of Fit Test
Weibull
AD = 0.550
P-Value = 0.168
Percent
Oct (m)
99.9
95
80
50
20
5
2
1
0.1
0.001
0.010
0.100
1.000


Probability Plot for Nov (m)
Gamma - 95% CI
Goodness of Fit Test
Gamma
AD = 0.406
P-Value > 0.250
Percent
Nov (m)
99.9
99
95
80
50
20
5
2
1
0.1
0.0001
0.0010
0.0100
0.1000
1.0000


Probability Plot for Dec (m)
Gamma - 95% CI
Goodness of Fit Test
Gamma
AD = 0.299
P-Value > 0.250
Percent
Dec (m)
99.9
99
95
80
50
20
5
2
1
0.1
0.0001
0.0010
0.0100
0.1000
1.0000

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