Spring 5-2011

Economic Input-Output Life Cycle Assessment of Water Reuse Strategies in Residential Buildings and Communities

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Economic Input-Output Life Cycle Assessment of Water Reuse Strategies in Residential Buildings and Communities

by

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A THESIS

Presented to the Faculty of

The Graduate College at the University of Nebraska

In Partial Fulfillment of Requirements

For the Degree of Master of Science

Major: Civil Engineering

Under the Supervision of Professor John S. Stansbury

Lincoln, Nebraska

May, 2011

ECONOMIC INPUT-OUTPUT LIFE CYCLE ASSESSMENT OF WATER REUSE STRATEGIES IN RESIDENTIAL BUILDINGS AND COMMUNITIES

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University of Nebraska, 2011

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The objective of this study was to determine the environmental sustainability and economic feasibility of five water reuse designs using economic input-output life cycle assessments and benefit/cost analyses. These five water reuse designs were evaluated for four regions of the United States including the Northwest (Seattle), Southwest (Scottsdale), Midwest (Omaha), and Southeast (Tampa). The water reuse designs include a greywater reuse system with no treatment for sub-surface landscape irrigation for a single-family residential house (Model 1), an indoor greywater reuse system with treatment for toilet flushing and laundry washing for a single-family residential house (Model 2), a hybrid untreated greywater system for landscape irrigation with a rainwater reuse system for toilet flushing and laundry (Model 3), a rainwater reuse system for toilet flushing and laundry washing for an apartment building (Model 4), and a community dual distribution system with water reclamation for non-potable uses (Model 5).

The results of this study indicate that there are trade-offs with each of the designs. Models 1 and 5 had the best results in terms of environmental sustainability and

economic feasibility. Models 1 and 5 reduced greenhouse gas emissions and energy consumption compared to the baseline scenario. However, with both of these designs, there are additional environmental impacts and additional systems to operate and maintain. Overall, Models 2 and 3 were not environmentally sustainable or economically feasible as designed. Model 4 had mixed results based on regional variability in prices and precipition. In Seattle and Tampa, this design performed favorably in terms of environmental sustainability and economic feasibility due to plentiful amounts of rainfall and relatively high prices for water. However, this design did not have positive results in Scottsdale due to low availability of water. Even though a large amount of rainwater was collected and used in Omaha, Model 4 was determined to be not economically feasible due to the current low prices for water in Omaha.

AUTHOR'S ACKNOWLEDGMENTS

I would like to thank Dr. John S. Stansbury, Shannon Killion, and Meng Hu for there assistance on this project.

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1.0 Chapter 1 Introduction

1.1 Background

The overall goal of this project is to improve water and energy systems in residential buildings and communities. Water and energy are closely related in many ways. For example, in California, water-related services consume approximately 19% of the state's electricity (Stokes and Horvath, 2009). In addition, the United States Green Building Council (USGBC) has stated that during construction and use, buildings consume roughly 39% of all electricity and approximately 10% of all potable water (USGBC 2008). The goal of this project is to look at ways to reduce the level of energy and water consumption in residential buildings and communities.

Freshwater is a scarce resource in many parts of the globe. In fact, the United States has been identified as a country that faces imminent water shortages (Kloss 2008). The growth of cities is putting great strains on existing freshwater supplies in many areas. Utilities across the world are looking at new ways to provide freshwater to customers. Some utilities along coastlines in water stressed areas are turning to desalination as a solution. However, this process is expensive and energy intensive (Stokes and Horvath, 2009). In addition, desalination is not a viable alternative for water stressed areas distant from the coastlines.

Thus, it is important to develop sustainable ways to reduce strain on existing water supplies (Fewkes 2007). It is also necessary to develop methods for reducing potable water use that are not only economically feasible, but also preferable in terms of environmental sustainability.

1.2 Objective

The objective of this study is to determine the environmental sustainability and economic feasibility of five water reuse designs through economic input-output life cycle assessments and benefit/cost analyses. These five water reuse designs are evaluated in 4 regions of the United States including the Pacific Northwest (Seattle), Desert Southwest (Scottsdale), Midwest (Omaha), and Southeast (Tampa). The water reuse designs include:

1. Simple Greywater Reuse System for Landscape Irrigation for a Single-Family Residential House
2. Indoor Greywater Reuse System for Toilet Flushing and Laundry Washing for a Single-Family Residential House
3. Hybrid Greywater and Rainwater Reuse System for Landscape Irrigation, Toilet Flushing and Laundry Washing for a Single-Family Residential House
4. Rainwater Reuse System for Toilet Flushing and Laundry Washing for an Apartment Complex
5. Community Water Reclamation System

The list above is not meant to be an all-inclusive list of water reuse strategies but rather five commonly used and potentially economically viable water reuse strategies. It is known that large quantities of water can be saved through implementing these water reuse strategies. However, these designs require additional materials, and in some cases, significant amounts of energy for treatment and/or pumping. The goal of this study is to analyze the trade-offs between the added required materials, and the potential water savings in 4 regions of the United States.

2.0 Chapter 2 Literature Review

2.1 Current Water Distribution Systems

In general, current water distribution systems are centralized. Water is withdrawn from an aquifer or surface water body, treated, and then distributed to homes and businesses through water mains. This treated potable water is then used by occupants for indoor uses (such as laundry washing, toilet flushing, bathing, drinking, etc.) and outdoor uses (including landscape irrigation and fire protection).

Wastewater, which is a combination of greywater and blackwater, is collected from the buildings through collector sewers and conveyed to a centralized wastewater treatment plant where this water is treated and then discharged into a receiving water body. Stormwater is collected separately through inlets (e.g., curb inlets) and discharged into streams and other receiving water bodies. However, some municipalities still have combined sewers in which wastewater and stormwater is collected and conveyed by a common sewer network to the wastewater treatment plant.

Many of the daily uses for potable water do not require a high level of treatment. For example, water used for landscape irrigation, fire protection, toilet flushing, and car washing does not require the same level of treatment as water that will be ingested (Asano et al. 2007). This is a sustainability problem because water treatment is an energy intensive process. There are two main approaches to solving this problem. The first approach is to use naturally supplied rainwater or reuse greywater at the household/building level for non-potable uses. Another potential solution is to construct reclaimed water facilities and reuse water at the community or neighborhood level. These facilities supply reclaimed water for uses such as irrigation, etc. The problem with these systems is that they require additional infrastructure to convey the reclaimed water to its end use.

2.2 Water Reuse

2.2.1 Greywater

Greywater is untreated wastewater excluding water from toilets, water closets, and urinals, and often excluding water from kitchen sinks and dishwashers (Sheikh 2010). The greywater standards in California define greywater as:

> … "graywater" means untreated wastewater that has not been contaminated by any toilet discharge, has not been affected by infectious, contaminated, or unhealthy bodily wastes, and does not present a threat from contamination by unhealthful processing, manufacturing, or operating wastes. "Graywater" includes but is not limited to wastewater from bathtubs, showers, bathrooms washbasins, clothes washing machines, and laundry tubs, but does not include wastewater from kitchen sinks or dishwashers. (California Building Standards Commission, 2009).

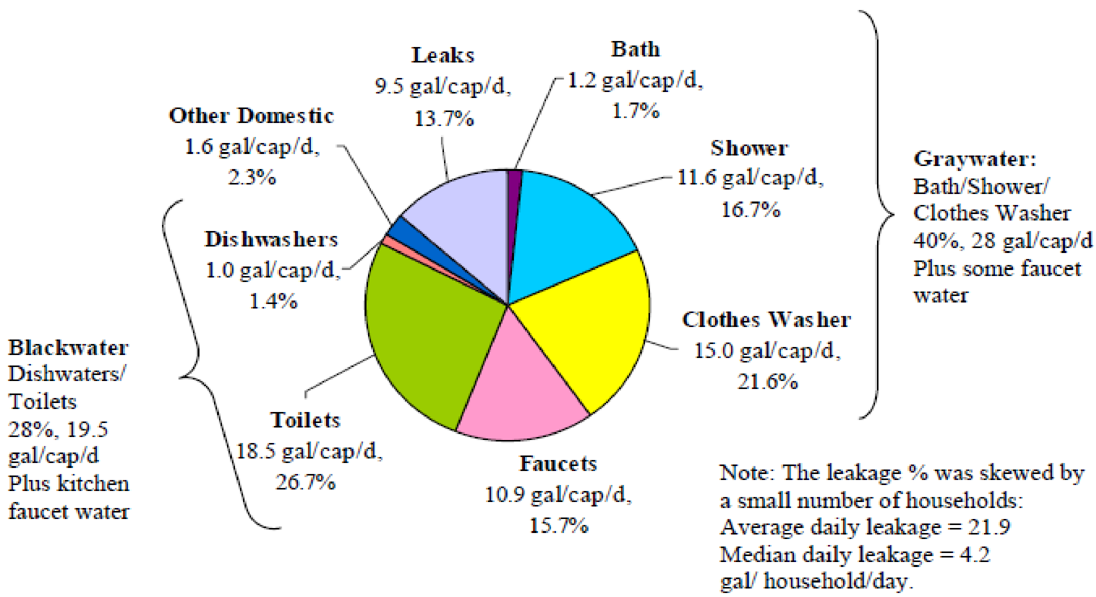
The reuse of greywater in residential houses has increased in popularity recently primarily due to the establishment of the United States Green Building Council (USGBC) and the LEED rating system (United States Green Building Council 2008). The current LEED rating system, version 3, gives points for reducing water consumption through greywater reuse. It also gives points for the implementation of innovative wastewater treatment technologies which has increased the popularity of greywater reuse.

2.2.1.1 Sources of Greywater

The sources for greywater can include bathroom and kitchen sinks, showers, dishwashers, and laundry machines. However, kitchen sinks and dishwashers are generally excluded from greywater calculations due to their relatively high microbial concentrations and the potential presence of pathogens.

2.2.1.2 Quantity of Greywater

The flowrate or daily quantity of greywater depends heavily on the habits of building occupants as well as the number of occupants in the building. Mayer et al. (1999) studied the end uses of water in residences in 12 North American cities. The cities that participated in this study were Boulder, CO; Denver, CO; Eugene, OR; Seattle, WA; San Diego, CA; Tampa, FL; Phoenix, AZ; Tempe and Scottsdale, AZ; the Regional Municipality of Waterloo, Ontario; Walnut Valley Water District, CA; Las Virgenes Municipal Water, CA; and Lompoc, CA. In each city, 1000 single family residences were sampled. The average household water usage for the 12 sites was 146.1 kgal (553.7 m^3) of water per year. Of this, 42% was used indoors, and 58% was used outdoors. Figure 2.1 shows the distribution of the various indoor uses (Mayer et al. 1999).



Source: Residential End Uses of Water (Mayer et al. 1999)

Figure 2.1 – Distribution of Indoor Water Uses

Asano et al. (2007) had slightly different estimates for the quantity of greywater generated. They estimated greywater production at 40.6 gpcd or 154 L, but they included dishwashers as an acceptable source. If dishwashing is excluded, the total becomes 135 L/capita*d for typical devices, and 66 L/capita*d for buildings using water saving devices (Asano et al. 2007).

The quantity of greywater generated depends on whether the building has water efficient fixtures and appliances as well as the habits of the occupants. Table 2.1 displays water usage from various sources.

Table 2.1 – Water Usage Rates of Appliances with and without Water Conservation Measures

Device/appliance	Water Usage, gal/capita*d (L/capita*d), Without water conservation measures	Water Usage, gal/capita*d (L/capita*d), With Water Conservation
Faucet	7.1 (27)	4.2 (16)
Bathing/Showering	14.5 (55)	9.2 (35)
Dishwashing	5.0 (19)	2.9 (11)
Clothes washing	14.0 (53)	4.0 (15)
Total	**40.6 (154)**	**20.3 (77)**

Source: Water Reuse (Asano et al. 2007)

Ludwig (2009) reports average household greywater production of 43.1 gpcd (164 Lpcd). Table 2.2 shows typical greywater sources and typical quantities for each source reported by Ludwig (2009).

Table 2.2 – Water Usage Rates of Appliances

Device/Source	Quantity
Laundry washing machine	85-100 gal/person/week (320-380 L/person/week)
Automatic dishwasher	7 gal/person/week (27 L/person/week)
Shower	70-100 gal/person/week (260-380 L/person/week)
Tub	40 gal/adult bath (150 L/adult bath) 25 gal/kid bath (95 L/kid bath)

Bathroom sink	7-35 gal/person/week (26-130 L/person/week)
Kitchen sink	35-105 gal/person/week (133-398 L/person/week)

Source: (Ludwig 2009)

2.2.1.3 Water Quality of Greywater

The water quality of greywater is highly variable, both temporally and spatially. In general, greywater may contain pathogenic microorganisms, sodium, nitrogen, phosphates, chloride, oils, fats, soaps, detergents, and other solvents used for cleaning (Crook 2009). Greywater generally has a pH above 7 (Crook 2009). Depending on the source, greywater can be contaminated by clothes washing, chemicals dumped into the sink, human excretions from bathing, clothes washing, food preparation, and others (Crook 2009). Table 2.3 shows the characteristics of the greywater from each source.

Table 2.3 – Water Quality Characteristics of Various Sources of Greywater

Greywater Source	Characteristics
Automatic clothes washer	Bacteria, viruses, bleach, foam, high pH, hot water, nitrate, oil and grease, oxygen demand, phosphate, salinity, soaps, nitrates and phosphates, sodium, lint and other suspended solids, and turbidity
Automatic dish washer	Bacteria, foam, food particles, high pH, hot water, odor, fat, oil and grease, organic matter, oxygen demand, salinity, soaps, suspended solids, and turbidity
Bath tub and shower	Bacteria, hair, shampoos, hair dyes, toothpaste, body fats, hot water, odor, organic matter, oil and grease, oxygen demand, soaps, lint and other suspended solids, and turbidity
Evaporative cooler	Salinity
Sinks, including kitchen	Bacteria, food particles, hot water, odor, oil and grease, organic matter, oxygen demand, soaps, detergents, suspended solids, and turbidity
Swimming pools	Chlorine, salinity, organic matter, suspended solids

Source: Adapted from New Mexico State University [1994] and Western Aurstralia Department of Health [2002]

A study by Ishida et al. (2009) shows the variability of greywater quality. Their study compiled water quality data from several studies and compared the data. Table 2.4 compares the findings of the 5 separate studies (Ishida et al. 2009).

Table 2.4 – Water Quality Studies of Greywater

	Casanova et al. (2001)	Eriksson et al. (2003)	Laine (2001)	Rose et al. (1990)	Surrendran & Wheatley (1998)
pH	7.47	7.6-8.6	7.3-7.5	5-7	7.7
BOD (mg/L)	64.8	26-130	129-155	NR	216-252
COD (mg/L)	NR	77-240	367-587	NR	424-433
TSS (mg/L	35.1	7-207	58-153	NR	40-76
Ammonia (mg/L as N)	NR	0.02-0.42	NR	0.15-3.2	0.5-1.6
Nitrate (mg/L as N)	NR	<0.02-0.26	NR	NR	NR
Total Phosphorus (mg/L as P)	NR	NR	0.3-0.4	4-35	1.6-45.5

Source: Ishida et al. (2009)
Note: Greywater sources for all studies include a composite sample of shower, bath, sink and laundry washwater.
NR = Not reported by that particular study

2.2.1.4 Greywater Reuse System Costs

The cost for a greywater reuse system varies from a few hundred dollars for a very simple system to several thousand dollars for a more complex system (Sheikh 2010). A study in Los Angeles showing prices (in 2009 U.S. dollars) by manufacturers for systems of varying complexity is summarized below (Crook 2009):

- $400-$800: Applies to low-technology systems that tap the discharge from washing machines only. The lower-end of the price range applies to the do-it-yourself installation, and the upper end applies to professional installation.

- $1000-$1500: Applies to systems where all potential greywater sources are connected to the system. The collection and distribution is relatively simple and low-technology. The total cost depends on the number of greywater sources connected.
- $2500-$5000: Applies to fully automatic greywater systems that are connected to nearly all sources of greywater in a home and possibly backed up by potable water systems when greywater is not available. The only intervention on the part of the resident is to switch the system on and off when it is not needed during periods of heavy rainfall.

Generally, it is much cheaper to install greywater systems in new construction versus installation in existing buildings (Crook 2009). Installing greywater reuse systems in new buildings prevents wasting materials. Installing a greywater reuse systems in an existing building will result in the disposal of functional materials no longer needed for the plumbing in the building. Plumbing the building for reuse in the beginning prevents the waste of materials, which reduces costs for materials and labor.

Cobacho et al. (2007) did a study on the feasibility of greywater reuse systems in Spain. They determined that the feasibility of greywater systems depends very heavily on the value of water. They studied the feasibility in household and multi-occupant (apartment) buildings. They found scale economies in their analysis with apartment buildings having shorter payback periods than households.

2.2.2 Water Quality Requirements for Greywater Reuse

2.2.2.1 Landscape Irrigation

The use of greywater for landscape irrigation is particularly attractive. However, many states require any irrigation system incorporating the use of greywater be buried under the ground due to health concerns. Some states require the irrigation system to be located below the frost depth which restricts its use in many areas. For example, the state of California limits greywater reuse to sub-surface irrigation or areas with at least 2 inches of cover with mulch or soil (Ishida et al. 2009). The state of Arizona allows surface irrigation of greywater, but it cannot be applied to food plants (Ishida et al. 2009). Other states have similar restrictions. Water quality considerations include levels of salinity, alkalinity, pathogens, and other contaminants.

Greywater can have detrimental effects to the soil which include an increase in soil alkalinity and salinity, and a decrease in the soil's ability to absorb and retain water. Some plants are more sensitive to soil alkalinity and salinity than others. Greywater can contain high levels of boron which is toxic for many plants. However, some of the constituents of greywater are beneficial to plant growth including nutrients such as nitrogen and phosphorus (Crook 2009). Table 2.5 displays water quality guidelines for irrigation.

Table 2.5 – Water Quality Guidelines for Landscape Irrigation for Applications with Varying Levels of Human Contact Restrictions

Parameter	Units	No Restrictions	Slight to Moderate Restrictions	Severe Restrictions
Electrical Conductivity	dS/m	<0.7	0.7-3.0	>3.0
TDS	mg/L	<450	450-2000	>2000
Sodium (Na)	mg/L	<70	>70	
Chloride (Cl)	mg/L	<100	>100	

Boron (B)	mg/L	<0.7	0.7-3.0	>3.0
Nitrogen (Total N)	mg/L	<5	5-30	>30

Source: (Asano et al. 2007)

2.2.2.2 Fireflow

Greywater can be used for fireflow; however, the source of water must be as reliable as conventional fire protection systems. In the United States, typically water used for fire protection must meet water quality requirements for unrestricted non-potable use as shown in Table 2.6 (Asano et al. 2007). Actual requirements vary slightly from state to state. Generally, meeting these water quality levels requires treatment that includes filtration and disinfection.

Table 2.6 – Water Quality Requirements for Fireflow

Parameter	**Water Quality Requirement**
Total Suspended Solids (mg/L)	5.0
Turbidity (NTU)	2-5
pH	6.0-8.5
Coliform (Fecal)	75% of samples below detection, 25 CFU/100 mL (max)

Source: Asano et al. 2007

2.2.2.3 Non-Potable Uses including Toilet Flushing and Laundry Washing

Greywater can also be used for other non-potable uses including toilet flushing, laundry washing, and vehicle washing. The actual guidelines for these uses vary by state, but the EPA has set guidelines for the reuse of wastewater or greywater for these particular uses. The EPA suggests a level of treatment equal to disinfected tertiary treatment (Metcalf & Eddy 2003). They also suggest the following reclaimed water quality parameters: pH between 6 and 9; BOD_5 less than or equal to 10 mg/L; turbidity less than or equal to 2 NTU; non-detectable for E. Coli; and residual chlorine greater than or equal to 1 mg/L (Metcalf & Eddy 2003).

2.2.3 Rainwater Collection and Use

For the purpose of this thesis, rainwater is defined as water harvested from some form of precipitation (i.e., rain, snow, etc.). Some studies include condensation water from cooling towers in their definition of rainwater. In this study, condensation water is excluded.

Humans have been harvesting rainwater in various ways for centuries. However, only recently has harvesting rainwater re-emerged as a popular solution to reducing potable water consumption in residential houses and developments. Some of the increased popularity is due to the establishment of the United States Green Building Council (USGBC) and the LEED rating system (United States Green Building Council 2008). The current LEED rating system, version 3, gives points for reducing water consumption and rainwater harvesting in particular.

2.2.3.1 Water Quality of Rainwater

Rainwater generally has very good water quality. Rainwater has very little sodium making it desirable for irrigation and potable uses. It is also soft or mineral free which extends the life of equipment. However, rainwater is generally slightly acidic with a pH of around 5.7 as it collects some nitrogen and carbon dioxide as it falls to the ground (Brown et al. 2005). Rainwater does contain some particulate matter from dust particles from the air. The level of total dissolved solids varies from region to region but is typically between 2 and 20 mg/l (Brown et al. 2005).

The water quality of collected rainwater depends significantly on the surface from which the water is collected (Brown et al. 2005). Common contaminants from harvested rainwater include windblown dust, bird and rodent droppings, leaves and twigs, and other vegetative debris (Sheikh 2010). The University of Oregon conducted a study in which they monitored the quality of the rainwater at different stages in the collection of the rainwater and from different collection surfaces. They used a sand filter to remove some of the suspended solids. Table 2.7 displays the results of their study. The final row includes the water quality of the rainwater after sand filtration.

Table 2.7 – Water Quality of Harvested Rainwater from Various Surfaces

Sample	pH	Turbidity (NTU)	Conductivity (µSiemens)	Hardness(ppm $CaCO_3$)	TSS (ppm)	Coliform (CFU/mL)
Metal Roof	5.97	1.3	12.4	0.5	3	100
Plumbing	6.89	0.5	17.1	6	6	>500
Cistern	8.91	2.4	735	10	9	3
Tap Water	7.32	0.3	77.1	24	2	0
Shingle Roof	5.94	8.3	455	41	6	>500
EWEB Range	7.5-7.8	0.02-0.04	45-65	18-25	<0.5	0

Note: The rainwater collection system did not include a first flush diverter.
Source: http://www.uoregon.edu/~hof/S01havestingrain/rawdata.html

There are multiple ways to improve the quality of rainwater including the use of roof washers, downspout filters, leaf guards, first flush diverters, or other filters (Brown et al. 2005). Leaf screens/guards and downspout filters prevent larger items from entering the rainwater storage tank. First flush diverters are commonly used to divert the first flush, or a pre-determined amount (generally 10 gal for every 1000' of collection surface) of water at the beginning of rainstorm containing a higher concentration of contaminants (Brown et al. 2005). Filters and diverters improve water quality by keeping sediment and organic material from entering the tank. Sediments entering the tank increase turbidity, and reduce tank storage volume over time. Organic matter entering the tank can cause the water in the tank to have an odor and increase in turbidity (Brown et al. 2005).

2.3.2.2 Requirements for Rainwater Reuse

Currently, few states or local jurisdictions regulate rainwater harvesting (Kloss 2008). The Uniform Plumbing Code (UPC) and the International Plumbing Code (IPC) address the reuse of reclaimed water and greywater. However, the IPC and the UPC do not directly address rainwater harvesting in their codes. One current problem restricting the implementation of rainwater harvesting is that many local jurisdictions have regulated rainwater as reclaimed water. Table 2.8 displays the minimum requirements for rainwater or stormwater reuse.

Table 2.8 – Minimum Water Quality Guidelines and Treatment Options for Stormwater Reuse

Use	Minimum Water Quality Guidelines	Suggested Treatment Options
Potable indoor uses	• Total coliforms – 0 • Fecal coliforms – 0 • Protozoan cysts – 0 • Viruses – 0 • Turbidity < 1 NTU	• Pre-filtration – first flush diverter • Cartridge filtration – 3 micron sediment filter followed by 3 micron activated carbon filter • Disinfection – chlorine residual of 0.2 ppm or UV disinfection
Non-potable indoor uses	• Total coliforms < 500 cfu per 100 mL • Fecal coliforms < 100 cfu per 100 mL	• Pre-filtration – first flush diverter • Cartridge filtration – 5 micron sediment filter • Disinfection – chlorination with household bleach or UV disinfection
Outdoor uses	N/A	Pre-filtration – first flush diverter

Note: cfu: colony forming units; NTU: nephelometric turbidity units
Source: (Asano et al. 2007)

2.3.2.3 Rainwater Quantity

The amount of rainwater that can be captured for use varies greatly from location to location based on local precipitation patterns. In addition, other factors can affect the amount of rainwater available for reuse including rainfall intensity, size of gutters, amount diverted through first-flush diverters, size of cistern, etc. Theoretically, a homeowner could capture approximately 0.62 gallons per square foot of roof area or collection surface for every inch of rain (Brown et al. 2005). However, the amount of rainwater captured is generally much less than that. Usually, a capture efficiency of 75-90% is assumed due to water diverted to first flush diverters, and overflow from gutters (Brown et al. 2005). Fewkes (2007) conducted 3 experimental studies on rainwater harvesting systems and measured their capture efficiencies. He reported capture efficiencies of 93%, 95% and 104% (Fewkes 2007). The last house had some runoff from another area which is the reason for the efficiency above 100%.

2.3.2.4 System Costs of Rainwater Harvesting System

A study by Marsden Jacob Associates (MJA) (2007) found that the cost of rainwater tanks range from $2.15 - $12.30 per thousand liters in Australia. These costs depend predominantly on the roof collection area of the given house, the rainfall conditions of the given site, and the size of the cistern (MJA, 2007).

MJA also discussed the benefits that harvesting rainwater have on the stormwater collection system. They noted that a detailed engineering analysis would be needed to quantify the marginal impact of capturing stormwater from a given site. The potential impacts would vary from site to site, and from city to city (MJA 2007). Local drains could be reduced if all lots captured rainwater, but larger inlet and drains collecting from roadways and other impervious areas would be less affected (MJA 2007). Another Australian study by Coombes and Kuzcera (2003) found that the savings from harvesting stormwater could be as high as $959 per lot over the life of the design, with annual savings of $10-$23.

The MJA study also noted that rainwater harvesting also reduces the amount of nutrients in the stormwater collection system. In Melbourne, Australia, the Melbourne Water Utility estimates the reduction in nitrogen in receiving water bodies from the use of rainwater tanks to be 0.2 kg of nitrogen per 150 square meters of roof surface (MJA 2007).

2.4 Life Cycle Analysis

In order to assess the feasibility and sustainability of any design, a holistic approach considering all impacts in the life cycle of the design is necessary. A thorough life cycle assessment (LCA) is a "cradle to grave" examination of a product's environmental impacts. Figure 2.2 shows the typical supply chain of a product or process. This figure is a general representation of a typical product, but it can be applied to almost any product in principal. Using copper pipe as an example, copper ore is first mined and extracted. It is then smelted or refined and processed into copper sheets. These copper sheets are then manufactured into parts such as copper tubing and wires. These materials are used in residential and other construction. After use, generally copper pipe is recycled and manufactured into new copper materials.

Source: www.scienceinthebox.com

Figure 2.2 – Typical Supply Chain Life Cycle of a Product or Good

In practice, complete process LCAs are very time consuming and expensive. In some cases, specific material or process data can be difficult to find. Several software packages (i.e., Gabi, Simapro, and TEAM Discovery) have been developed for LCAs with attached life cycle inventory databases for materials and processes. The Department of Energy has also developed a life cycle inventory database (http://www.nrel.gov/lci) which is available for public use through the National Renewable Energy Laboratory (NREL). Whether a life cycle assessment practitioner uses software or develops his/her own spreadsheet, they all follow the same basic process (Hendrickson et al. 2006).

The first step is to define goal of study. In this step, the project team determines the purpose of the study and the intended audience for the results of the study. The second step includes defining the scope (breadth and depth of the study). Here, the project develops and defines the system boundaries. The limitations of the study are realized in this step. The team will set requirements for data quality and reliability.

The third step includes conducting a Life Cycle Inventory (LCI). The project team either collects their own process and material data, or they use a computer database. Next, the project team conducts a Life Cycle Impact Assessment (LCIA): The data are now classified and normalized (step also called valuation). Classification is the identification of environmental impacts resulting from the inventory discussed in the previous step. For example, carbon dioxide emissions would be tied to the impact of global warming. Valuation is the step where the data is normalized and then weighting factors are applied to each impact for comparisons (Graedel 1998). Finally, the results of the study are evaluated and analyzed. The results can now be reported.

LCAs can become very complex with complicated products. Since material and energy balances are required for each process, completing an LCA for a system as complex as an automobile or an airplane is impossible for all practical purposes. For example, automobiles have thousands of components each involving processes for the mining, refining, and transportation of materials along with manufacturing and production processes. For this reason, other assessment methods have been developed to deal with this complexity (Hendrickson et al. 2006). One alternative approach is called an Economic Input-Output Life Cycle Assessment (EIO-LCA). This approach classifies all production and service industries in the entire U.S. economy into 428 sectors, and then estimates impacts resulting from additional demand in each sector.

The original economic input-output model was developed by a Harvard economist, Wassily Leontief (1986). He developed a general equilibrium model that identified the required inputs from any sector in the economy to produce a unit of output in a distinct sector (Leontief, 1986). He divided the entire U.S. economy into sectors which allowed him to trace all direct and indirect inputs of a product or process. One interesting assumption of the model is that an increase in production in any sector result from proportional increases in inputs from each sector (Hendrickson et al. 1998). Leontief recognized the potential to use this model to assess environmental impacts, but did not do so.

Dr. Chris Hendrickson, Dr. Lester Lave, and Dr. Scott Matthews (all faculty of the Green Design Institute at Carnegie Mellon University) took Leontief's work a step further. They used these economic input-output models and made matrices so that computations could be made with software. They then used environmental data associated with each of the sectors in the economic model to calculate the environmental impacts associated with the monetary transactions in each sector. The steps for an EIO-LCA are as follows (Hendrickson et al. 2006):

1. Estimate output changes in final demand by sector (F)
2. Assess direct and indirect economic change with input-output model (X)
3. Assess environmental discharges as a result of sector output changes (E)
4. Sum sector discharges to find overall discharges

Their method can also be described using tables and mathematic equations. For example, Table 2.9 displays the structure of an economic input-output table. This table will be used to describe the derivation of the matrix used for model calculations.

Table 2.9 – Economic Input-Output Table Structure

	Input to sectors (j)				Inter-mediate output O	Final Demand Y	Total output X
Output from sectors (i)	1	2	3	n			
1	X_{11}	X_{12}	X_{13}	X_{1n}	O_1	Y_1	X_1
2	X_{21}	X_{22}	X_{23}	X_{2n}	O_2	Y_2	X_2
3	X_{31}	X_{32}	X_{33}	X_{3n}	O_3	Y_3	X_3
n	X_{n1}	X_{n2}	X_{n3}	X_{nn}	O_n	Y_n	X_n
Intermediate input I	I_1	I_2	I_3	I_n	GDP		
Value added V	V_1	V_2	V_3	V_n			
Total input X	X_1	X_2	X_3	X_n			

Source (Hendrickson et al. 2006)
Note: X_{ij} is the input to sector j from sector i

In Table 2.9, X_{ij} is the input to sector j from sector i; O_i is the intermediate outputs used by other sectors; I_i is the sum of the individual O_i; Y_i is the final demand for each sector; and GDP is the overall sum of all final demands. Along the bottom of Table 1, I_j is the intermediate input; X_j is the total input for each sector; and V_j is the value added to each sector (or $X_j – I_j$).

Another table is needed to display the proportional input for each sector to result in one unit of output. This table is useful for calculation purposes. In order to calculate and tabulate this table, each X_{ij} entry is divided by the output or X_{ij} / X_{ij}. Equation 2.1 shows this derivation (Hendrickson et al. 2006).

$$x = (I + A + A * A + A * A * A + \ldots) * y = (I - A)^{-1} y \qquad \text{(Eq. 2.1)}$$

where x is the vector of required inputs, I is the identity matrix, A is the input-output direct requirements matrix, and y is the vector of desired output.

This model can be used in many ways. For example, these equations can be used to represent the various supply chain requirements such as the purchases of a pump manufacturer from the iron and steel mill industries. In the above equation, the desired output is represented by (I x y), contributions of direct suppliers (A x y), contributions of indirect or second level suppliers (A x A x y), third level contributions (A x A x A x y), etc. The ability of the model to take into account the second level suppliers, third level suppliers, etc. is one of the advantages of using an EIO-LCA model over a traditional LCA. In a traditional LCA, the analyst must draw system boundaries which add uncertainty into the study. In the EIO-LCA model, the vector of required outputs is multiplied by the average environmental impact or resource requirement for each sector, and the sum of these individual impacts represents the supply chain impact of a purchase. In other words, the above equation can be used to estimate the supply chain impacts to produce a product or service in one of the EIO-LCA sectors.

With the economic output, a vector of direct environmental outputs can be calculated by multiplying the economic output by the environmental impact per dollar of output. This is shown in Equation 2.2 (Hendrickson et al. 2006).

$$b_i = R_i x = R_i(I - A)^{-1} y \qquad \text{(Eq. 2.2)}$$

Where b is the vector of environmental burdens (such as greenhouse gas emissions, energy consumption or toxic releases for each production sector), and R is a matrix with diagonal elements representing the impact per dollar of output for each stage. Researchers from Carnegie Mellon University developed an online tool for this method. It can be found at the following website: http://www.eiolca.net.

EIO-LCA models are not exclusive to the United States. In fact, economic input-output models have now been developed for many countries. In the United States, a new model for the U.S. economy is typically produced every 5 years. The last three models are in 1992, 1997, and 2002. The 2007 model is expected soon. Each of these models includes different impact categories, so some studies use old models in order to analyze a different environmental impact. For example, the 1992 model has data for fertilizers and Resource Conservation and Recovery Act (RCRA) data whereas the other models do not.

One assumption of the model is that the model is linear, and can be scaled. That is, a 25% increase in production from a facility will directly result in a 25% increase in each of the inputs to the facility. Occasionally, it is necessary to use process data for one portion of the LCA, and to use the EIO-LCA model for another portion of the project. These types of models are termed hybrid models.

In this project, an EIO-LCA model (Hendrickson et al. 2006) was used for the material extraction, material processing, and manufacturing phases for each material or component such as copper pipes or pumping equipment. The EIO-LCA model was also used for the use phase (e.g., water reuse, processes during occupancy of the home) of the LCA which included the decrease/increase in demand in the water treatment sector and energy used to process and pump the reused water. The model was also used to model impacts stemming from the disposal of the materials required for the design. In this study, only materials beyond what is required for the conventional system were considered.

For the greywater reuse scenario, the materials identified for the life cycle assessment are the materials needed for the water reuse system (e.g., copper pipe, PVC pipe, storage tanks, and pumps). For each material, a sector was identified (e.g., Plastic Pipe and Pipe Fitting Manufacturing, etc.) for the increase in demand. For example, if greywater reuse required additional copper piping, a certain increase in demand would take place in this sector which in turn would affect other sectors of the economy such as mining and transportation, and it would also affect emissions of pollutants such as greenhouse gases.

The EIO-LCA model is linear, so the results of each simulation can be scaled easily and can be used to evaluate impacts (e.g., greenhouse gas emissions and energy use) per dollar of demand. An example of a hypothetical $1 million expenditure for copper pipe is shown in Tables 2.10-2.12. As mentioned, the input to this model is a hypothetical $1 million U.S. 2002 dollars of increased demand in Sector 331420: "Copper rolling, drawing, extruding and alloying". Table 2.10 shows the economic impacts of increased demand in copper pipe manufacturing. For example, $1 million increased demand in copper pipe manufacturing results in a $312,000 increase in Sector 331411: "Primary Smelting and refining of copper". Table 2.11 shows the greenhouse gas emissions, and Table 2.12 shows the energy consumed from $1 million in purchases in the "Primary smelting and refining of copper".

Table 2.10 – Economic Impacts of $1 Million Expenditure in the Copper Rolling, Drawing, Extruding, and Alloying Sector

	Sector	Total Economic $mill	Direct Economic $mill	Direct Economic %
	Total for all sectors	*2.63*	*1.71*	*65.0*
331420	Copper rolling, drawing, extruding and alloying	1.29	1.17	90.8
331411	Primary smelting and refining of copper	0.312	0.151	48.3
420000	Wholesale trade	0.136	0.075	54.9
550000	Management of companies and enterprises	0.064	0.025	39.0
335920	Communication and energy wire and cable manufacturing	0.057	0.046	82.1
212230	Copper, nickel, lead, and zinc mining	0.039	0.001	3.13
221100	Power generation and supply	0.038	0.015	39.3
484000	Truck transportation	0.029	0.012	42.4
52A000	Monetary authorities and depository credit intermediation	0.021	0.007	34.3
531000	Real estate	0.019	0.003	15.3

Source: Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 1 Jun, 2010]
Note: Direct Economic effects signify the purchases made by the particular industry of interest (in this case, sector 331420). Total Economic effects represent the total supply chain purchases.

Table 2.11 – Greenhouse Gas Emissions from $1 Million Expenditure in the Copper Rolling, Drawing, Extruding, and Alloying Sector

	Sector	GWP MTCO2E	CO2 Fossil MTCO2E	CO2 Process MTCO2E	CH4 MTCO2E	N2O MTCO2E	HFC/PFCs MTCO2E
	Total for all sectors	*821.*	*744.*	*23.1*	*37.2*	*6.17*	*10.1*
221100	Power generation and supply	335.0	334.0	0.416	0	0	1.06
331420	Copper rolling, drawing, extruding and alloying	136.0	136.0	0	0	0	0
331411	Primary smelting and	81.7	81.7	0	0	0	0

	Sector	GWP MTCO2E	CO2 Fossil MTCO2E	CO2 Process MTCO2E	CH4 MTCO2E	N2O MTCO2E	HFC/PFCs MTCO2E
	refining of copper						
484000	Truck transportation	28.2	28.2	0	0	0	0
331110	Iron and steel mills	20.0	9.42	10.4	0.190	0	0
211000	Oil and gas extraction	17.7	7.47	1.06	9.18	0	0
212230	Copper, nickel, lead, and zinc mining	15.2	15.2	0	0	0	0
325190	Other basic organic chemical manufacturing	14.2	12.5	0	0	1.73	0
482000	Rail transportation	14.1	14.1	0	0	0	0
212100	Coal mining	14.0	1.87	0	12.2	0	0

Source: Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 1 Jun, 2010]

Table 2.12 – Energy Consumption from $1 Million Expenditure in the Copper Rolling, Drawing, Extruding, and Alloying Sector

	Sector	Total Energy TJ	Coal TJ	NatGas TJ	Petrol TJ	Bio/Waste TJ	NonFossElec TJ
	Total for all sectors	*14.2*	*4.16*	*4.82*	*2.00*	*0.539*	*2.73*
221100	Power generation and supply	4.25	3.10	0.906	0.151	0	0.097
331420	Copper rolling, drawing, extruding and alloying	3.58	0.462	1.68	0.123	0.123	1.20
331411	Primary smelting and refining of copper	1.96	0.277	1.01	0.069	0.069	0.533
212230	Copper, nickel, lead, and zinc mining	0.475	0	0	0.220	0	0.255

	Sector	Total Energy TJ	Coal TJ	NatGas TJ	Petrol TJ	Bio/Waste TJ	NonFossElec TJ
484000	Truck transportation	0.386	0	0	0.383	0	0.004
331110	Iron and steel mills	0.292	0.172	0.079	0.002	0.004	0.035
325190	Other basic organic chemical manufacturing	0.278	0.046	0.131	0.028	0.051	0.021
482000	Rail transportation	0.210	0	0	0.206	0	0.003
324110	Petroleum refineries	0.202	0.000	0.054	0.131	0.010	0.007
322130	Paperboard Mills	0.178	0.016	0.037	0.008	0.105	0.012

Source: Carnegie Mellon University Green Design Institute. (2011) Economic Input-Output Life Cycle Assessment (EIO-LCA) US 2002 (428) model [Internet], Available from: <http://www.eiolca.net/> [Accessed 1 Jun, 2010]

It is evident from the previous 3 tables that the largest environmental impacts from the increase in demand in copper pipe manufacturing are due to Power Generation and Supply.

2.6 Relevant LCA Studies

Memon et al. (2007) investigated the life cycle impacts of four different treatment technologies for a greywater recycling system. The four treatment technologies analyzed included membrane bioreactors (MBR), reed beds, membrane chemical reactors (MCR), and an innovative green roof water recycling system (GROW). They analyzed the construction and operation phases of these systems over 20 development scales. They found that the natural treatment processes (reed beds and GROW) had lower environmental impact than the other two treatment technologies. The use or operation phase for all four had larger environmental impacts than the construction phase, predominantly due to energy consumption (Memon et al. 2007).

Crettaz, et al. (1999) investigated the life cycle impacts of using rainwater versus treated potable water for toilet flushing. They found that conventional water supply was environmentally preferable unless the energy required for water supply is greater than 0.8 kWh/m^3. This study also found that low-flow toilets are better environmentally than conventional toilets over the life-cycle (Crettaz et al. 1999). Flower et al. (2007) did an LCA on different water demand management strategies. They found that using different structural and non-structural water demand management strategies could reduce household water consumption and greenhouse gas emissions by 65% and 63%, respectively.

Memon (2007) and Crettaz (1999) have done life cycle studies on greywater treatment technologies and rainwater harvesting, respectively. However, Memon (2007) only studied various treatment technologies and did not look at the entire greywater reuse system. Crettaz (1999) only analyzed the use of rainwater for toilet flushing, and did not look at the use of rainwater for other uses including laundry washing and landscape irrigation. This study is the first comprehensive study looking at all phases for water reuse in residential buildings including the collection, treatment, and distribution, of greywater, rainwater and treated wastewater. This study builds on existing work to determine the life cycle impacts of the total residential water reuse system for multiple uses. In addition, five water reuse systems are analyzed which allows for further regional comparisons.

2.7 Other LCA Studies

Keoleian et al. (2001) investigated the life-cycle energy consumption and costs of a typical 2450 sq. ft. home and a similar energy-efficient house. They found the life-cycle greenhouse gas emissions of the standard home to be 1010 metric tons of CO_2 equivalents versus 370 metric tons of CO_2 equivalents for the energy efficient home. The energy consumption was also greatly reduced with the energy efficient home (from 16,000 GJ to 6,400 GJ). For the typical home, 91% of the energy was consumed in the use or operation phase (Keoleian, Blanchard and Reppe 2001).

Ochoa et al. (2002) conducted an EIO-LCA on residential buildings in the United States. They found that residential buildings account for over 5% of U.S. GDP, 26% of energy consumption, and 24% of all greenhouse gas emissions. The study also found that the use or operation phase accounted for 93% of the energy consumed by the residential building and 92% of all greenhouse gases emitted by the building over its life-cycle (Ochoa, Hendrickson and Matthews 2002).

Filion et al. (2004) conducted an EIO-LCA analysis of energy consumption from a water distribution system. They looked at the construction, use or operation, and disposal stages of the pipes in a water distribution system with replacement schedules of 10, 20, 50, and 100 years. They found that a pipe-replacement of 50 years was the best in terms of total energy consumption and environmental impacts.

Stokes and Horvath (2009) did a study on the energy and air emission effects of water supply. They predominantly focused on water supply in the state of California. They found that desalinating seawater has an ecological footprint that is 1.5-2.4 times larger than importing water or reusing water. Recycling or reusing water had nearly the same environmental impacts as importing water in their study.

Arpke et al. (2005) did an LCA and a life cycle cost analysis (LCCA) on water use in four multi-occupant buildings (apartment, college dormitory, motel, and an office building). They analyzed the impacts of plumbing fixtures and appliances over a 25-year life span. They found that the high efficiency plumbing fixtures and appliances were environmentally and economically preferable in the scenarios analyzed.

Kats (2003) analyzed the costs and financial benefits of using green building methods. He found that green building costs about 2% more upfront. However, the study also found that green building resulted in costs recovered over the life of the building of ten times the initial cost premium. The financial benefits were realized through lower energy consumption, lower water costs, less waste disposal, lower emissions costs, and savings from increased productivity and health. Savings from increased productivity and health were conservatively estimated, since these benefits have a lot of uncertainty.

Hendrickson et al. (1997) compared two separate life cycle assessment approaches. They compared a process model LCA vs. an EIO-LCA. They looked at multiple processes and products and concluded that the EIO-LCA leads to similar results as a process model, with less upfront work. The results between the two approaches were within a factor of 10. Hendrickson et al. (2006) also looked the annual energy requirements to produce platinum group metals (PGM). In this study, they used the Gabi (process LCA software) and the EIO-LCA model. The results were very similar for the three scenarios analyzed: baseline, new emissions standard scenario, and the fully effective nanotechnology scenario. These scenarios were evaluated over the 2005 to 2030 timeframe. The minor differences between the two analyzes were primarily due to the way the recycled PGM materials were accounted in each model (Hendrickson et al. 2006).

Racoviceanu and Karney (2010) did a hybrid LCA on residential water conservation strategies. They analyzed three scenarios including a base case, water efficiency measures, and rainwater harvesting. They found that the results depend on where the system boundaries are drawn. For example, when the water-heating impacts were omitted, the rainwater harvesting scenario proved to be environmentally taxing. However, when the water-heating impacts were included, the system performed favorably compared to the base case in terms of greenhouse gas emissions and energy consumption.

3.0 Chapter 3 Methods

For the greywater reuse analysis, our study considers 4 regions of the United States which include the Northwest, Southwest, Midwest, and Southeast. One city in each region was chosen to represent that climate or region. The cities chosen to represent each of the regions are Seattle, Washington (NW); Scottsdale, Arizona (SW); Omaha, Nebraska (MW); and Tampa, Florida (SE). In each region, several water reuse design scenarios are analyzed which include three single family residence scenarios, an apartment complex, and a community reuse project.

3.1 Model 1 - Development of an EIO-LCA for a Simple Greywater Reuse Design in a Single Family Residence

The first analysis includes a simple greywater reuse design for a single family residence in each of the four study sites. In this system, greywater from showers, bath tubs, bathroom sinks, and laundry machines is used for sub-surface landscape irrigation. Since the water is applied to the plants below the ground surface, no treatment is necessary. The system includes greywater collection piping from bathroom sinks, tubs, showers, and laundry machines; a splitter box that diverts greywater flow to the various landscape components; and distribution piping that distributes the greywater to each landscape irrigation component. See Figures 3.1-3.4 for site layouts.

3.1.1 Calculation of Irrigation Demand

In order to calculate the quantity of greywater that can be used for landscape irrigation, the Landscape Coefficient Method was used to estimate the evapotranspiration rate of a typical residential landscape planting (Costello et al. 2000). This method estimates landscape evapotranspiration, ET_L, as:

$$ET_L = K_L \times ET_O \qquad \text{(Eq. 3.1)}$$

where K_L is the landscape coefficient for a particular planting (unitless), and ET_O is the reference evapotranspiration rate (inches/month) for a cool season grass that is 4-7 inches tall (Costello, Matheny and Clark 2000). In order to determine ET_O, local evaporation information (pan evaporation rate) was needed for each of the four study sites.

Then, these data were compared to local evapotranspiration rates. The local data were compared to calculated evapotranspiration data (data calculated using Penman equation). The local and calculated data were very similar; therefore, the local data were used for all analyses and calculations. Each of the following sections will note the location from which the data were retrieved. Equation 3.1 was used to convert the evapotranspiration of the grass reference crop to the evapotranspiration of a typical landscape using landscape coefficient, K_L. K_L is found using Equation 3.2:

$$K_L = k_s \times k_d \times k_{mc} \qquad \text{(Eq. 3.2)}$$

where k_s is the species factor, k_d is the vegetation density factor, and k_{mc} is the microclimate factor (Costello, Matheny and Clark 2000). Trees and shrubs with moderate species factors like the western dogwood tree and blue marguerite shrubs were chosen to represent a residential landscape planting with moderate water needs. Consequently, a moderate species factor of 0.5 (range 0.1 to 0.9) was chosen (Costello, Matheny and Clark 2000). Vegetation densities can vary significantly from planting to planting. Likewise, microclimate factors vary depending on the location of plants in relation to buildings, shadows, and wind exposure. Average values of 1.0 (range is typically between 0.5 and 1.3 for both factors) (Costello, Matheny and Clark 2000) were used for both of these factors in order to estimate consumptive use of a typical landscape for all four study sites. The landscape coefficient for all study sites, calculated using Equation 3.2 was:

$$K_L = 0.5 \times 1.0 \times 1.0 = 0.5.$$

For all 4 sites, ET_L was found using Eq. 3.1. Typically, irrigation efficiencies vary from 65% - 90% (Costello, Matheny and Clark 2000). Gupta (2008) estimates average irrigation efficiencies to be between 40% - 70%. Irrigation efficiency is affected by the method of applying water, the texture and condition of the soil, the slope of the land, the preparation of the land, and wind speed for sprinkler systems (Gupta 2008). The LEED for Homes Reference Guide published by the United States Green Building Council (USGBC) estimates typical lawn sprinklers irrigation efficiency to be 50% (United States Green Building Council 2008). In addition, greywater systems often irrigate the landscape even when plants do not need the water, which reduces the efficiency. Therefore, unless the greywater reuse system incorporates storage and drip irrigation, the irrigation efficiency is generally less than 50% (Ludwig 2009). In this study, the irrigation efficiency of the greywater distribution system was assumed to be 40%. When calculating water savings, the conventional lawn irrigation efficiencies were assumed to be 50%.

Monthly rainfall totals were taken from historical data from The Weather Channel website (http://www.weather.com). Effective rainfall is affected by the soil moisture, cropping pattern, application of irrigation, and the rainfall characteristics (Gupta 2008). Effective rainfall (i.e., the rainfall used by plants) was found on a monthly basis for each of the sites using methods from United States Soil Conservation Service (1964), which is now the Natural Resources Conservation Service (NRCS). The method calculates effective rainfall based on the site's average monthly rainfall and the average monthly consumptive use. The irrigation requirement, IR_{net} (in./month), is the difference between the average monthly evapotranspiration, ET_L (in./month), and the effective rainfall (in./month) divided by the irrigation efficiency, IE (%) (Costello, Matheny and Clark 2000). This is shown in Equation 3.3:

$$IR_{net} = (ET_L - \text{Effective Rainfall}) / IE \qquad \text{(Eq. 3.3)}$$

The monthly irrigation demand volume was then calculated by applying the IR_{net} in inches over the designed irrigated area. Each region has a different designed irrigated area because the irrigated area was sized such that the average monthly amount of greywater produced (e.g. 2290 gallons for Seattle) is equal to the average dry season demand as recommended by Ludwig (2009). The average dry season demand is the average irrigation demand of the 3 months with the highest demand. Thus, supplemental irrigation will be needed at peak irrigation times.

This type of design is beneficial because it provides a good balance between greywater use and plumbing material requirements (Ludwig 2009). This is because during the dry season, the available greywater is adequate to irrigate only a small area and consequently requires less infrastructure. If a homeowner wanted to maximize greywater reuse efficiency, he could design the system for the average irrigation demand during the wet season. However, this would require significantly more plumbing work and materials because a larger area would be required to distribute the available greywater during the wet season. The homeowner would also have an extensive irrigation network to maintain. The homeowner could also design a system to meet peak irrigation demand. In this scenario, reuse would be reduced, and in effect waste some of the greywater. The homeowner would run a greater risk of over-watering plants during the wet season than in a system designed for the average dry season demand. Also, due to the level of salts in the greywater reuse system, it is a good idea to supplement greywater irrigation with freshwater irrigation to flush the salts and minerals through the soil, especially in dryer areas (Ludwig 2009).

Consequently, each site was sized so that the average greywater generation rate matched the irrigation demand of the designed area. The greywater production was calculated using data from Mayer (1999). That study included data for Seattle, Scottsdale, and Tampa. The overall study average for indoor sources of greywater was used to calculate the greywater production in Omaha.

The irrigated area was sized according to the greywater amount produced and the irrigation demand of the given area. As designed, the monthly average dry season irrigation demand is equal to the average monthly greywater generated in the respective cities. Table 3.1 shows the greywater produced and the area that could be irrigated with greywater for the four study sites. Greywater production rates were taken from the Residential End Uses of Water study by Mayer et al. (1999) for Seattle, Scottsdale, and Tampa. In Omaha, the total indoor water demand was taken from the average water use during winter months. The average percentage of water used from each source of greywater from Mayer's study (1999) was then applied to the total indoor water demand to calculate the total greywater production rates. The actual greywater production rates were not available in Omaha, so this information was the best available for this site. The outdoor water use varies significantly from site to site, but the indoor water usage and greywater production rates did not vary much from site to site, making this a reasonable assumption of the Omaha climate.

Table 3.1 – Irrigated Area Calculation for the Four Sites

Site	Average amount of greywater produced per month, gal (L)	Area irrigated by greywater, sq. ft. (sq. m)
Seattle, Washington	2300 (8700)	1000 (93)
Scottsdale, Arizona	2200 (8200)	300 (27)
Omaha, Nebraska	2400 (8900)	1400 (130)
Tampa, Florida	2100 (8000)	1000 (93)

Note: Less area can be irrigated in arid climates such as Scottsdale as compared to more humid climates such as Tampa, Omaha, and Seattle. This is because the arid climates have much higher evapotranspiration rates than in climates with higher humidity and more rainfall.

3.1.1.1 Irrigation demand calculation for Seattle, Washington

Local evapotranspiration data for a grass reference crop were found on the Agweather website from Washington State University (www.weather.wsu.edu). The Penman-Monteith method was used to calculate the reference evapotranspiration from available meteorological data (http://www.fao.org/docrep/X0490E/x0490e06.htm). The meteorological data were then converted to the landscape evapotranspiration rate as described in Section 3.1.1. Table 3.2 shows the irrigation demand for a 1000 square foot landscape in Seattle.

Table 3.2 – Calculation of Irrigation Demand in Seattle, WA

Month	(a) ET_O - Grass		(b) ET_L		(c) Rainfall		(d) Effective Rainfall		(e) IRnet		(f) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	0.56	1.43	0.28	0.72	5.24	13.31	1.00	2.54	-1.80	-4.56	0	0
February	0.85	2.17	0.43	1.08	4.09	10.39	1.00	2.54	-1.43	-3.64	0	0
March	1.43	3.64	0.72	1.82	3.92	9.96	1.00	2.54	-0.71	-1.80	0	0
April	2.49	6.32	1.25	3.16	2.75	6.99	1.00	2.54	0.61	1.56	382	1443
May	3.82	9.70	1.91	4.85	2.03	5.16	1.25	3.18	1.65	4.19	1029	3888
June	4.24	10.76	2.12	5.38	1.55	3.94	0.91	2.31	3.02	7.67	1883	7119
July	4.92	12.50	2.46	6.25	0.93	2.36	0.62	1.57	4.60	11.69	2868	10841
August	3.93	9.99	1.97	4.99	1.16	2.95	0.60	1.52	3.42	8.67	2129	8046
September	2.69	6.83	1.34	3.42	1.61	4.09	0.86	2.18	1.21	3.08	755	2854

October	1.16	2.95	0.58	1.47	3.24	8.23	1.00	2.54	-1.05	-2.67	0	0
November	0.62	1.57	0.31	0.78	5.67	14.40	1.00	2.54	-1.73	-4.39	0	0
December	0.46	1.17	0.23	0.59	6.06	15.39	1.00	2.54	-1.92	-4.89	0	0
Total											**9045**	**34191**

Note: Evapotranspiration data in column (a) was provided courtesy of Washington State University AgWeatherNet. Data are copyright of Washington State University. Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (d) was taken from Gupta (2008). Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

3.1.1.2 Irrigation demand calculation for Scottsdale, Arizona

Irrigation demand was calculated for Scottsdale, Arizona. Scottsdale has a much higher evapotranspiration rate than Seattle. Reference evapotranspiration data for a grass crop were found from: http://ag.arizona.edu/azmet/azdata.htm. Measured meteorological data were used with the Penman-Monteith mathematical model to calculate the evapotranspiration for a cool season grass (The University of Arizona Cooperative Extension 2000). Table 3.3 shows the irrigation demand for a 295 square foot landscape in Scottsdale.

Table 3.3 – Calculation of Irrigation Demand in Scottsdale, AZ

Month	**(a) ET_O - Grass**		**(b) ET_L**		**(c) Rainfall**		**(d) Effective Rainfall**		**(e) IRnet**		**(f) Irrigation Demand**	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	2.77	7.04	1.39	3.52	1.01	2.57	0.57	1.45	2.04	5.18	375	1419
February	3.37	8.57	1.69	4.28	1.04	2.64	0.58	1.47	2.77	7.03	509	1923
March	5.72	14.53	2.86	7.26	1.15	2.92	0.65	1.65	5.53	14.03	1016	3840
April	7.96	20.22	3.98	10.11	0.25	0.64	0.20	0.51	9.45	24.01	1738	6570
May	9.53	24.21	4.77	12.10	0.21	0.53	0.17	0.43	11.49	29.18	2113	7986
June	10.61	26.96	5.31	13.48	0.07	0.18	0.06	0.15	13.12	33.31	2412	9117
July	10.16	25.81	5.08	12.90	0.89	2.26	0.70	1.78	10.95	27.82	2014	7612
August	9.10	23.11	4.55	11.56	1.20	3.05	0.72	1.83	9.58	24.32	1761	6655
September	7.41	18.83	3.71	9.42	0.86	2.18	0.70	1.78	7.52	19.09	1382	5225
October	6.17	15.66	3.08	7.83	0.85	2.16	0.65	1.65	6.08	15.45	1119	4229
November	3.65	9.27	1.83	4.64	0.80	2.03	0.56	1.42	3.16	8.03	582	2198
December	2.49	6.33	1.25	3.17	1.03	2.62	0.55	1.40	1.74	4.42	320	1210
Total											**15340**	**57984**

Note: Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (d) was taken from Gupta (2008). Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

3.1.1.3 Irrigation demand calculation for Omaha, Nebraska

Irrigation demand for Omaha, Nebraska was calculated using same methods stated previously. The reference evapotranspiration data for an alfalfa reference crop were retrieved from the High Plains Climate Center (http://www.hprcc.unl.edu/awdn/et/) for the past 10 years. The data were retrieved from a station near Mead, Nebraska which is about 20 miles west of Omaha. The reference evapotranspiration data were calculated using the Penman equation. These data were averaged, and then converted to a grass reference crop using a conversion factor developed by Irmak et al. (2008). These conversion factors were computed for several regions across the country. Rockport, Missouri (60 miles southeast of Omaha) had the most similar climate conditions to Omaha, so monthly values computed at this location were used for this study. Several methods were used in the study, but the values computed using the FAO56 method had the smallest standard deviations and were, therefore, considered to be the most accurate. Thus, these were used in for this study. Table 3.4 displays the calculation of irrigation demand for Omaha.

Table 3.4 – Calculation of Irrigation Demand in Omaha, NE

Month	(a) ET_O - Alfalfa		(b) ET_O - Grass		(c) ET_L		(d) Rainfall		(e) Effective Rainfall		(f) IRnet		(g) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	1.57	3.99	1.53	3.88	0.76	1.94	0.77	1.96	0.60	1.52	0.41	1.04	0	0
February	1.92	4.89	1.85	4.70	0.93	2.35	0.80	2.03	0.60	1.52	0.81	2.07	0	0
March	3.78	9.60	3.50	8.89	1.75	4.44	2.13	5.41	1.25	3.18	1.25	3.17	1106	4180
April	6.10	15.51	5.60	14.23	2.80	7.11	2.94	7.47	1.93	4.90	2.18	5.53	1926	7280
May	7.78	19.75	7.34	18.63	3.67	9.32	4.44	11.28	2.65	6.73	2.54	6.46	2252	8512
June	7.89	20.03	7.58	19.26	3.79	9.63	3.95	10.03	2.67	6.78	2.80	7.12	2482	9383
July	7.25	18.42	7.11	18.05	3.55	9.03	3.86	9.80	2.55	6.48	2.51	6.38	2222	8399
August	6.14	15.60	6.02	15.29	3.01	7.65	3.21	8.15	1.95	4.95	2.65	6.73	2346	8867
September	5.53	14.04	5.26	13.37	2.63	6.68	3.17	8.05	1.90	4.83	1.83	4.65	1619	6120
October	3.84	9.76	3.63	9.21	1.81	4.60	2.21	5.61	1.25	3.18	1.41	3.57	1245	4705

November	2.37	6.02	2.26	5.74	1.13	2.87	1.82	4.62	1.10	2.79	0.07	0.18	0	0
December	1.36	3.45	1.32	3.35	0.66	1.67	0.92	2.34	0.66	1.66	0.01	0.03	0	0
Total													**15197**	**57446**

Note: Column (a) is evapotranspiration data retrieved from the High Plains Regional Climate Center. Column (b) using conversion factors (Irmak et al. 2008). Column (c) was calculated using Eq. 3.1. Column (d) comes from monthly averages from www.weather.com. Column (e) was calculated using a table from Gupta (2008). Column (f) was calculated using Eq. 3.3. Column (g) was calculated by applying the irrigation depth over the irrigated area.

3.1.1.4 Irrigation demand calculation for Tampa, Florida

Irrigation demand for Tampa, Florida was calculated using the same methods stated previously. Reference evapotranspiration data were retrieved from studies done by the United States Geological Survey (USGS) near Tampa (http://hdwp.er.usgs.gov/et2005-2007.asp). The Penman-Monteith method was used to calculate the reference evapotranspiration in this study (http://hdwp.er.usgs.gov/ET/GOES_FinalReport.pdf).

Table 3.5 – Calculation of Irrigation Demand in Tampa, FL

Month	**(a) ET_O - Grass**		**(b) ET_L**		**(c) Rainfall**		**(d) Effective Rainfall**		**(e) IRnet**		**(f) Irrigation Demand**	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	3.16	8.03	1.58	4.01	2.27	5.77	1.20	3.05	0.95	2.42	600	2267
February	2.80	7.12	1.40	3.56	2.67	6.78	1.26	3.20	0.35	0.90	222	840
March	5.02	12.75	2.51	6.38	2.84	7.21	1.88	4.78	1.57	4.00	992	3751
April	6.15	15.63	3.08	7.82	1.80	4.57	1.25	3.18	4.57	11.60	2879	10881
May	6.96	17.69	3.48	8.84	2.85	7.24	1.94	4.93	3.85	9.79	2429	9182
June	6.12	15.55	3.06	7.78	5.50	13.97	3.06	7.77	0.00	0.01	3	11
July	5.95	15.12	2.98	7.56	6.49	16.48	2.97	7.54	0.02	0.04	10	36
August	5.85	14.87	2.93	7.43	7.60	19.30	2.93	7.43	0.00	0.00	0	0
September	5.52	14.03	2.76	7.01	6.54	16.61	2.76	7.01	0.00	0.01	2	6
October	4.96	12.59	2.48	6.30	2.29	5.82	1.48	3.76	2.50	6.34	1574	5950
November	3.70	9.40	1.85	4.70	1.62	4.11	1.07	2.72	1.95	4.95	1229	4645
December	3.00	7.61	1.50	3.81	2.30	5.84	1.22	3.10	0.70	1.77	439	1659
Total											**10378**	**39228**

Note: Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (d) was taken from Gupta (2008). Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

3.1.2 Simple Greywater Reuse System Design for a Residential House

Greywater reuse systems vary in size and complexity. The purpose of the first analysis is to create a simple greywater design with minimal components that can be widely used in all four designated climates. Gravity flow systems are the most widely used for landscape irrigation designs, require little maintenance, and are the most cost effective (Ludwig 2009). A common 80' x 90' residential lot was chosen for each of the four study sites for easy comparison. A typical 2-story, 1260 square foot per floor house with an attached garage was chosen for analysis. The garage is approximately 500 square feet. The house has 2 bathrooms on the main floor and an additional bathroom on the second floor. This house was chosen because it is a common floorplan with a moderate size for a new construction residence. The type of house and floorplan has minimal impacts on the overall design as a change in floorplan would only impact the length of PVC pipe needed for the collection of the greywater. More specific information on the floorplan chosen can be found in the study by Killion (2011)

As mentioned in Section 3.1.1, the irrigated area for each study site was sized to meet the average dry season demand. Thus, a landscape was designed according to each site's irrigation requirement. The irrigated area for each of the four sites is given in Table 3.1. The material requirements are specific for each study site. Seattle and Tampa have the same irrigation area requirements, so the designs for the simple greywater reuse system are identical for these two sites.

3.1.2.1 Life Cycle Assessment: Manufacturing of Materials Phase

After the design was complete, all materials for the construction of the simple greywater reuse system were compiled. The list of materials is not meant to be a comprehensive list for any homeowner, but rather a typical list of materials to implement the system in the given region. The amount of materials varies significantly between regions, because of the large differences in irrigated area between the sites. However, since the same design home was used for all four sites, the indoor materials are the same for all four sites. The necessary materials for the components of the greywater system inside the house are displayed in Table 3.6.

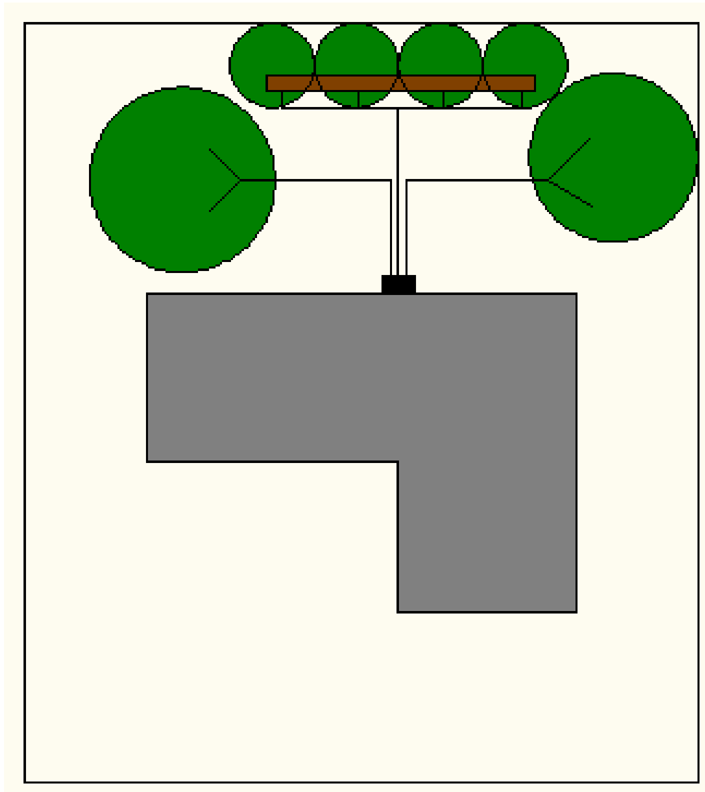
Table 3.6 – Indoor Materials for the Simple Greywater Reuse System for all 4 Study Sites

Materials	Unit Price	Unit	Quantity	Total Price	Producer Price	EIO-LCA Sector
2" schedule 40 ABS	$1.34	LF	132	$176.88	$133.19	326122 Plastics Pipe and Pipe Fitting Manufacturing
90 degree elbows	$4.25	EA	6	$25.50	$19.20	326122 Plastics Pipe and Pipe Fitting Manufacturing
Double ell (90 degrees)	$3.50	EA	7	$24.50	$18.45	326122 Plastics Pipe and Pipe Fitting Manufacturing
Diverter valves	$59.00	EA	1	$59.00	$44.43	326122 Plastics Pipe and Pipe Fitting Manufacturing
Total				**$285.88**	**$215.27**	

Note: Unit prices in column 2 are taken from Ludwig (2009). The Producer Prices in column 6 are calculated using the markup factor from Equation 3.4. The total prices are reduced by this factor resulting in the value shown in column 6.

3.1.2.1.1 Materials Needed for the Simple Greywater Reuse System Design in Seattle and Tampa

From the previous section, it was shown that the average household produces about the same amount of greywater as the dry season irrigation demand for 1000 square feet in Seattle and Tampa. Therefore, the system was designed to irrigate 1000 square feet for both Seattle and Tampa. Figure 3.1 shows the lot layout irrigation design for the simple greywater reuse system in Seattle and Tampa.



Note: The L-shape represents a house with an attached garage. The total square feet of house and garage is 1870 sq. ft. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.1 – Landscape Irrigation Design for the Simple Greywater Reuse System in Seattle and Tampa

The residential lot is 80' wide and 90' deep. The small black box shown in the figure is the splitter box, and in this case, it splits the flow into three lines. The total irrigated area is the area of the drip lines of the trees and shrubs. In this design, two different 2" lines go to two large trees. The middle 2" line is split into for discharge points and irrigates a mulched trench that serves 4 medium sized fruit trees. All lines are reduced from a 2" line to a 1 ½" line after a line split. Table 3.7 shows the total amount of outdoor materials and their prices.

Table 3.7 – Outdoor Materials in Seattle and Tampa for the Simple Greywater Reuse System

Materials	Unit Price	Unit	Quantity	Total Price	Producer Price	EIO-LCA Sector
1 1/2" schedule 40 ABS	$1.09	LF	60	$65.40	$49.25	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 ABS	$1.34	LF	79	$105.86	$79.71	326122 Plastics Pipe and Pipe Fitting Manufacturing
Double ell (90 degrees)	$3.50	EA	5	$17.50	$13.18	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	$17.99	326130 Laminated Plastics Plate, Sheet, and Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	$73.53	327390 Other Concrete Product Manufacturing
Reducers (2-1 1/2)	$2.00	EA	6	$12.00	$9.04	326122 Plastics Pipe and Pipe Fitting Manufacturing
45 degree bend	$2.75	EA	4	$11.00	$8.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
90 degree elbows	$4.25	EA	4	$17.00	$12.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
Total				**$358.76**	**$263.78**	

Note: Unit prices in column 2 are taken from Ludwig (2009). The Producer Prices in column 6 are calculated using the markup factor from Equation 3.4. The total prices are reduced by this factor resulting in the value shown in column 6.

The corresponding sectors from the EIO-LCA model were identified for the given materials. The amounts given in column 5 of Table 3.7 represent consumer prices. For the EIO-LCA, producer prices are needed. Producer prices are defined as the total price from the producer's perspective, as it leaves the factory. To calculate the producer price, it is necessary to determine the markup factor. The markup value for a particular material was determined using Equation 3.4 (U.S. Department of Commerce 2006).

$$\text{Markup Factor} = (TV - CM - CL - CE) / (TV) \quad \text{(Eq. 3.4)}$$

where TV is the total value of shipments, CM is the cost of materials, CL is the cost of labor, and CE is the capital expenditures. This calculation has to be done for each sector. The total value of shipments and other data necessary for this calculation can be found in the "Statistics for Industry Groups and Industries: 2005" document (U.S. Department of

Commerce 2006). For example, using Equation 3.4 for the plastics pipe and pipe fitting manufacturing sector yields a 26.6% mark-up. This percentage is then used to determine the producer price for each material by reducing the consumer price by the mark-up percentage. Column 6 in Table 3.7 gives the producer prices for the materials in 2009 U.S. dollars.

However, the EIO-LCA model used for this study is based on 2002 data (The 2002 model is the most current model available). Consequently, the values from Table 3.7 need to be adjusted from 2009 dollars to 2002 dollars. Table 3.8 displays the producer prices in 2009 and 2002 dollars for each of the sectors. Each sector is scaled up by a factor of 1000 to represent the environmental impacts of 1000 households. The amount going into each sector for the simple greywater reuse system scaled to represent 1000 households, is shown in Table 3.8. The third column is the actual amount used as an input into the EIO-LCA model. This amount is adjusted for inflation using the Consumer Price Index (CPI) Index (http://www.bls.gov). It is also scaled to represent 1000 households.

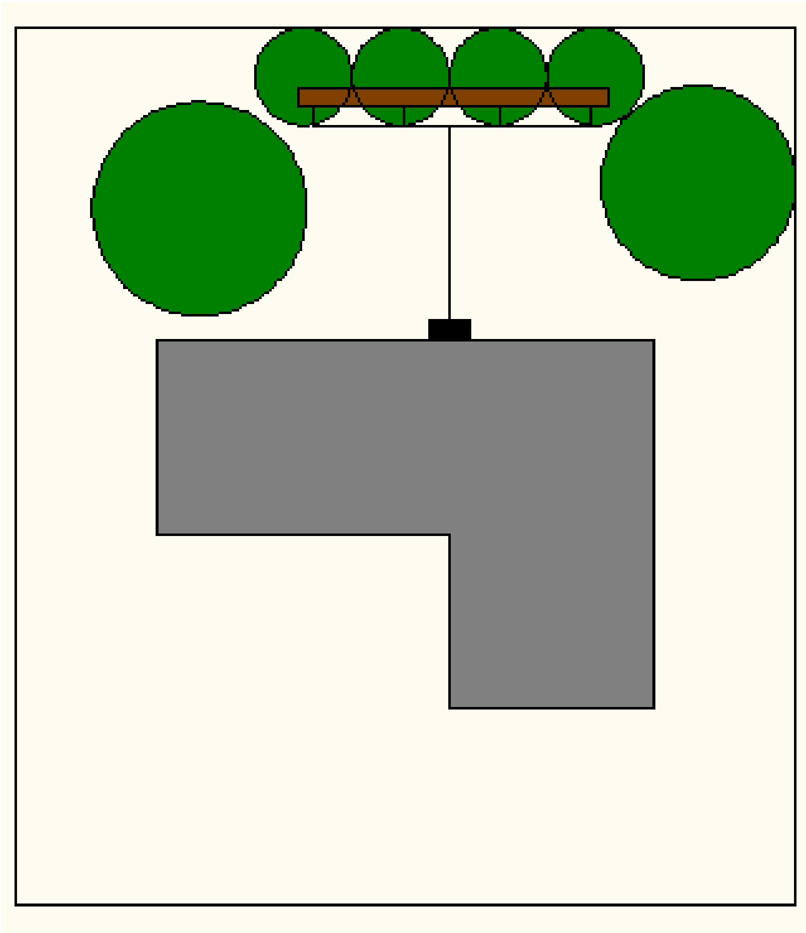
Table 3.8 – Producer's Price for all Necessary Materials in the Simple Greywater Reuse System in Seattle and Tampa

EIO-LCA Sector	Producer's Price (2009 U.S. $)	Producer's Price (2002 U.S. $)
326122 Plastics Pipe and Pipe Fitting Manufacturing	$387,530	$325,530
326121 Unlaminated Plastics Profile Shape Manufacturing	$17,990	$15,110
327390 Other Concrete Product Manufacturing	$73,530	$61,770

The 2002 Producer Price in each sector is adjusted from 2009 dollars using the CPI index (http://www.bls.org)

3.1.2.1.2 Materials needed for the Simple Greywater Reuse System in Scottsdale

The area that can be irrigated with the available greywater is much less in Scottsdale because the evapotranspiration is much greater. Therefore, the amount of materials necessary is greatly reduced compared to the other sites. Figure 3.2 shows the layout design for Scottsdale. Table 3.9 shows the materials needed for the design in Scottsdale, and Table 3.10 shows the adjustment for inflation.



Note: The L-shape represents a house with an attached garage. The total square feet of house and garage is 1870 sq. ft. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.2 – Landscape Irrigation design for the Simple Greywater Reuse System in Scottsdale

Table 3.9 – Outdoor Materials for a Simple Greywater Reuse System in Scottsdale

Materials	Unit Price	Unit	Quantity	Total Price	Producer Price	Sector
1 1/2" schedule 40 ABS	$1.09	LF	37	$40.33	$30.37	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 ABS	$1.34	LF	20	$26.80	$20.18	326122 Plastics Pipe and Pipe Fitting Manufacturing
Double ell (90 degrees)	$3.50	EA	3	$10.50	$7.91	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	$17.99	326130 Laminated Plastics Plate, Sheet, and Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	$73.53	327390 Other Concrete Product Manufacturing
Reducers (2-1 1/2)	$2.00	EA	2	$4.00	$3.01	326122 Plastics Pipe and Pipe Fitting Manufacturing
90 degree elbows	$4.25	EA	2	$8.50	$6.40	326122 Plastics Pipe and Pipe Fitting Manufacturing
Total				**$220.13**	**$159.39**	

Note: Unit prices in column 2 are taken from Ludwig (2009). The Producer Prices in column 6 are calculated using the markup factor from Equation 3.4. The total prices are reduced by this factor resulting in the value shown in column 6.

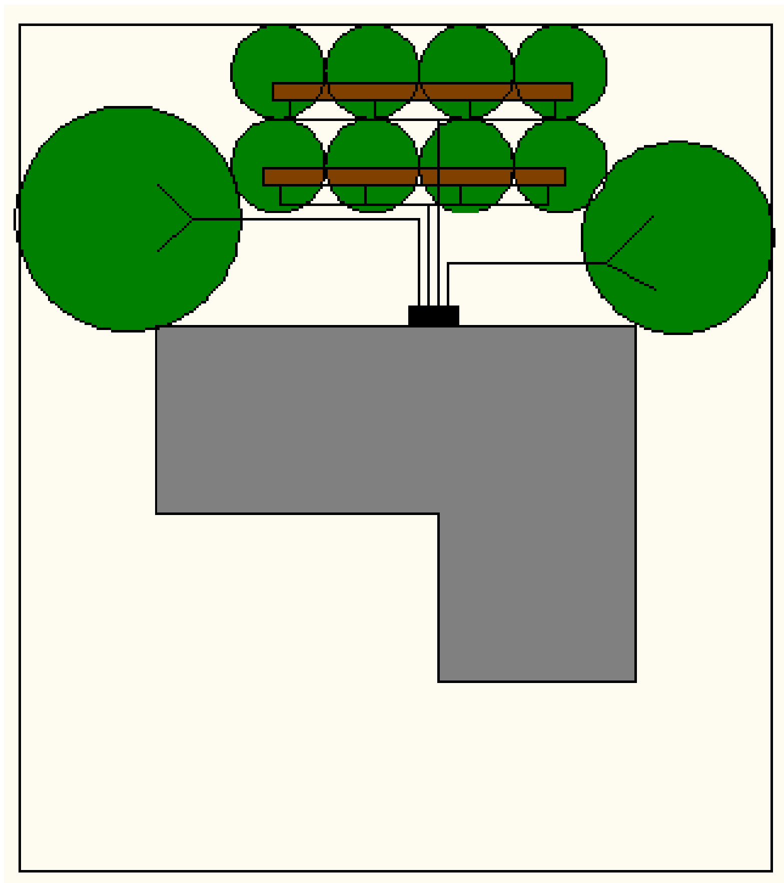
Table 3.10 – Producer's Price for all necessary Materials in the Simple Greywater Reuse System for Scottsdale

EIO-LCA Sector	Producer's Price (2009 U.S. $)	Producer's Price (2002 U.S. $)
326122 Plastics Pipe and Pipe Fitting Manufacturing	$283,140	$237,840
326121 Unlaminated Plastics Profile Shape Manufacturing	$17,990	$15,110
327390 Other Concrete Product Manufacturing	$73,530	$61,770

The 2002 Producer Price in each sector is adjusted from 2009 dollars using the CPI index (http://www.bls.org).

3.1.2.1.3 Materials needed in Omaha

Because the timing of the rainfall better matches the plants' needs, the area that can be irrigated with greywater in Omaha is larger than for the other sites. Therefore, the necessary materials and their associated costs were also significantly higher. Figure 3.3 shows the design layout for Omaha. The design was modified from the original Seattle design to include an extra row of medium sized fruit trees. Table 3.11 shows the materials and their associated costs, and Table 3.12 shows the producer prices adjusted to 2002 U.S. dollars for use in the EIO-LCA.



Note: The L-shape represents a house with an attached garage. The total square feet of house and garage is 1870 sq. ft. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.3 – Landscape Irrigation Design for the Simple Greywater Reuse System in Omaha

Table 3.11 – Outdoor Materials for the Simple Greywater Reuse System in Omaha

Materials	Unit Price	Unit	Quantity	Total Price	Producer Price	Sector
1 1/2" schedule 40 ABS	$1.09	LF	97	$105.73	$79.61	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 ABS	$1.34	LF	87	$116.58	$87.78	326122 Plastics Pipe and Pipe Fitting Manufacturing
Double ell (90 degrees)	$3.50	EA	8	$28.00	$21.08	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	$17.99	326130 Laminated Plastics Plate, Sheet, and Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	$73.53	327390 Other Concrete Product Manufacturing
Reducers (2-1 1/2)	$2.00	EA	8	$16.00	$12.05	326122 Plastics Pipe and Pipe Fitting Manufacturing
90 degree elbows	$2.75	EA	4	$11.00	$8.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
Total				**$432.81**	**$319.54**	

Note: Unit prices in column 2 are taken from Ludwig (2009). The Producer Prices in column 6 are calculated using the markup factor from Equation 3.4. The total prices are reduced by this factor resulting in the value shown in column 6.

Table 3.12 – Producer's Price for all Necessary Materials in the Simple Greywater Reuse System for Omaha

EIO-LCA Sector	Producer's Price (2009 U.S. $)	Producer's Price (2002 U.S. $)
326122 Plastics Pipe and Pipe Fitting Manufacturing	$443,290	$372,360
326121 Unlaminated Plastics Profile Shape Manufacturing	$17,990	$15,110
327390 Other Concrete Product Manufacturing	$73,530	$61,770

The 2002 Producer Price in each sector is adjusted from 2009 dollars using the CPI index (http://www.bls.org).

3.1.2.2 Life Cycle Assessment: Use Phase

Impacts during the use phase of the greywater reuse process stem from a decreased demand for municipal potable water and reduced demand in wastewater treatment. This decrease in demand results in less material used (e.g. for smaller distribution and treatment systems) and less energy for the treatment and distribution of municipal potable water and treatment of wastewater. The EIO-LCA sector titled "Water, sewage, and other systems" in the 2002 EIO-LCA model was used for this assessment phase. This sector was used to assess all impacts related to reductions in potable water use, and reduction in wastewater treatment. The irrigation demand due to greywater reuse was calculated in Section 3.1.1 for each of the four study sites. This information was used to determine how much potable water is saved with this irrigation demand at each site. The amount of water that is saved is the lesser of the irrigation demand for the given month and the amount of greywater generated during that month. This represents the reduction in the potable water used for irrigation.

3.1.2.2.1 Life Cycle Assessment: Use Phase for Seattle

The irrigation demand throughout the year was calculated for Seattle in Section 3.1.1. Mayer (1999) found that the typical household in Seattle has 2.8 residents and generates 26.9 gpcd of greywater from acceptable sources including baths, showers, bathroom faucets, and laundry machines. This means the average household in Seattle generates 2.29 kgal per month or 27.5 kgal per year.

The average annual use of potable water for a typical household in Seattle is 80.1 kgal (Mayer et al. 1999). The study found the sewer rate to be $5.41 per kgal of potable water used. The water rates in Seattle are based on a block structure. The rate payer is assessed $1.88 for the first 3.74 kgal each month, and $2.95 for each kgal after that. So, the average customer in Seattle who consumes 80.1 kgal pays $621.62 per year in water and sewer fees. However, if a homeowner can reuse greywater, this amount will be reduced. Table 3.13 shows how much the typical residential customer will pay in water and sewer fees per month if they use greywater to irrigate 1000 square feet of landscaping. The fourth column of Table 3.13 shows the amount of potable water that is replaced. Since the irrigation efficiency of a greywater reuse system (40%) is less than a traditional irrigation system (50%), the amount of potable water actually replaced is 80% of the amount of greywater reused.

Table 3.13 – Water and Sewer Fee Calculations for Typical Customers Using the Simple Greywater Reuse Systems in Seattle

Month	(a) Irrigation Demand		(b) Greywater Reused		(c) Potable Water Replaced		(d) Total Potable Water Used		(e) Water Costs	(f) Sewer Costs
	gal	L	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	0	0	0	0	0	0	4800	18144	$10.16	$25.97
February	0	0	0	0	0	0	4800	18144	$10.16	$25.97
March	0	0	0	0	0	0	4800	18144	$10.16	$25.97
April	382	1443	382	1443	305	1155	8245	31164	$20.32	$44.60
May	1029	3888	1029	3888	823	3110	7727	29209	$18.79	$41.80
June	1883	7119	1883	7119	1507	5695	7043	26624	$16.78	$38.10
July	2868	10841	2290	8656	1832	6925	6718	25394	$15.82	$36.34
August	2129	8046	2129	8046	1703	6437	6847	25882	$16.20	$37.04
September	755	2854	755	2854	604	2283	7946	30036	$19.44	$42.99
October	0	0	0	0	0	0	4800	18144	$10.16	$25.97
November	0	0	0	0	0	0	4800	18144	$10.16	$25.97
December	0	0	0	0	0	0	4800	18144	$10.16	$25.97
Total									$168.29	$396.69

Note: Column (a) represents the irrigation demand from column (f) of Table 3.2. Column (b) represents the actual amount of greywater reused for landscape irrigation purposes. Column (c) represents the amount of potable water actually replaced. Since the irrigation efficiency of a greywater reuse system (40%) is less than a traditional irrigation system (50%), the amount of potable water actually replaced is 80% of the amount of greywater reused. Column (d) is based on average consumption rates minus the amount of potable water usage replaced by greywater. Columns (e) and (f) are based on local water and sewer rates.

Since the average monthly production of greywater is 2,290 gal, Table 3.13 shows that the average irrigation requirement for a 1000 square foot landscape planting could be met using greywater during the dry season in a typical household. However, potable water will be needed to supplement irrigation demand occasionally during peak irrigation need (e.g., July). Therefore, the water and sewer fees for a residential customer using greywater to irrigate a 1000 square foot landscape would be $564.98 per year. This results in a savings of $56.64 per year. Of course, any landscape irrigation on other parts of the property would still be met using potable water and would not affect these savings calculations.

The design life for this system is 50 years; therefore, these savings would be realized over a 50-year period. The present value of an annualized amount is calculated using a discounting factor:

$$P/A = (((1 + i)^{n} - 1))/(i * (1 + i)^{n}) \quad \text{(Eq. 3.5)}$$

where P is present value, A is annual savings, n is number of years, and i is interest rate. In this scenario, the design life of the project is 50 years, and it was assumed that the interest rate over this period is 3%. Thus, the P/A factor is:

$$P/A = (((1 + 0.03)^{50} - 1))/(0.03 * (1 + 0.03)^{50}) = 25.7298$$

Consequently, the present value of $56.64 per year for 50 years is:

25.7298 * $56.64 = $1,457.34

Using the Consumer Price Index (CPI), prices in 2002 needed for input to the EIO-LCA are 1.08 times higher than prices in 1999 (cost and usage data). In other words, the rate of inflation over this time period is 2.67% per year. So, the present value of the savings, stated in 2002 U.S. dollars is $1,573.9, which is the value used in the economic input-output model. This amount was scaled up to include 1,000 homes resulting in $1.573 million saved for the 1,000 homes over 50 years. These savings are used in the EIO-LCA to represent the reduced construction and operation expenditures in the municipal water supply and wastewater treatment sector (and consequent energy use and emissions).

3.1.2.2.2 Life Cycle Assessment: Use Phase for Scottsdale

The average annual water use for a typical household in Scottsdale is 184.9 kgal (Mayer et al. 1999) This translates into approximately 15.41 kgal per month. The water rates in Scottsdale are tiered with customers paying $1.22 for the first 6.00 kgal, and $1.89 for everything after that. So, the annual water bill for a traditional customer is:

$1.22 * 6.00 + (15.41 - 6.0) * $1.89 = $25.10 per month or $301.26 per year

The sewer rates in Scottsdale are $1.18 per kgal of water use. Consequently, a traditional customer pays:

$1.18 * 15.41 = $18.18 per month or $218.21 per year

So, the total water and sewer fees for a Scottsdale resident are $519.47 per year. However if a homeowner installs a greywater reuse system, these yearly expenses can be reduced. Mayer et al. (1999) also found that of the 81.4 gpcd used indoors, 31.05 gpcd or 2.17 kgal per month produces acceptable (i.e., excluding toilets and kitchen sinks) greywater sources in Scottsdale.

The irrigation demand was calculated in Section 3.1.1 (Table 3.3). Table 3.14 displays the amount of greywater, on average, that can be used for landscape irrigation for a given month.

Table 3.14 – Water and Sewer Fee Calculations for Typical Customers Using the Simple Greywater Reuse System in Scottsdale

Month	Irrigation Demand		Amount Reused		Amount Replaced		Total Amount Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	375	1419	375	1419	300	1135	15110	57115	$24.54	$17.83
February	509	1923	509	1923	407	1538	15003	56712	$24.34	$17.70
March	1016	3840	1016	3840	813	3072	14597	55178	$23.57	$17.22
April	1738	6570	1738	6570	1390	5256	14020	52994	$22.48	$16.54
May	2113	7986	2113	7986	1690	6389	13720	51861	$21.91	$16.19

June	2412	9117	2170	8203	1736	6562	13674	51688	$21.82	$16.14
July	2014	7612	2014	7612	1611	6090	13799	52160	$22.06	$16.28
August	1761	6655	1761	6655	1409	5324	14001	52925	$22.44	$16.52
September	1382	5225	1382	5225	1106	4180	14304	54070	$23.01	$16.88
October	1119	4229	1119	4229	895	3383	14515	54867	$23.41	$17.13
November	582	2198	582	2198	465	1759	14945	56491	$24.23	$17.63
December	320	1210	320	1210	256	968	15154	57282	$24.62	$17.88
Total									$278.43	$203.95

Note: Column (a) represents the irrigation demand from column (f) of Table 3.2. Column (b) represents the actual amount of greywater reused for landscape irrigation purposes. Column (c) represents the amount of potable water actually replaced. Since the irrigation efficiency of a greywater reuse system (40%) is less than a traditional irrigation system (50%), the amount of potable water actually replaced is 80% of the amount of greywater reused. Column (d) is based on average consumption rates minus the amount of potable water usage replaced by greywater. Columns (e) and (f) are based on local water and sewer rates.

Table 3.14 also shows the amount a greywater user would pay throughout the year with the simple greywater reuse system. This system would save approximately $37.09 per year in water and sewer fees. After adjusting for inflation to 2002 dollars, these savings over a 50-year design life with 1000 houses yields $1.03 million. These savings are used in the EIO-LCA to represent the reduced construction and operation expenditures in the municipal water supply and wastewater treatment sector (and consequent energy use and emissions).

3.1.2.2.3 Life Cycle Assessment: Use Phase for Omaha

From the Metropolitan Utilities District (MUD) website, the average residential customer uses approximately 96.0 kgal per year. The average resident with a 5/8” service line is charged $5.12 per month service fee (http://www.mudomaha.com/rates/rates.html). MUD charges $1.26 for every kgal throughout the year, but charges $1.76 for every kgal above 6.7 kgal used in June through October. The average indoor use in Omaha is 5.3 kgal per month throughout the year. In November through March, no irrigation is needed, so use is assumed to be for indoor uses. The usage rate for November through March is 5.3 kgal per month which is equivalent to the average indoor use in Omaha. Usage in excess of 5.3 kgal per month is assumed to be for outdoor uses (e.g., landscape irrigation) for the rest of the year. With these considerations, the average MUD customer pays $190.52 per year in water fees. MUD charges residential customers a flat rate of $9.19 per month or $110.28 per year for sewer fees. Since there are no apparent cost savings for reduced wastewater production, that can be related to reduced sewer construction and operations expenditures, Scottsdale's sewer rates are used to calculate monetary sewer savings derived from greywater reuse water savings. The sewer rate in Scottsdale is $1.18 per kgal, which is comparable to Omaha's flat rate. This results in $113.28 per year in Omaha, which is very close to the existing average in Omaha of $110.28 per year. So, based on this assumption, the average residential customer in Omaha would pay $303.80 per year in water and sewer fees. Table 3.15 shows the savings of a customer implementing the greywater reuse system in Omaha using the irrigation demand calculated in the Section 3.1.1.

Table 3.15 – Water and Sewer Fee Calculations for Typical Customers Using the Simple Greywater Reuse in Omaha

Month	Irrigation Demand		Amount Reused		Amount Replaced		Total Amount Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	0	0	0	0	0	0	5300	20034	$11.80	$6.25
February	0	0	0	0	0	0	5300	20034	$11.80	$6.25
March	1106	4180	1106	4180	885	3344	4415	16690	$10.68	$5.21
April	1926	7280	1926	7280	1541	5824	8389	31712	$15.69	$9.90
May	2252	8512	2252	8512	1801	6810	8129	30726	$15.36	$9.59
June	2482	9383	2360	8921	1888	7137	8042	30399	$15.93	$9.49
July	2222	8399	2222	8399	1778	6719	8152	30816	$16.12	$9.62
August	2346	8867	2346	8867	1877	7093	8053	30442	$15.95	$9.50
September	1619	6120	1619	6120	1295	4896	8635	32640	$16.97	$10.19
October	1245	4705	1245	4705	996	3764	8934	33771	$17.50	$10.54

November	0	0	0	0	0	0	5300	20034	$11.80	$6.25
December	0	0	0	0	0	0	5300	20034	$11.80	$6.25
Total									$171.39	$99.06

Note: Column (a) represents the irrigation demand from column (f) of Table 3.2. Column (b) represents the actual amount of greywater reused for landscape irrigation purposes. Column (c) represents the amount of potable water actually replaced. Since the irrigation efficiency of a greywater reuse system (40%) is less than a traditional irrigation system (50%), the amount of potable water actually replaced is 80% of the amount of greywater reused. Column (d) is based on average consumption rates minus the amount of potable water usage replaced by greywater. Columns (e) and (f) are based on local water and sewer rates.

So, the average residential customer who implements the simple greywater reuse system saves $33.35 in water and sewer fees per year. After adjusting to 2002 dollars, these savings over a 50-year design life with 1000 houses yields $0.712 million. These savings are used in the EIO-LCA to represent the reduced construction and operation expenditures in the municipal water supply and wastewater treatment sector (and consequent energy use and emissions).

3.1.2.2.4 Life Cycle Assessment: Use Phase for Tampa

The average annual use for a typical household in Tampa is 80.6 kgal (Mayer et al. 1999). This study also found the water rates to be $1.20 for the first 9.72 kgal and $1.95 after that. The sewer rates are $3.72 per kgal of water used. Thus, the average residential customer who uses 80.6 kgal or 6.72 kgal per month pays:

$$6.72 * \$1.20 + 6.72 * \$3.72 = \$33.06 \text{ per month or } \$396.75 \text{ per year}$$

Table 3.16 shows the water and sewer fees for a simple greywater reuse system in Tampa.

Table 3.16 – Water and Sewer Fee Calculations for Typical Customers Using the Simple Greywater Reuse in Tampa

Month	Irrigation Demand		Amount Reused		Amount Replaced		Total Amount Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	600	2267	600	2267	480	1814	6240	23588	$7.49	$23.21
February	222	840	222	840	178	672	6542	24730	$7.85	$24.34
March	992	3751	992	3751	794	3001	5926	22401	$7.11	$22.04
April	2879	10881	2100	7938	1680	6350	5040	19051	$6.05	$18.75
May	2429	9182	2100	7938	1680	6350	5040	19051	$6.05	$18.75
June	3	11	3	11	2	9	6718	25393	$8.06	$24.99
July	10	36	10	36	8	29	6712	25373	$8.05	$24.97
August	0	0	0	0	0	0	6720	25402	$8.06	$25.00
September	2	6	2	6	1	5	6719	25397	$8.06	$24.99
October	1574	5950	1574	5950	1259	4760	5461	20641	$6.55	$20.31
November	1229	4645	1229	4645	983	3716	5737	21686	$6.88	$21.34
December	439	1659	439	1659	351	1327	6369	24075	$7.64	$23.69
Total									$87.87	$272.39

Note: Column (a) represents the irrigation demand from column (f) of Table 3.2. Column (b) represents the actual amount of greywater reused for landscape irrigation purposes. Column (c) represents the amount of potable water actually replaced. Since the irrigation efficiency of a greywater reuse system (40%) is less than a traditional irrigation system (50%), the amount of potable water actually replaced is 80% of the amount of greywater reused. Column (d) is based on average consumption rates minus the amount of potable water usage replaced by greywater. Columns (e) and (f) are based on local water and sewer rates.

So, a resident implementing the simple greywater reuse system in Tampa would save approximately $36.49 in water and sewer fees every year. After adjusting to 2002 dollars, these savings for 1,000 houses over a 50-year design life yields $1.01 million. These savings are used in the EIO-LCA to represent the reduced construction and operation expenditures in the municipal water supply and wastewater treatment sector (and consequent energy use and emissions).

3.1.2.3 Waste or Disposal Phase

The purpose of this section is to determine the environmental impacts of the disposal of the materials used for the greywater reuse system. An assumption is made that none of the materials used in this design will be recycled. This is a reasonable assumption considering the pipes are made from PVC or ABS, and have little recyclable value. Local landfill rates were found for each of the study sites. Table 3.17 displays the landfill fees for each of the four study sites. The weight of the materials used in the design in each site was calculated and reported in column 5 of Table 3.17. Eq. 3.4 was used to find producer prices (column 3) from consumer prices (column 2). Column 4 shows the adjustment for inflation.

Table 3.17 – Landfill Fees for Disposal of Materials Used in Simple Greywater Reuse System

Site	2009 Consumer Price for Landfill fees (per ton)	2009 Producer Price for Landfill fees (per ton)	2002 Producer Price for Landfill fees (per ton)	Disposal Amount for 1000 homes (tons)	Total for 1000 homes (2002 U.S. dollars)
Seattle	$102.05	$89.91	$75.42	277	$20,890
Scottsdale	$37.00	$32.60	$27.34	248	$6,780
Omaha	$23.12	$20.37	$17.09	290	$4,960
Tampa	$41.00	$36.12	$30.30	277	$8,390

The values in column six of Table 3.17 are used in the EIO-LCA to represent the increase of expenditures and the consequent construction, energy, and emissions for the disposal sector.

3.2 Model 2 - Development of an EIO-LCA for an Indoor Greywater Reuse System with Treatment

This system is composed of greywater collection, treatment, and distribution to toilets and laundry machines. A collection system was designed to capture greywater from bathroom sinks, tubs, and showers. This collected greywater is then treated, stored, and used as needed for toilet flushing and clothes washing. The usage rates for the fixtures were for high-efficiency fixtures from the LEED for Homes rating system. High-efficiency fixtures were used for this system because it was assumed that home owners who would invest in a complex greywater reuse system would also install high-efficiency fixtures. In this system, no greywater is used outdoors for landscape irrigation. Since the entire system is indoors, the design and required materials for this design are exactly the same for each of the four study sites. Consequently, only one EIO-LCA is necessary for this analysis. The usage rates, water cost savings, and sewer cost savings for all four sites were calculated and averaged across the four study sites. The average savings were used in the assessment.

3.2.1 Calculation of Greywater Production

Mayer et al. (1999) gave average uses for residences in each of the four study site cities. These usage rates were used with updated fixture water rates from the LEED for Homes rating system. Table 3.18 displays updated greywater production rates for each of the four study sites as well as the average for the four sites. For this design, greywater from laundry machines was not included as a source for greywater because the other sources (bathroom sinks, tubs, and showers) already exceeded the non-potable indoor demand (i.e., toilet flushing and laundry washing).

Table 3.18 – Greywater Production Calculation Using High-Efficiency Water Fixtures

Study Site	Seattle	Scottsdale	Omaha	Tampa	Average
Mean persons per household	2.8	2.4	2.3	2.8	2.6
Toilet flushes per capita per day	4.5	4.9	5.1	5.1	4.9
Toilet flush volume, gpcd (Lpcd)	5.8 (22.0)	6.3 (23.8)	6.7 (25.4)	6.6 (25.0)	6.4 (24.2)
Shower uses per capita per day	0.8	0.7	0.8	0.8	0.8
Showers & bath usage per capita per day (min)	7.9	8.2	7.9	8.2	8.1
Shower water volume, gpcd (Lpcd)	11.9 (45.0)	11.5 (43.5)	13.0 (49.2)	12.3 (46.6)	12.2 (46.2)

Clothes washer uses per capita per day	0.3	0.4	0.4	0.4	0.4
Clothes washer volume, gpcd (Lpcd)	4.5 (17.0)	5.3 (20.1)	5.3 (20.1)	5.5 (20.8)	5.2 (19.7)
Faucet usage per capita per day (min)	1.9	2.6	2.3	2.2	2.3
Faucet volume, gpcd (Lpcd)	2.5 (9.5)	3.4 (12.9)	3.1 (11.7)	3.0 (11.4)	3.0 11.4)
Greywater produced, gpd (Lpd)	40.2 (152.2)	35.8 (135.5)	37.0 (140.0)	42.7 (161.6)	38.9 (147.2)
Non-potable water used gpd (Lpd)	28.8 (109.0)	28.0 (106.0)	27.6 (104.5)	33.8 (127.9)	29.6 (112.0)

Note: Toilets were calculated as 1.3 gpf. Showers were calculated based on a rate of 2 gpm. Faucets were calculated based on an average rate of 1.34 gpm. Clothes washers were calculated based on energy star appliances with an average water usage of 14.85 gallons per load.

3.2.2 Treatment System Design

In order to be used for toilet flushing and laundry washing, the greywater needs to meet the EPA's non-potable water quality requirements. There are many treatment systems available that could meet these requirements. However, the design used for this study is a biofilter followed by a Membrane Bioreactor (MBR). The biofilter consists of ground tires and removes 50-70% of the BOD (which saves energy) and much of the suspended solids from the greywater (Hu, 2011). There is also a disposal issue with tires, so the use of ground tires for treatment is a good use of a material that would otherwise most likely be landfilled (Hu, 2011). The MBR then treats the remaining total suspended solids, turbidity, remaining BOD, and pathogens. Figure 3.4 displays a schematic of the biofilter. Figure 3.5 displays a process schematic for the MBR.

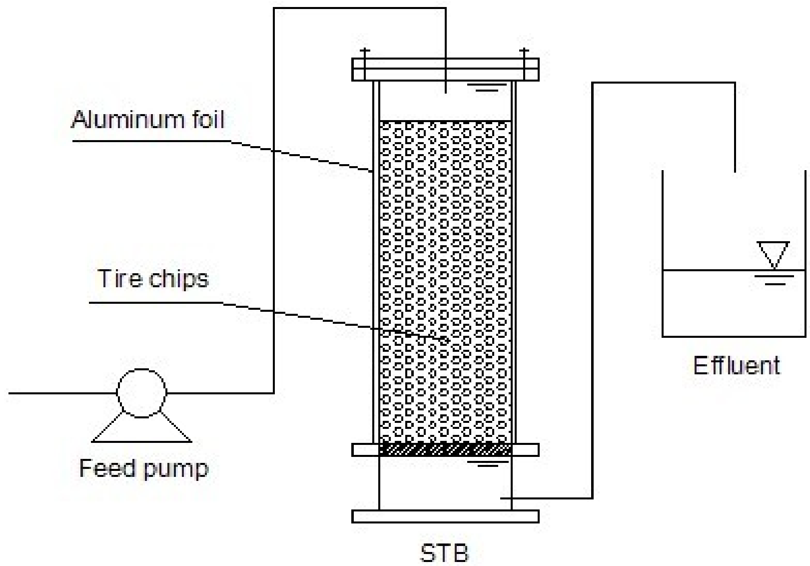


Figure 3.4 – Schematic of Biofilter

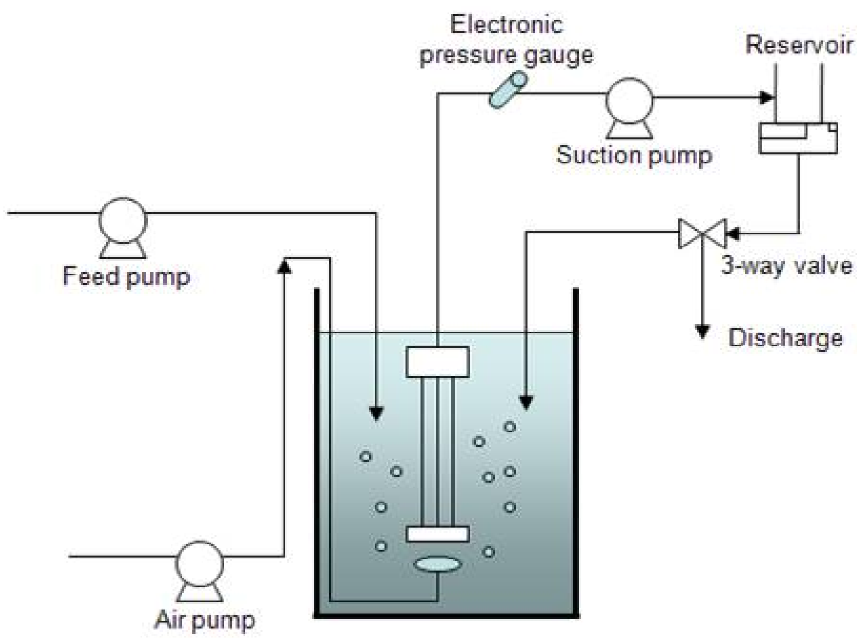


Figure 3.5 – Schematic of MBR

3.2.2.1 Life Cycle Assessment: Manufacturing of Materials Phase

The greywater reuse system design includes a collection system, a treatment system, and a delivery system. The delivery system is not included in the LCA because a similar delivery system is required in a house with no greywater reuse. The necessary materials include pumps, tanks, collection pipes, distribution pipes, pipe fittings, PEX manifolds, and treatment system materials. Table 3.19 displays a list of all materials included in this design as well as their associated prices. Since the same floor plan was used for all four sites, the required materials are identical in all four study sites. As in the previous section, the producer price is calculated from Eq. 3.4 from the retail price.

Table 3.19 – Materials Required for Indoor Greywater Reuse Design

Materials	Unit Price	Unit	Quantity	Total Price	Producer Price
1/2" PEX Pipe	$0.23	LF	127	$29.21	$22.00
2" ABS Pipe	$1.71	LF	109	$186.39	$140.35
2" PVC T-intersections	$2.49	EA	7	$17.43	$13.12
2" 90 degree elbows	$1.68	EA	7	$11.76	$8.86
PEX Manifold	$12.95	EA	1	$12.95	$12.05
MBR membranes	$50.00	EA	4	$200.00	$150.60
Biofilter - plastic	$17.00	LF	4	$68.00	$51.20
Biofilter - ground tires	$0.00	EA	1	$0.00	$0.00
Pump 1 - supply pump	$693.00	EA	1	$693.00	$488.565
Pressure Tank	$127.00	EA	1	$127.00	$105.263
Pump 2 - aerator pump	$111.99	EA	1	$111.99	$78.953
Pump 3 - MBR pump	$58.00	EA	1	$58.00	$40.890
Tank 1 -75 gal	$122.01	EA	1	$122.01	$100.10
Tank 2 - 65 gal	$114.76	EA	1	$114.76	$94.15
Backflow valve	$56.90	EA	1	$56.90	$43.40
Total				**$1,809.40**	**$1,349.50**

Note: Units prices shown are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), Ludwig (2009), and local suppliers.

The majority of the producer prices are in 2009 dollars. However, some are in 2004 U.S. dollars. They are all converted to 2002 U.S. dollars using the CPI index (www.bls.gov). Table 3.20 shows the value of the materials in 2002 U.S. dollars used in the LCA and their associated EIO-LCA sectors.

Table 3.20 – 2002 Producer Prices for All Materials and Their Corresponding Sectors

Materials	Producer Price[(a)]	2002 Producer Price	EIO-LCA Sector
1/2" PEX Pipe	$22.00	$20.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" ABS Pipe	$140.35	$133.33	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC T-intersections	$13.12	$12.47	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 90 degree elbows	$8.86	$8.41	326122 Plastics Pipe and Pipe Fitting Manufacturing
PEX Manifold	$12.05	$10.00	33142 Copper Rolling, Drawing, Extruding, and Alloying
MBR membranes	$150.60	$125.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
Biofilter - plastic	$51.20	$42.50	326122 Plastics Pipe and Pipe Fitting Manufacturing
Biofilter - ground tires	$0.00	$0.00	32629 Other Rubber Product Manufacturing
Pump 1 - supply pump	$488.565	$405.51	333911 Pump and Pumping Equipment Manufacturing
Pressure Tank	$105.263	$87.37	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Pump 2 - aerator pump	$78.953	$65.53	333911 Pump and Pumping Equipment Manufacturing
Pump 3 - MBR pump	$40.890	$33.94	333911 Pump and Pumping Equipment Manufacturing
Tank 1 -75 gal	$100.10	$83.08	326121 Unlaminated Plastics Profile Shape Manufacturing
Tank 2 - 65 gal	$94.15	$78.14	326121 Unlaminated Plastics Profile Shape Manufacturing
Backflow valve	$43.40	$36.02	33291 Metal Valve Manufacturing

Note: (a) Values are in either 2004 or 2009 U.S. dollars.

3.2.2.2 Life Cycle Assessment: Use Phase for Indoor Greywater Reuse System

During the use phase, water is saved through the reuse of treated greywater. On average, 38.9 gpd of greywater is produced from showers, bathtubs, and bathroom sinks. This water is treated and used for toilet flushing and laundry washing. Since the greywater supply is greater than the non-potable demand, essentially the total demand should be met by greywater. A reuse efficiency of 95% is assumed for this analysis resulting in the reuse of approximately 29.6 gpd of greywater or 10,800 gallons per year.

Since the water rate structures are different in each of the study site cities, the water and sewer savings were calculated for each of the cities and then averaged. Table 3.21 displays the average water and sewer savings for the four study sites. The final column represents the present value of the savings for 1,000 houses over 50 years stated in 2002 U.S. dollars. This value was used as the input into the EIO-LCA model. The EIO-LCA sectors used are 22131 Water Supply and 22132 Sewage Treatment Facilities.

Table 3.21 – Four-Study-Site Average Water and Sewer Savings from Indoor Greywater Reuse

	1999 U.S. Dollars[(a)]	2002 U.S. Dollars per house per year	Total EIO-LCA Model Input (2002 U.S. $)[(b)]
Water Cost Savings	$19.56	$21.13	$543,605.64
Sewer Cost Savings	$28.81	$31.11	$800,579.54
Total Cost Savings	$48.37	$52.24	$1,344,185.18

Note: Based on 10,800 gallon (40,900L) of greywater used per year.
(a) Based on a site calculating the savings over all four sites, and averaging the savings.
(b) Based on 1,000 houses over a 50-year design life

One of the main differences between this design and the previous design using greywater to irrigate landscape plants is that this design requires treatment of the greywater for indoor reuse. This treatment requires energy to run the pumps. The design calls for 3 pumps. The first pump supplies the necessary pressure to move water through the MBR and into the storage tank. The second pump aerates the MBR tank. The third pump supplies the necessary head to move treated water to its end use. The required energy to run the two water pumps (i.e., first and third pumps) for the year is calculated using Eq. 3.6.

$$P = Q * h * \gamma / \eta \quad \text{(Eq. 3.6)}$$

where P is power (kW), Q is flow rate (cms), h is head (m), γ is specific weight of water 1000 kg/m^3, and η is the pump efficiency. The amount of time the pump will run throughout the year is calculated next using Eq. 3.7.

$$T = V / Q \quad \text{(Eq. 3.7)}$$

where T is time in hours, and V is volume of water pumped in m^3, and Q is flow rate in m^3 per hour. The required pump power is then multiplied by the required time giving the amount of electricity consumed by each pump. The MBR pump requires 1.6 kWh of electricity for the year, and the supply (delivery) pump requires 1.9 kWh of electricity for the year. The aerator pump's required energy is calculated using Eq. 3.8.

$$P_w = \frac{wRT_0}{8.41e}\left[\left(\frac{P}{P_0}\right)^{0.283} - 1\right] \quad \text{(Eq. 3.8)}$$

where P_w is power requirement for the aerator pump in kW, w is air mass flow rate in kg/s, R is the universal gas constant, T_0 is inlet temperature in degrees Kelvin, P is absolute outlet pressure, P_0 is absolute inlet pressure, and e is the efficiency of the aerator pump (Qasim, 1985). The aerator pump needs to run all the time, so this power requirement is multiplied by 24 hours/day and 365 days/year to give the amount of electricity consumed by this pump in a year. This pump consumes 510 kWh of electricity. The three pumps altogether require 513.5 kWh of electricity for operation throughout the year. The first two pumps probably require slightly more energy than what was calculated due to inefficiencies in the system, but since they are small in comparison with energy requirement of aerator pump, this was ignored.

In January of 2010, the average retail price for electricity was 10.54 cents per kilowatt-hour. Thus, it currently would cost $54.12 dollars to operate the pumps for the year. For the EIO-LCA, the average wholesale price of electricity in 2002 was 3.56 cents per kilowatt-hour. This value was discounted over the 50 year design life of the project and over 1000 houses. Thus, the input price for the EIO-LCA in the Power Generation and Supply sector is:

$0.0356 / kWh * 513.5 kWh * 1000 houses * 25.7298 = $0.470 million

3.2.2.3 Life Cycle Assessment: Disposal of Materials Phase

The landfill prices for each of the four sites in our study were averaged. This average was used as the input for the EIO-LCA. The weight of each material used in the design was estimated. The weight of all material was then summed, and the total price for disposal equals the total weight times the average landfill price. Table 3.22 shows the materials and their corresponding weights.

Table 3.22 – Weight of Materials Used in Design

Materials	Unit	Quantity	Weight (lbs.)
1/2" PEX	LF	127	4.445
2" ABS	LF	109	77.39
T-intersections	EA	7	1.75
Elbows	EA	7	1.75
PEX Manifold	EA	1	2
1 Module with 4 MBR membranes	EA	4	3.52
Biofilter - plastic	LF	4	30.2
Biofilter - ground tires	EA	1	15
Pump 1 - supply pump	EA	1	31
Pressure Tank	EA	1	15
Pump 2 - aerator pump	EA	1	7
Pump 3 - MBR pump	EA	1	10
Tank 1 -75 gal	EA	1	28
Tank 2 - 65 gal	EA	1	25
Backflow valve	EA	1	1
Total			**253.1**

This total is then multiplied by 1000 since the LCA is based on 1,000 households. The average landfill price is $50.79 per ton of waste disposed in a landfill. Thus, after adjusting to 2002 U.S. dollars, the disposal cost is $5,398 for 1000 houses. This value was used as an input into the 562212 Solid Waste Landfill sector in the EIO-LCA model.

3.2.3 Best Case Scenario Evaluation

The indoor treatment system has a capacity of 83.4 gallons per day. If a reuse efficiency of 95% is assumed as in Section 3.2.2.2, it is possible to re-use 79.2 gallons of greywater per day. If the homeowner uses most of a portion of this indoors, and uses a hose or something to water the landscape (any use that uses the entire amount throughout the year), it is possible to reuse 28,919 gallons per year. This water could be supplied with a sprinkler as well, because it has been treated. Assuming a site-average of $1.81 per kgal for water, and $2.67 per kgal for wastewater (same as Section 3.2), it is possible to save approximately $129.56 per year with this system.

In this case, the energy costs would also be higher. The energy for aeration would remain the same, as the aerator pump runs all of the time anyway. However, the energy required for the supply pumps would increase, and the total required for electricity would be approximately $55.11, leaving a savings of $74.45 per year.

The difference between the actual design system and the hypothetical scenario is the amount of greywater produced and reused. In Section 3.2.1, it was assumed that a homeowner who employs a water reuse system would also have water efficient appliances. This may or may not be the case. However, it would take more than the average household (approximately 2.8 people) and inefficient appliances to produce the assumed amount of greywater.

3.3 Model 3 - Development of an EIO-LCA for a Hybrid Greywater and Rainwater Reuse System

This system includes the reuse of both rainwater and greywater. Rainwater has better water quality than greywater, but is less reliable and, therefore, requires a larger storage tank. Thus, the goal of this design is to combine the two sources and take advantage of the benefits of each. This system will use greywater to irrigate a portion of the landscape. Rainwater will be used for indoor uses such as toilet flushing and laundry washing since it has higher quality than greywater. Excess rainwater will also be used for landscape irrigation, car washing, or any other non-potable use at the discretion of the residents. Because of the good water quality of the rainwater, this system will not require any treatment other than the filtration in the downspouts and first flush diverters (to exclude pollutants that may have accumulated on catchment surfaces such as roofs).

The greywater production quantities for each of the sites are discussed in Section 3.2. This design incorporates the LEED high-efficiency fixtures used in the previous indoor greywater reuse design (United States Green Building Council 2008).

3.3.1 Calculation of Irrigation Demand for Greywater Irrigation System

The irrigation demands for each of the four sites were calculated in Section 3.1.1. As with the previous design, the landscape was sized so that the average greywater production meets the average dry season demand. Table 3.23 displays the average greywater production and the corresponding landscaped areas for each of the sites. Table 3.23 also displays the amount of area planted to turfgrass in the lawn. This area is calculated by subtracting landscaped area irrigated by greywater and the building footprint area including the driveway from the total lot area.

Table 3.23 – Irrigated Area Calculation for the Four Sites

Site	Average amount of greywater produced per month		Area Irrigated by Greywater		Area Irrigated by Rainwater[(a)]	
	gal	L	ft^2	m^2	ft^2	m^2
Seattle	1580	5980	690	64	4415	410
Scottsdale	1480	5602	200	19	4905	456
Omaha	1740	6586	1050	98	4055	377
Tampa	1460	5526	700	65	4405	409

Note: (a) Supplemented with potable water as needed

3.3.2 Design of Rainwater Capture System

The rainwater cistern needs to capture as much rainwater as possible for toilet flushing, laundry washing, and landscape irrigation in a cost effective way. The area assumed to be turfgrass is the entire lot area minus house area, porch area, garage area, driveway, and area irrigated by the greywater irrigation system. The turfgrass areas for Seattle, Scottsdale, Omaha, and Tampa are 4415, 4905, 4055, and 4405 square feet, respectively. The collection area (i.e., area of roof) for the design house is 2171 square feet. However, not all of the water that falls on the roof will be captured. Some water will be captured in the first flush diverters, some will overflow the gutters, and some will evaporate. For this study, the capture efficiency is assumed to be 90%. The Texas Rainwater Harvesting Manual (Brown et al. 2005) recommends a value between 85-90%.

90% was assumed for this project because pipes and gutters are adequately sized. The indoor usage rates (i.e., for toilet flushing and laundry washing) were calculated in the Section 3.2. The excess rainwater will be used to irrigate the turfgrass in the lawn. In order to insure that there is always water available for toilet flushing and landscape irrigation, each cistern has a back-up potable water connection. In this study, the back-up begins to run when the water level falls below the 5% full mark and continues to run until the cistern is 10% full.

The optimum cistern size was determined by trading off the percentage of rainwater captured and the payback period. The Rainwater Harvester program (North Carolina State University, 2010) was used to determine the percent of rainwater captured in a given year for various cistern sizes. Historic daily rainfall data were found for each of the sites to run the model. The model calculates the water level or storage in the tank at the end of each day. The payback period was calculated from the tank cost and the savings from reduced water use.

The optimum cistern size was determined from a weighted average of the two goals (criteria) of maximizing the percent water captured (PWC) and minimizing the pay-back period (PBP). The values of the criteria (PWC and PBP) for various sizes of tanks were first normalized using the following relationship:

$$c_i = |(V_i - V_{worst})/(V_{best} - V_{worst})| \quad \text{(Eq. 3.9)}$$

where: c_i = normalized value of criterion i (either PWC or PBP); V_i = the actual criterion value for tank size i; V_{worst} = the worst criterion value over all tank sizes; and V_{best} = the best criterion value over all tank sizes. The normalized criterion values are then traded-off using the following relationship to determine the optimum tank size:

$$Z_i = w_{PWC} \times c_{PWC,i} + w_{PBP} \times c_{PBP,i} \quad \text{(Eq. 3.10)}$$

where: Z_i is the trade-off value for tank size i; w_{PWC} and w_{PBP} are relative weights for the two criteria (equal values of 0.5 were used); and c_{PWC} and c_{PBP} are the normalized values of the criteria for tank size i. The tank size that produced the highest value for Z_i is the optimum-sized tank. The analysis resulted in 2500 gal tanks for all four sites.

3.3.2.1 Sizing the Rainwater Cistern in Seattle

In Seattle, historic daily rainfall was retrieved from the Agweather website from Washington State University (www.weather.wsu.edu). Using this historic rainfall and water and sewer prices from Mayer's study (1999), the Rainwater Harvester model was used to find the optimum tank size (North Carolina State University, 2010). The tanks simulated had volumes of 500, 1000, 2000, 2500, 5000, and 10000 gallons. Using Equation 3.9 and the results of the simulations, a 2500 gallon cistern was chosen in Seattle.

The Rainwater Harvester model calculates the cistern storage volume at the end of each day. The rainfall from historic rainfall is the only water input. However, there are several uses or outputs. In Seattle, the indoor usage rate for toilets and laundry that was calculated in Section 3.2 is 28.8 gallons/day, so 28.8 gallons are withdrawn each day for toilet flushing and laundry washing. The irrigation needs for turfgrass were calculated using the model. The evapotranspiration data used was the same data from Section 3.1. An average silt loam soil was assumed for the Seattle area. Impact sprinklers (which have an irrigation efficiency of 75%) were assumed to be the irrigation application method. Figure B.1 in Appendix B displays the water level in the cistern over the modeled year.

Figure B.1 shows that the need for supplementing irrigation with potable water is minimal.

3.3.2.2 Sizing the Rainwater Cistern in Scottsdale

In Scottsdale, historic daily rainfall was retrieved for the Scottsdale Municipal Airport from the Natural Resources Conservation Service (NRCS, 2010). Using this historic rainfall and water and sewer prices from Mayer et al. (1999), the Rainwater Harvester model was used to determine the tank size. The tanks simulated had volumes of 500, 1000, 2000, 2500, and 5000 gallons. Using Equation 3.9 and the results of the simulations, a 2500 gallon cistern was chosen in Scottsdale.

In Scottsdale, the indoor usage rate for toilets and laundry washing that was calculated in Section 3.2 is 27.6 gallons/day, so 27.6 gallons are withdrawn each day for toilet flushing and laundry washing. The irrigation needs for turfgrass were calculated using the model. The evapotranspiration data used was the same data from Section 3.1. An average silt loam soil was assumed for the Scottsdale area. Impact sprinklers (which have an irrigation efficiency of 75%) were assumed to be the irrigation application method. Figure B.2 in Appendix B displays the water level in the cistern over the modeled year. Figure B.2 shows that the need for supplemental irrigation with potable water is substantial throughout the year.

3.3.2.3 Sizing the Rainwater Cistern in Omaha

In Omaha, historic daily rainfall was retrieved from the High Plains Regional Climate Center (http://www.hprcc.unl.edu). Using this historic daily rainfall and water and sewer prices from Mayer et al. (1999), the Rainwater Harvester model was used to determine the tank size. The tanks simulated had volumes of 500, 1000, 2000, 2500, and

5000 gallons. Using Equation 3.9 and the results of the simulations, a 2500 gallon cistern was chosen in Omaha.

In Omaha, the indoor usage rate for toilets and laundry washing that was calculated in Section 3.2 is 33.8 gallons/day, so 33.8 gallons are withdrawn each day for toilet flushing and laundry washing. The irrigation needs for turfgrass were calculated using the model. The evapotranspiration data used was the same data from Section 3.1. An average silt loam soil was assumed for the Omaha area. Impact sprinklers (which have an irrigation efficiency of 75%) were assumed to be the irrigation application method. Figure B.3 in Appendix B displays the water level in the cistern over the modeled year. Figure B.3 shows that little supplemental potable water is needed for irrigation purposes.

3.3.2.4 Sizing the Rainwater Cistern in Tampa

In Tampa, historic daily rainfall was retrieved from the Florida Climate Center. Using this historic daily rainfall and water and sewer prices from Mayer et al. (1999), the Rainwater Harvester model was used to determine the tank size. The tanks simulated had volumes of 500, 1000, 2000, 2500, 5000, and 10000 gallons. Using Equation 3.9 and the results of the simulations, a 2500 gallon cistern was chosen in Tampa.

In Tampa, the indoor usage rate for toilet flushing and laundry washing that was calculated in Section 3.2 is 28.0 gallons/day, so 28.0 gallons are withdrawn each day for toilet flushing and laundry washing. The irrigation needs for turgrass were calculated using the model. The evapotranspiration data used was the same data from Section 3.1. An average silt loam soil was assumed for the Tampa area. Impact sprinklers (which have an irrigation efficiency of 75%) were assumed to be the irrigation application method.

Figure B.4 in Appendix B displays the water level in the cistern over the modeled year. Figure B.4 shows that minimal supplemental potable water is needed for landscape irrigation.

3.3.3 Life Cycle Assessment: Materials Phase

Although no treatment is included in this design, the necessary materials are extensive for the collection, storage and use of greywater and rainwater. Excavation is also necessary for the underground cistern. The underground cistern has a diameter of 10 feet and a height of approximately 4.3 feet. In addition to the tank volume, it is conservatively assumed that the contractor will need to excavate 1' below the tank, and that the tank will be buried 3' on average at all sites. The resulting quantity of excavation needed for each rainwater cistern is 24 cubic yards. The 2002 Means Sitework and Landscape Cost Data book estimates excavation costs to be $1.73 per cubic yard. Thus, the overall cost of excavation for 1000 homes is $41,540 in 2002 U.S. dollars.

The indoor plumbing, rainwater collection, and rainwater storage cisterns are identified for all sites. Table 3.24 shows the common materials of the four sites. The four sites have somewhat different designs for the outdoor irrigation systems because of differing irrigation demands. Sections 3.3.3.1-3.3.3.4 describe the site-specific materials in greater detail.

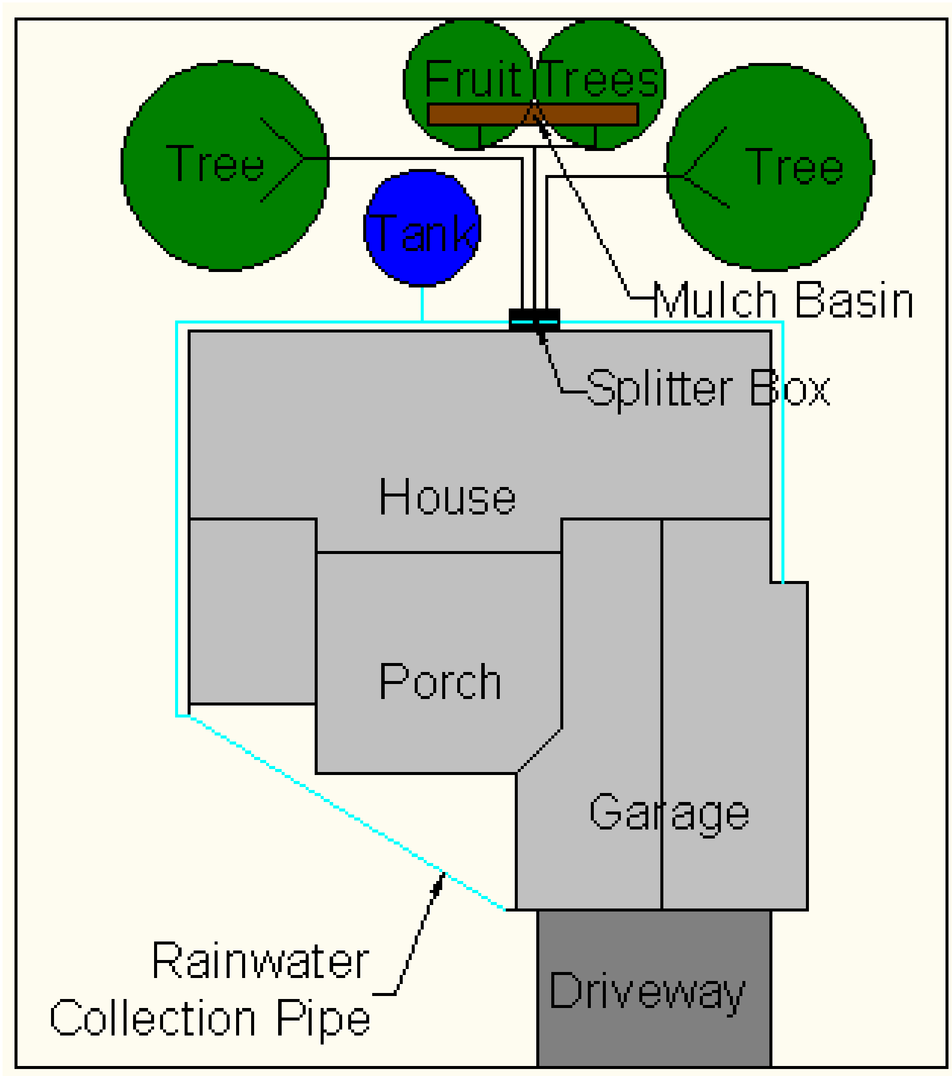
Table 3.24 – Common Materials used at all Sites in Hybrid Design

Materials	Unit Price	Unit	Quantity	Total Price	Sector
1" schedule 40 PVC pipe	$1.66	LF	6	$9.96	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 PVC pipe	$2.30	LF	115	$264.50	326122 Plastics Pipe and Pipe Fitting Manufacturing
1/2" PEX Pipe	$0.23	LF	164	$37.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC Tee	$2.07	EA	5	$10.35	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC Elbow	$1.97	EA	7	$13.79	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" schedule 40 PVC elbows	$6.10	EA	4	$24.40	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" schedule 40 PVC pipe	$3.77	LF	60	$226.20	326122 Plastics Pipe and Pipe Fitting Manufacturing
Downspout filter	$34.95	EA	4	$139.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
First flush diverter	$23.95	EA	4	$95.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
2500 gallon underground steel tank (7 gauge shell)	$2,625.00	EA	1	$2,625.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Pump 1 - supply pump	$693.00	EA	1	$693.00	333911 Pump and Pumping Equipment Manufacturing
Pressure Tank	$127.00	EA	1	$127.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
PEX Manifold	$12.95	EA	1	$12.95	33142 Copper Rolling, Drawing, Extruding, and Alloying
Backflow preventer (overflow valve)	$56.90	EA	2	$113.80	33291 Metal Valve Manufacturing

Note: Prices listed in Table 3.24 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

3.3.3.1 Life Cycle Assessment: Materials Phase for Hybrid Design in Seattle

In Seattle, a sub-surface outdoor greywater reuse system was designed to irrigate a 690 square foot landscape as shown in Figure 3.6. Site-specific materials for the water reuse system in Seattle are shown in Table 3.25.



Note: The total square roof surface area is 2171 square feet including the porch, garage, and house. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.6 – Landscape Irrigation Design for Hybrid Greywater Reuse System in Seattle

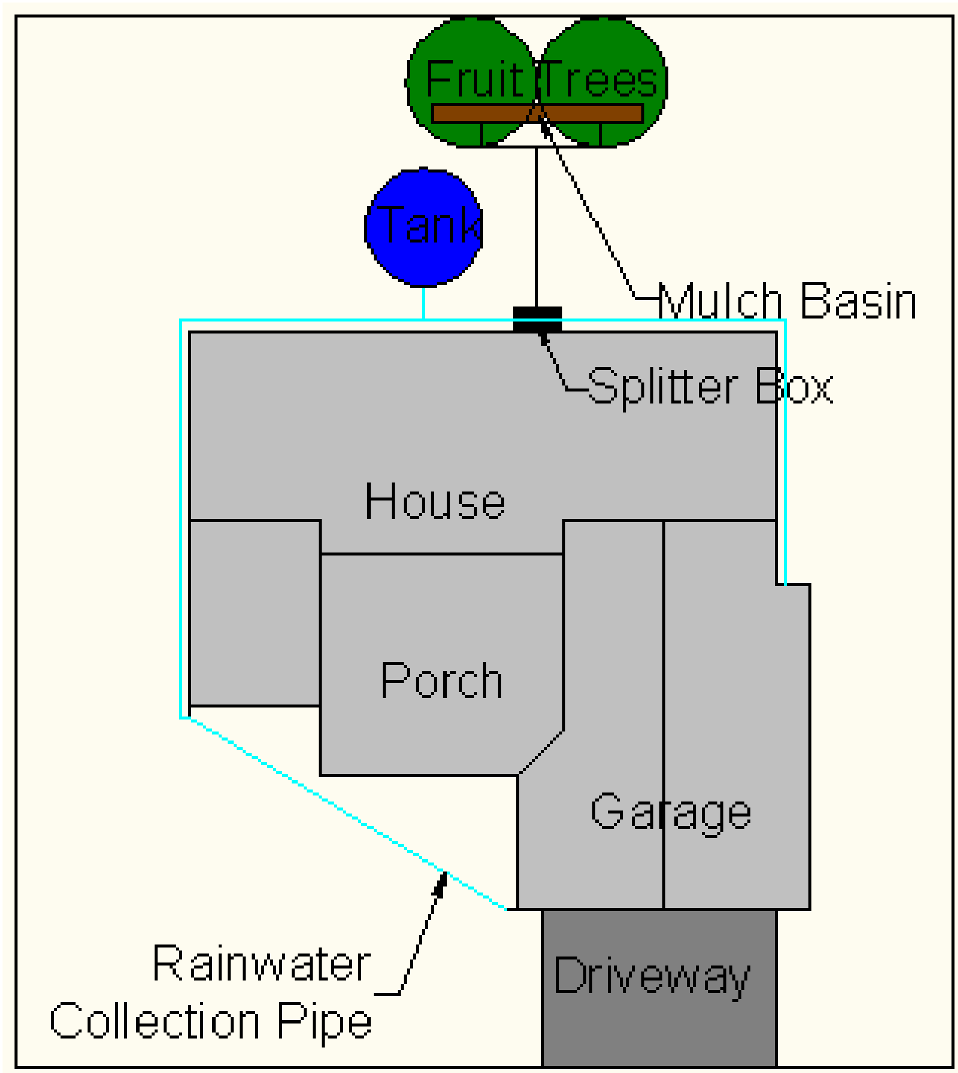
Table 3.25 – Materials in Seattle

Materials	Unit Price	Unit	Quantity	Total Price	EIO-LCA Sector
1 1/2" schedule 40 PVC	$1.97	LF	36	$70.92	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 PVC	$2.30	LF	70	$161.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC schedule 40 tees	$2.07	EA	3	$6.21	326122 Plastics Pipe and Pipe Fitting Manufacturing
Reducers (2-1 1/2)	$0.76	EA	3	$2.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 45 degree bend	$1.97	EA	4	$7.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 90 degree elbows	$1.68	EA	4	$6.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" PVC schedule 40 pipe	$3.77	LF	147	$554.19	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" PVC elbows schedule 40	$6.10	EA	4	$24.40	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" PVC Tees schedule 40	$13.55	EA	3	$40.65	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	326121 Unlaminated Plastics Profile Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	327390 Other Concrete Product Manufacturing
Total				**$1,004.25**	

Note: Prices listed in Table 3.25 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

3.3.3.2 Life Cycle Assessment: Materials Phase for Hybrid Design in Scottsdale

In Scottsdale, a sub-surface outdoor greywater reuse system was designed to irrigate a 200 square foot landscape (see Section 3.3.1) as shown in Figure 3.7. Site-specific materials for the water reuse system in Scottsdale are shown in Table 3.26.



Note: The total square roof surface area is 2171 square feet including the porch, garage, and house. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.7 – Landscape Irrigation Design for Hybrid Greywater Reuse System in Scottsdale

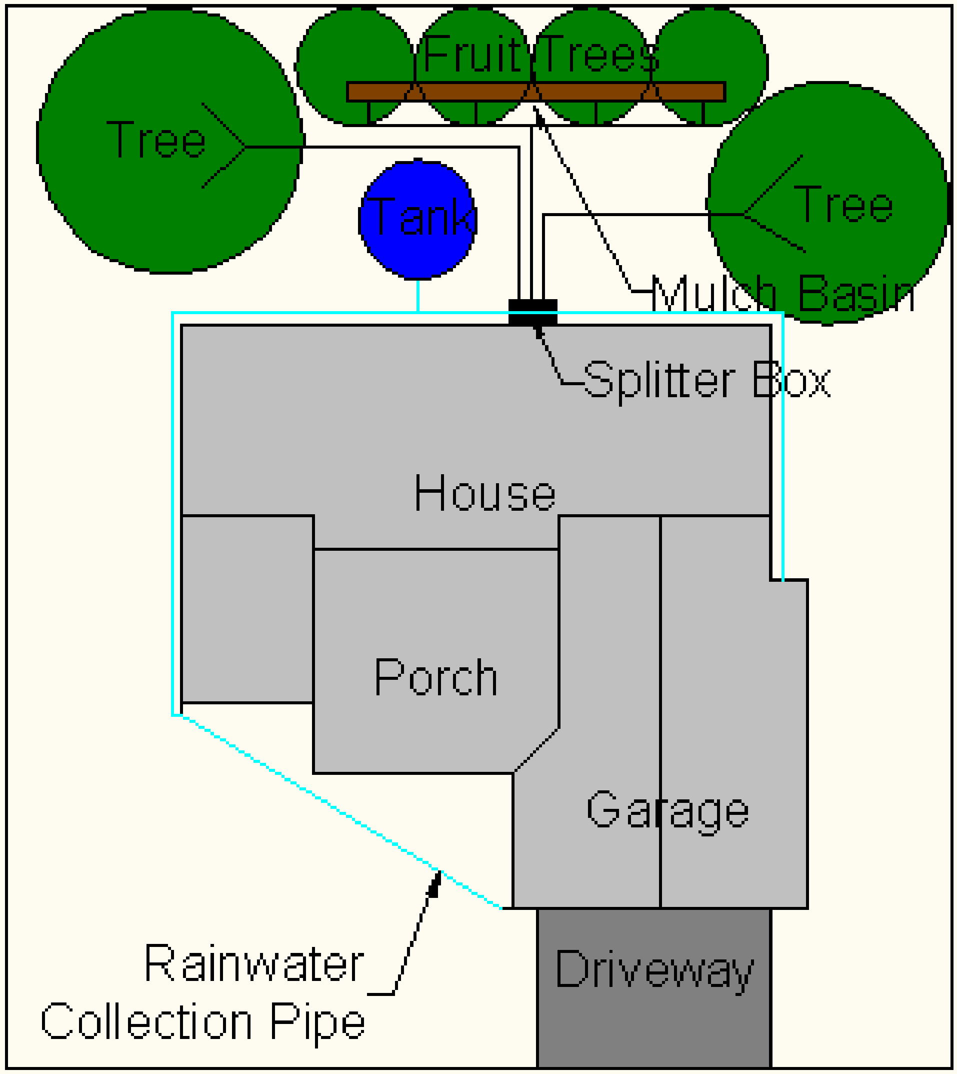
Table 3.26 – Materials in Scottsdale

Materials	Unit Price	Unit	Quantity	Total Price	Sector
1 1/2" schedule 40 PVC	$1.97	LF	14	$27.58	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 PVC	$2.30	LF	14	$32.20	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC schedule 40 tees	$2.07	EA	1	$2.07	326122 Plastics Pipe and Pipe Fitting Manufacturing
Reducers (2-1 1/2)	$0.76	EA	1	$0.76	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 90 degree elbows	$1.68	EA	2	$3.36	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 pipe	$4.76	LF	147	$699.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 elbow	$10.95	EA	4	$43.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 tee	$16.25	EA	3	$48.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	326121 Unlaminated Plastics Profile Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	327390 Other Concrete Product Manufacturing
Total				**$988.24**	

Note: Prices listed in Table 3.26 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

3.3.3.3 Life Cycle Assessment: Materials Phase for Hybrid Design in Omaha

In Omaha, a sub-surface outdoor greywater reuse system was designed to irrigate a 690 square foot landscape (see Section 3.3.1) as shown in Figure 3.8. Site-specific materials for the water reuse system in Omaha are shown in Table 3.27.



Note: The total square roof surface area is 2171 square feet including the porch, garage, and house. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.8 – Landscape Irrigation Design for Hybrid Greywater Reuse System in Omaha

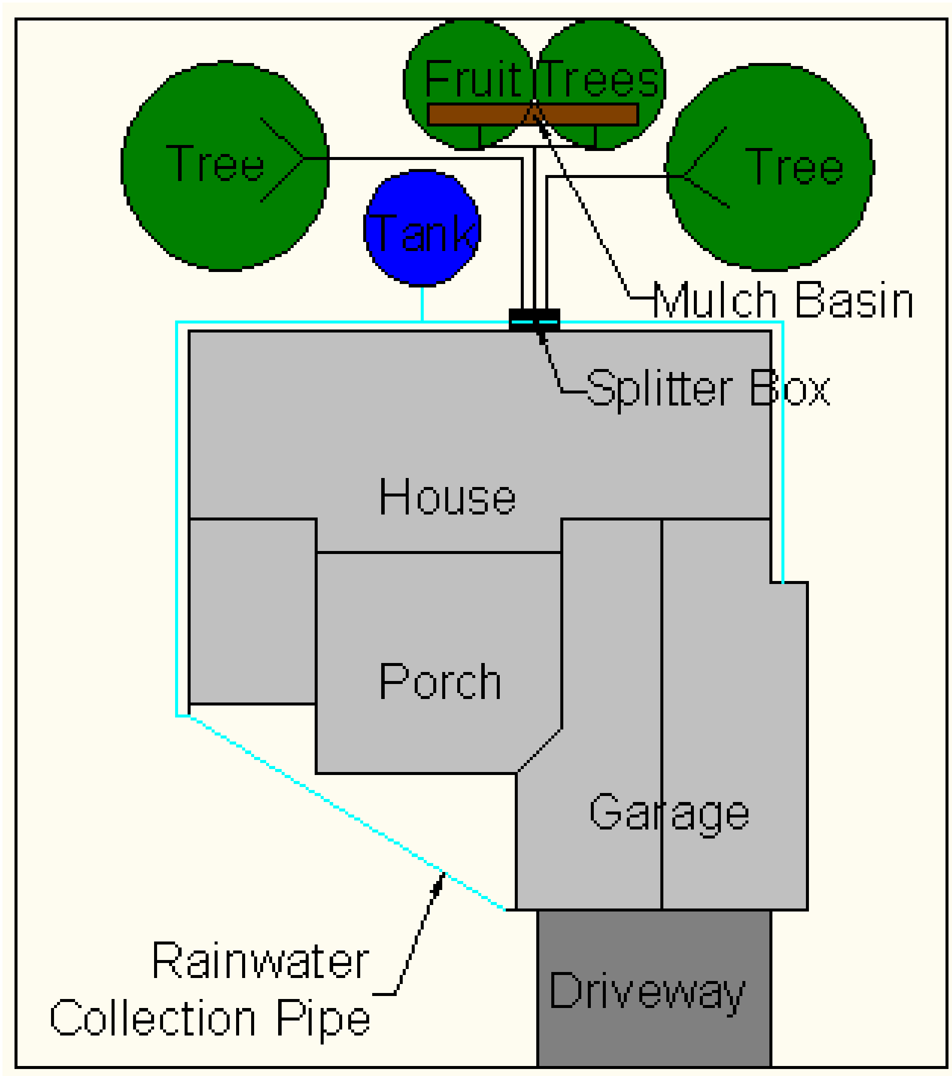
Table 3.27 – Materials in Omaha

Materials	Unit Price	Unit	Quantity	Total Price	Sector
1 1/2" schedule 40 PVC	$1.97	LF	59	$116.23	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 PVC	$2.30	LF	76	$174.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC schedule 40 tees	$2.07	EA	5	$10.35	326122 Plastics Pipe and Pipe Fitting Manufacturing
Reducers (2-1 1/2)	$0.76	EA	3	$2.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 45 degree bend	$1.97	EA	4	$7.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 90 degree elbows	$1.68	EA	4	$6.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 pipe	$4.76	LF	153	$728.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 elbow	$10.95	EA	4	$43.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC schedule 40 tee	$16.25	EA	3	$48.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	326121 Unlaminated Plastics Profile Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	327390 Other Concrete Product Manufacturing
Total				$1,269.09	

Note: Prices listed in Table 3.27 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

3.3.3.4 Life Cycle Assessment: Materials Phase for Hybrid Design in Tampa

In Tampa, a sub-surface outdoor greywater reuse system was designed to irrigate a 690 square foot landscape (see Section 3.3.1) as shown in Figure 3.9. Site-specific materials for the water reuse system in Tampa are shown in Table 3.28.



Note: The total square roof surface area is 2171 square feet including the porch, garage, and house. The small black box is the splitter box with 2" lines going out to the trees. The long rectangle near the small fruit trees represents a mulch basin.

Figure 3.9 – Landscape Irrigation Design for Hybrid Greywater Reuse System in Tampa

Table 3.28 – Materials in Tampa

Materials	Unit Price	Unit	Quantity	Total Price	Sector
1 1/2" schedule 40 PVC	$1.97	LF	36	$70.92	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" schedule 40 PVC	$2.30	LF	70	$161.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" PVC schedule 40 tees	$2.07	EA	3	$6.21	326122 Plastics Pipe and Pipe Fitting Manufacturing
Reducers (2-1 1/2)	$0.76	EA	3	$2.28	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 45 degree bend	$1.97	EA	4	$7.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 90 degree elbows	$1.68	EA	4	$6.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
5" PVC pipe schedule 40 pipe	$6.15	LF	147	$904.05	326122 Plastics Pipe and Pipe Fitting Manufacturing
5" PVC schedule 40 elbow	$28.50	EA	4	$114.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
5" PVC schedule 40 tee	$39.00	EA	3	$117.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
Plastic Dipper	$26.00	EA	1	$26.00	326121 Unlaminated Plastics Profile Shape Manufacturing
Pre-cast concrete dipper box	$104.00	EA	1	$104.00	327390 Other Concrete Product Manufacturing
Total				**$1,520.06**	

Note: Prices listed in Table 3.28 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

3.3.3.4 Life Cycle Assessment: Materials Phase Overview

The materials (indoor and outdoor) at each of the sites were summed in each of their corresponding sectors. The totals were then adjusted to 2002 U.S. dollars and multiplied by 1000 to incorporate the material costs of 1000 houses. Table 3.29 displays the total prices in each sector which were used as inputs in the EIO-LCA model.

Table 3.29 – Materials Phase Summary

	Seattle	Tampa	Scottsdale	Omaha
326122 Plastics Pipe and Pipe Fitting Manufacturing	$1,116,101.65	$1,438,477.74	$1,160,603.42	$1,287,339.27
33291 Metal Valve Manufacturing	$72,047.29	$72,047.29	$72,047.29	$72,047.29
33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing	$2,157,180.92	$2,157,180.92	$2,157,180.92	$2,157,180.92
333911 Pump and Pumping Equipment Manufacturing	$405,508.95	$405,508.95	$405,508.95	$405,508.95
326121 Unlaminated Plastics Profile Shape Manufacturing	$17,704.49	$17,704.49	$17,704.49	$17,704.49
327390 Other Concrete Product Manufacturing	$61,028.24	$61,028.24	$61,028.24	$61,028.24
33142 Copper Rolling, Drawing, Extruding, and Alloying	$9,998.60	$9,998.60	$9,998.60	$9,998.60

Note: All prices shown in this table are in 2002 U.S. dollars.

3.3.4 Life Cycle Assessment: Use Phase

For this design, no energy is required for treatment. However, a pump is necessary to deliver the rainwater from the underground cistern to uses in the house and outdoors. This pump and associated pressure tank are identical to the pump and pressure tank in Section 3.2. Using Equation 3.6, the power consumed at each of the sites was calculated. Table 3.30 shows the amount of electricity consumed in each of the study sites as well as the wholesale and retail costs of the electricity.

Table 3.30 – Electricity Calculation for Operation of Pumps

Site	Rainwater Captured in gal (L)	Electricity consumed annually in kWh	NPV of Wholesale cost of electricity for all homes over 50 years in 2002 U.S. $	NPV of Retail Cost of electricity for all homes over 50 years in 2010 U.S. $
Seattle	15420 (58360)	3.6	$3,276.87	$9,701.73
Scottsdale	8680 (32850)	2.0	$1,844.57	$5,461.16
Omaha	28410 (107530)	6.6	$6,037.34	$17,874.60
Tampa	31310 (118510)	7.3	$6,653.61	$19,699.18

Note: The average wholesale price of electricity in the United States was found to be 3.56 cents per kWh in 2002. The average retail price of electricity in 2010 was 10.54 cents per kWh. NPV stands for Net Present Value. The values in column 4 were used as an input into the EIO-LCA model. The values in column 5 were used for the economic feasibility calculations in Section 4.0.

These values in Table 3.30 represent the total costs for 1,000 houses to operate the pumps, discounted over 50 years. For this design, significant water savings are realized through the reuse of greywater and rainwater. The amount of greywater used on the landscape was calculated in Section 3.1.1. Table 3.31 displays amount of water used at each of the sites. The amount of greywater used differs from the amount of potable water replaced by greywater in the tables in the following sections because the irrigation efficiency of the greywater irrigation system is lower than a typical drip or sprinkler irrigation system. These differences are taken into consideration in these calculations.

Table 3.31 – Annual Amount of Water Reused from Greywater and Rainwater Sources

Site	Amount of Rainwater Captured and Used		Amount of Greywater Used		Total	
	gal	L	gal	L	gal	L
Seattle	15420	58365	6240	23618	21660	81983
Scottsdale	8680	32854	10400	39364	19080	72218
Omaha	28410	107532	10420	39440	38830	146972
Tampa	31310	118508	7190	27214	38500	145723

3.3.4.1 Water and Sewer Savings Calculation for Seattle

The irrigation demand for a 690 square foot landscape is displayed in Table 3.32. The irrigation demand for a 690 square foot landscape matches the average dry season irrigation demand as shown in Table 3.32.

Table 3.32 – Calculation of Irrigation Demand in Seattle

Month	(a) ET_O - Grass		(b) ET_L		(c) Rainfall		(d) Effective Rainfall		(e) IRnet		(f) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	0.56	1.43	0.28	0.72	5.24	13.31	1.00	2.54	-1.80	-4.56	0	0
February	0.85	2.17	0.43	1.08	4.09	10.39	1.00	2.54	-1.43	-3.64	0	0
March	1.43	3.64	0.72	1.82	3.92	9.96	1.00	2.54	-0.71	-1.80	0	0
April	2.49	6.32	1.25	3.16	2.75	6.99	1.00	2.54	0.61	1.56	263	994
May	3.82	9.70	1.91	4.85	2.03	5.16	1.25	3.18	1.65	4.19	710	2684
June	4.24	10.76	2.12	5.38	1.55	3.94	0.91	2.31	3.02	7.67	1299	4910
July	4.92	12.50	2.46	6.25	0.93	2.36	0.62	1.57	4.60	11.69	1979	7490
August	3.93	9.99	1.97	4.99	1.16	2.95	0.60	1.52	3.42	8.67	1469	5553
September	2.69	6.83	1.34	3.42	1.61	4.09	0.86	2.18	1.21	3.08	521	1969
October	1.16	2.95	0.58	1.47	3.24	8.23	1.00	2.54	-1.05	-2.67	0	0
November	0.62	1.57	0.31	0.78	5.67	14.40	1.00	2.54	-1.73	-4.39	0	0
December	0.46	1.17	0.23	0.59	6.06	15.39	1.00	2.54	-1.92	-4.89	0	0
Total											**6241**	**23591**

Note: Evapotranspiration data in column (a) was provided courtesy of Washington State University AgWeatherNet. Data are copyright of Washington State University. Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

The typical household in Seattle with standard (not high-efficient) currently uses 80.1 kgal. However, this study design includes efficient fixtures. Using the usage patterns by residents, the fixture water usage rates were revised, and the average water usage by a household using more efficient fixtures was calculated. The fixture rates are described in the previous sections. The average household using the fixtures included in this design would use approximately 60.3 kgal, saving about 19.8 kgal/year. This results in yearly water and sewer bills of approximately $130.04 and $326.55, respectively. Table 3.33 displays the amount of potable water displaced by both captured rainwater and greywater. It also displays the water and sewer costs for the household reusing rainwater and greywater.

Table 3.33 – Amount of Water Reused from Greywater and Rainwater Sources in Seattle

Month	(a) Amount of PW Replaced by GW		(b) Amount Replaced of PW by RW		(c) Total Amount of PW Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	0	0	1285	4864	1865	7059	$3.51	$10.09
February	0	0	1285	4864	1865	7059	$3.51	$10.09
March	0	0	1285	4864	1865	7059	$3.51	$10.09
April	211	798	1285	4864	5404	20455	$11.94	$29.24
May	568	2149	1285	4864	5047	19104	$10.89	$27.31
June	1040	3935	1285	4864	4575	17318	$9.50	$24.75
July	1265	4787	1285	4864	4350	16466	$8.83	$23.53
August	1175	4448	1285	4864	4440	16805	$9.10	$24.02
September	417	1577	1285	4864	5198	19675	$11.33	$28.12
October	0	0	1285	4864	1865	7059	$3.51	$10.09
November	0	0	1285	4864	1865	7059	$3.51	$10.09
December	0	0	1285	4864	1865	7059	$3.51	$10.09
Total	4675	17693	15420	58365	40205	152177	$82.62	$217.51

Note: PW means potable water, GW means greywater, and RW means rainwater. The amount of greywater used in the landscape was calculated by taking the minimum of the irrigation demand or amount of greywater produced in a month. Column (a) is 80% of the total amount of water reused because the irrigation method for greywater irrigation is less efficient than a typical lawn sprinkler. Column (b) was calculated by taking the total amount of rainwater reused during a given year and distributing it equally over every month. Column (c) is the remainder after subtracting Columns (a) and (b) from the original potable water demand.

Thus, the average household reusing greywater and rainwater would save approximately 21.7 kgal and $156.46 per year. However, even though harvesting rainwater results in reduced sewer fees, because the sewer fees are tied to potable water usage, the utility still has to treat this captured rainwater. Thus, only greywater reuse results in a reduced sewer discharges and potable water use. This needs to be taken into account in the EIO-LCA. Thus, in Seattle, the water savings alone are $47.42 per year. The sewer savings from greywater reuse are $25.29. Thus, the entire annual savings for the EIO-LCA are $72.71. This results in a present value of $2.02 million after including savings over a 50 year design life for the 1000 household development and adjusting for inflation.

3.3.4.2 Water and Sewer Savings Calculation for Scottsdale

The irrigation demand for a 200 square foot landscape in Scottsdale is shown in Table 3.34.

Table 3.34 – Calculation of Irrigation Demand in Scottsdale

Month	(a) ET_O - Grass		(b) ET_L		(c) Rainfall		(d) Effective Rainfall		(e) IRnet		(f) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	2.77	7.04	1.39	3.52	1.01	2.57	0.57	1.45	2.04	5.18	254	963
February	3.37	8.57	1.69	4.28	1.04	2.64	0.58	1.47	2.77	7.03	345	1305
March	5.72	14.53	2.86	7.26	1.15	2.92	0.65	1.65	5.53	14.03	689	2607
April	7.96	20.22	3.98	10.11	0.25	0.64	0.20	0.51	9.45	24.01	1178	4460
May	9.53	24.21	4.77	12.10	0.21	0.53	0.17	0.43	11.49	29.18	1432	5421
June	10.61	26.96	5.31	13.48	0.07	0.18	0.06	0.15	13.12	33.31	1635	6189
July	10.16	25.81	5.08	12.90	0.89	2.26	0.70	1.78	10.95	27.82	1365	5168
August	9.10	23.11	4.55	11.56	1.20	3.05	0.72	1.83	9.58	24.32	1194	4518
September	7.41	18.83	3.71	9.42	0.86	2.18	0.70	1.78	7.52	19.09	937	3547
October	6.17	15.66	3.08	7.83	0.85	2.16	0.65	1.65	6.08	15.45	758	2871
November	3.65	9.27	1.83	4.64	0.80	2.03	0.56	1.42	3.16	8.03	394	1492
December	2.49	6.33	1.25	3.17	1.03	2.62	0.55	1.40	1.74	4.42	217	822
Total											**10400**	39364

Note: Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

The typical household in Scottsdale with standard (not high-efficient) fixtures uses 184.9 kgal. However, this study design includes efficient fixtures. Using the usage patterns by residents, the fixture water usage rates were revised, and the average water usage by a household using more efficient fixtures was calculated. The fixture rates are described in the previous sections. A household using water efficient fixtures will save approximately 18.9 kgal per year. Thus, a new baseline needs to be calculated before savings can be calculated. The average household using the fixtures included in this design would use approximately 166.0 kgal. This results in yearly water and sewer bills of approximately $265.65 and $195.97, respectively. Table 3.35 displays the amount of potable water displace by both captured rainwater and greywater. It also displays the water and sewer costs for the household reusing rainwater and greywater.

Table 3.35 – Amount of Water Reused from Greywater and Rainwater Sources in Scottsdale

Month	(a) Amount of PW Replaced by GW		(b) Amount Replaced of PW by RW		(c) Total Amount of PW Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	204	770	724	2740	12912	48874	$20.38	$15.24
February	276	1044	724	2740	12840	48600	$20.25	$15.15
March	551	2086	724	2740	12565	47558	$19.73	$14.83
April	943	3568	724	2740	12173	46076	$18.99	$14.36
May	1146	4337	724	2740	11970	45307	$18.60	$14.12
June	1184	4481	724	2740	11932	45163	$18.53	$14.08
July	1092	4134	724	2740	12024	45510	$18.70	$14.19
August	955	3614	724	2740	12161	46030	$18.96	$14.35
September	750	2838	724	2740	12366	46806	$19.35	$14.59
October	607	2297	724	2740	12509	47347	$19.62	$14.76
November	315	1194	724	2740	12801	48450	$20.17	$15.10
December	174	657	724	2740	12942	48987	$20.44	$15.27
Total	8196	31021	8688	32884	149196	564708	$233.74	$176.05

Note: PW means potable water, GW means greywater, and RW means rainwater. The amount of greywater used in the landscape was calculated by taking the minimum of the irrigation demand or amount of greywater produced in a month. Column (a) is 80% of the total amount of water reused because the irrigation method for greywater irrigation is less efficient than a typical lawn sprinkler. Column (b) was calculated by taking the total amount of rainwater reused during a given year and distributing it equally over every month. Column (c) is the remainder after subtracting Columns (a) and (b) from the original potable water demand.

Thus, the average household reusing greywater and rainwater would save 19.1 kgal and approximately $51.83 per year. However, even though harvesting rainwater results in reduced sewer fees, because the sewer fees are tied to potable water usage, the utility still has to treat this captured rainwater. Thus, only greywater reuse results in a reduced sewer discharges and potable water use. This needs to be taken into account in the EIO-LCA. Thus, in Scottsdale, the water savings alone are $31.91 per year. The sewer savings from greywater reuse are $9.67. Thus, the entire annual savings for the

EIO-LCA are $41.58. This results in a present value of $1.16 million after including savings over a 50 year design life for the 1000 household development and adjusting for inflation.

3.3.4.3 Water and Sewer Savings Calculation for Omaha

The irrigation demand for a 1050 square foot landscape in Omaha is displayed in Table 3.36.

Table 3.36 – Calculation of Irrigation Demand in Omaha

Month	(a) ET_O - Alfalfa		(b) ET_O - Grass		(c) ET_L		(d) Rainfall		(e) Effective Rainfall		(f) IRnet		(g) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	1.57	3.99	1.53	3.88	0.76	1.94	0.77	1.96	0.60	1.52	0	0	0	0
February	1.92	4.89	1.85	4.70	0.93	2.35	0.80	2.03	0.60	1.52	0	0	0	0
March	3.78	9.60	3.50	8.89	1.75	4.44	2.13	5.41	1.25	3.18	0	0	0	0
April	6.10	15.51	5.60	14.23	2.80	7.11	2.94	7.47	1.93	4.90	2.18	5.53	1424	5390
May	7.78	19.75	7.34	18.63	3.67	9.32	4.44	11.28	2.65	6.73	2.54	6.46	1665	6302
June	7.89	20.03	7.58	19.26	3.79	9.63	3.95	10.03	2.67	6.78	2.80	7.12	1835	6945
July	7.25	18.42	7.11	18.05	3.55	9.03	3.86	9.80	2.55	6.48	2.51	6.38	1642	6215
August	6.14	15.60	6.02	15.29	3.01	7.65	3.21	8.15	1.95	4.95	2.65	6.73	1734	6563
September	5.53	14.04	5.26	13.37	2.63	6.68	3.17	8.05	1.90	4.83	1.83	4.65	1197	4531
October	3.84	9.76	3.63	9.21	1.81	4.60	2.21	5.61	1.25	3.18	1.41	3.57	920	3482
November	2.37	6.02	2.26	5.74	1.13	2.87	1.82	4.62	1.10	2.79	0	0	0	0
December	1.36	3.45	1.32	3.35	0.66	1.67	0.92	2.34	0.66	1.66	0	0	0	0
Total													**10420**	**39428**

Note: Column (a) is evapotranspiration data retrieved from the High Plains Regional Climate Center. Column (b) using conversion factors (Irmak et al. 2008). Column (c) was calculated using Eq. 3.1. Column (d) comes from monthly averages from www.weather.com. Column (e) was calculated using a table from Gupta's book (2008). Column (f) was calculated using Eq. 3.3. Column (g) was calculated by applying the irrigation depth over the irrigated area.

The typical household in Omaha uses 96.0 kgal. However, this design includes efficient fixtures. Using the usage patterns by residents, we updated the fixture water usage rates and calculated the average water usage by a household using more efficient fixtures. The fixture rates are described in the previous sections. A household using water efficient fixtures saves approximately 17.7 kgal per year. Thus, a new baseline needs to be calculated before savings can be calculated. The average household using the fixtures included in this design would use approximately 78.3 kgal. This results in yearly water and sewer bills of approximately $163.86 and $92.50, respectively. Table 3.37 displays the amount of potable water displace by both captured rainwater and greywater. It also displays the water and sewer costs for the household reusing rainwater and greywater.

Table 3.37 – Amount of Water Reused from Greywater and Rainwater Sources in Omaha

Month	(a) Amount of PW Replaced by GW		(b) Amount Replaced of PW by RW		(c) Total Amount of PW Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	0	0	2370	8970	1460	5526	$6.96	$1.72
February	0	0	2370	8970	1460	5526	$6.96	$1.72
March	0	0	2370	8970	1460	5526	$6.96	$1.72
April	1139	4312	2370	8970	7321	27709	$14.34	$8.64
May	1332	5042	2370	8970	7128	26979	$14.10	$8.41
June	1394	5278	2370	8970	7066	26743	$14.21	$8.34
July	1314	4975	2370	8970	7146	27046	$14.35	$8.43
August	1388	5252	2370	8970	7072	26769	$14.22	$8.35
September	958	3625	2370	8970	7502	28396	$14.98	$8.85
October	736	2787	2370	8970	7724	29234	$15.37	$9.11
November	0	0	2370	8970	1460	5526	$6.96	$1.72
December	0	0	2370	8970	1460	5526	$6.96	$1.72
Total	8262	31271	28440	107645	58258	220508	$136.36	$68.74

Note: PW means potable water, GW means greywater, and RW means rainwater. The amount of greywater used in the landscape was calculated by taking the minimum of the irrigation demand or amount of greywater produced in a month. Column (a) is 80% of the total amount of water reused because the irrigation method for greywater irrigation is less efficient than a typical lawn sprinkler. Column (b) was calculated by taking the total amount of rainwater reused during a given year and distributing it equally over every month. Column (c) is the remainder after subtracting Columns (a) and (b) from the original potable water demand.

Thus, the average household using this design would save approximately 38.8 kgal and $51.26 per year. However, even though harvesting rainwater results in reduced sewer fees because the sewer fees are tied to potable water usage, the utility still has to treat this captured rainwater. Thus, only greywater reuse results in a reduced sewer discharges and potable water use. This needs to be taken into account in the EIO-LCA. Thus, in Omaha, the water savings alone are $27.50 per year. The sewer savings from greywater reuse are $9.75. Thus, the entire annual savings for the EIO-LCA are $37.25. This results in a present value of $0.81 million after including savings over a 50 year design life for the 1000 household development and adjusting for inflation.

3.3.4.4 Water and Sewer Savings Calculation for Tampa

The irrigation demand for a 700 square foot landscape in Tampa is displayed in Table 3.38.

Table 3.38 – Calculation of Irrigation Demand in Tampa

Month	(a) ET_O - Grass		(b) ET_L		(c) Rainfall		(d) Effective Rainfall		(e) IRnet		(f) Irrigation Demand	
	in.	cm	in.	cm	in.	cm	in.	cm	in.	cm	gal	L
January	3.16	8.03	1.58	4.01	2.27	5.77	1.20	3.05	0.95	2.42	415	1572
February	2.80	7.12	1.40	3.56	2.67	6.78	1.26	3.20	0.35	0.90	154	582
March	5.02	12.75	2.51	6.38	2.84	7.21	1.88	4.78	1.57	4.00	687	2601
April	6.15	15.63	3.08	7.82	1.80	4.57	1.25	3.18	4.57	11.60	1993	7544
May	6.96	17.69	3.48	8.84	2.85	7.24	1.94	4.93	3.85	9.79	1682	6366
June	6.12	15.55	3.06	7.78	5.50	13.97	3.06	7.77	0.00	0.01	2	7
July	5.95	15.12	2.98	7.56	6.49	16.48	2.97	7.54	0.02	0.04	7	25
August	5.85	14.87	2.93	7.43	7.60	19.30	2.93	7.43	0.00	0.00	0	0
September	5.52	14.03	2.76	7.01	6.54	16.61	2.76	7.01	0.00	0.01	1	4
October	4.96	12.59	2.48	6.30	2.29	5.82	1.48	3.76	2.50	6.34	1090	4125
November	3.70	9.40	1.85	4.70	1.62	4.11	1.07	2.72	1.95	4.95	851	3220
December	3.00	7.61	1.50	3.81	2.30	5.84	1.22	3.10	0.70	1.77	304	1150
Total											**7190**	**27214**

Note: Column (b) was calculated using Eq. 3.1. Column (c) comes from monthly averages from www.weather.com. Column (d) was calculated using a table from Gupta's book (2008). Column (e) was calculated using Eq. 3.3. Column (f) was calculated by applying the irrigation depth over the irrigated area.

The typical household in Tampa uses 80.6 kgal. However, this design includes efficient fixtures. Using the usage patterns by residents, we updated the fixture water usage rates and calculated the average water usage by a household using more efficient fixtures. The fixture rates are described in the previous sections. A household using water efficient fixtures will save approximately 16.7 kgal per year. Thus, a new baseline needs to be calculated before savings can be calculated. The average household using the fixtures included in this design would use approximately 63.9 kgal. This results in yearly water and sewer bills of approximately $76.70 and 237.78, respectively. Table 3.39 displays the amount of potable water displace by both captured rainwater and greywater. It also displays the water and sewer costs for the household reusing rainwater and greywater.

Table 3.39 – Amount of Water Reused from Greywater and Rainwater Sources

Month	(a) Amount of PW Replaced by GW		(b) Amount Replaced of PW by RW		(c) Total Amount of PW Used		Water Costs	Sewer Costs
	gal	L	gal	L	gal	L	1999 U.S.	1999 U.S.
January	332	1257	2609	9875	2389	9042	$2.87	$8.89
February	123	466	2609	9875	2598	9833	$3.12	$9.66
March	550	2081	2609	9875	2171	8218	$2.61	$8.08
April	1167	4418	2609	9875	1554	5881	$1.86	$5.78
May	1167	4418	2609	9875	1554	5881	$1.86	$5.78
June	2	6	2609	9875	2719	10293	$3.26	$10.12
July	5	20	2609	9875	2716	10279	$3.26	$10.10
August	0	0	2609	9875	2721	10299	$3.27	$10.12
September	1	3	2609	9875	2720	10296	$3.26	$10.12
October	872	3300	2609	9875	1849	6999	$2.22	$6.88
November	681	2576	2609	9875	2040	7723	$2.45	$7.59
December	243	920	2609	9875	2478	9379	$2.97	$9.22
Total	5143	19465	31308	118501	27509	104122	$33.01	$102.33

Note: PW means potable water, GW means greywater, and RW means rainwater. The amount of greywater used in the landscape was calculated by taking the minimum of the irrigation demand or amount of greywater produced in a month. Column (a) is 80% of the total amount of water reused because the irrigation method for greywater irrigation is less efficient than a typical lawn sprinkler. Column (b) was calculated by taking the total amount of rainwater reused during a given year and distributing it equally over every month. Column (c) is the remainder after subtracting Columns (a) and (b) from the original potable water demand.

Thus, the average household in Tampa using this design would save approximately 38.5 kgal and $179.34 per year. However, even though harvesting rainwater results in reduced sewer fees, because the sewer fees are tied to potable water usage, the utility still has to treat this captured rainwater. Thus, only greywater reuse results in a reduced sewer discharges and potable water use. This needs to be taken into account in the EIO-LCA. Thus, in Tampa, the water savings alone are $40.69 per year. The sewer savings from greywater reuse are $19.13. Thus, the entire annual savings for the EIO-LCA are $59.82. This results in a present value of $1.66 million after including savings over a 50 year design life for the 1000 household development and adjusting for inflation.

3.3.5 Disposal Phase for the Hybrid Water Reuse System

The final phase in this LCA is the disposal of materials. It is assumed that all materials used in the LCA are placed in a landfill even though materials such as the underground steel tank could be recycled. The environmental impacts of this phase are relatively small compared to the other phases of the study, so this assumption will have minor impacts on the results of this analysis. Table 3.40 displays the amount of materials that will be disposed of in each of the four sites as well as their corresponding landfill prices. These prices were adjusted for inflation to 2002 U.S. dollars and multiplied by 1000 to include impacts associated with a 1000-house development. These prices were then used as an input in the EIO-LCA model in the Waste Management and Remediation services sector.

Table 3.40 – Landfill Fees for Disposal of Materials Used in Hybrid Water Reuse System

Site	2009 Consumer Price for Landfill fees (per ton)	2009 Producer Price for Landfill fees (per ton)	2002 Producer Price for Landfill fees (per ton)	Disposal Amount for 1000 homes (tons)	Total for 1000 homes (2002 U.S. dollars)
Seattle	$102.05	$89.91	$75.42	733	$55,280
Scottsdale	$37.00	$32.60	$27.34	751	$20,530
Omaha	$23.12	$20.37	$17.09	791	$13,520
Tampa	$41.00	$36.12	$30.30	830	$25,150

The values in column six of Table 3.40 are used in the EIO-LCA to represent the increase of expenditures and the consequent construction, energy, and emissions for the disposal sector.

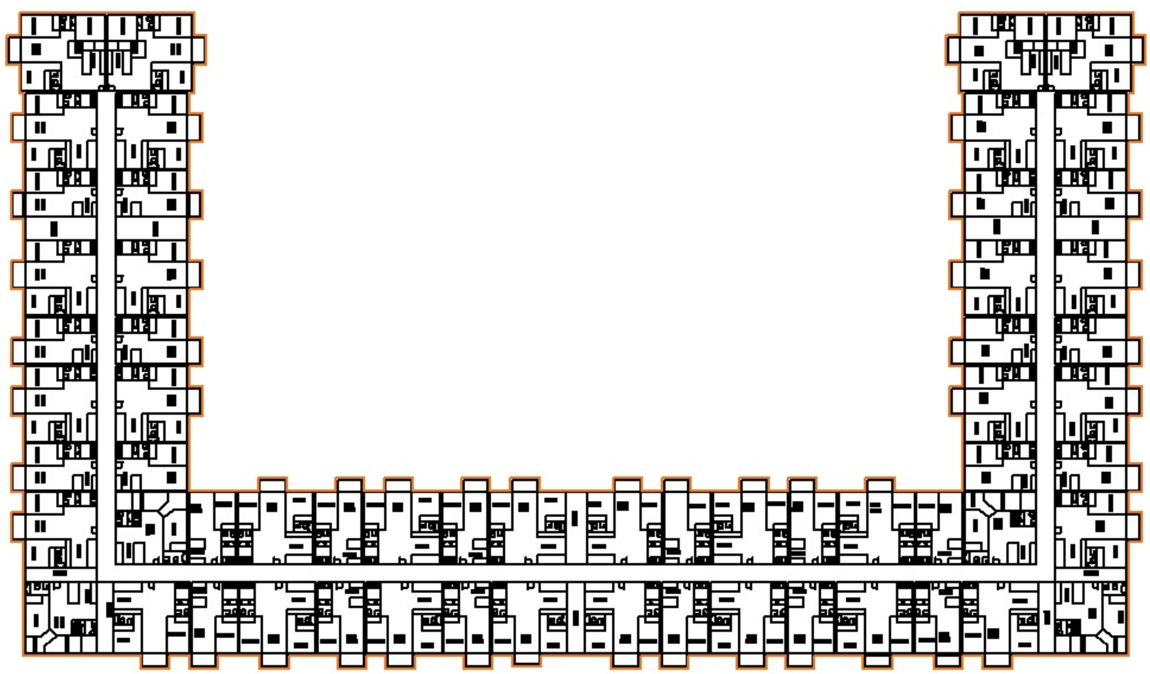
3.4 Model 4 - Development of an EIO-LCA for a Rainwater Harvesting System for an Apartment Building

The next design includes a rainwater harvesting system for an apartment building. Since multiple families will be living in the apartment building, which increases risk associated with reusing greywater, no greywater will be re-used in this design scenario. The increased health risks stem from the lack of control over what is discharged into the greywater collection system. The harvested rainwater will be stored in large cisterns and used for toilet flushing and laundry washing. The apartment building's floor plan was modeled after a newly constructed apartment complex in Omaha (Killion, 2011). This apartment building has one, two, and three bedroom apartments ranging from 700-1600 square feet.

The environmental impacts were analyzed for 50 apartment buildings. For the first three water reuse models or scenarios, the impacts were assessed over 1,000 households. In order to keep the scale of the analysis at a similar level, this model considers the impacts for 50 apartment buildings which make the material expenditures and number of occupants at a relatively equivalent scale for comparison purposes.

3.4.1 Design of Rainwater Harvesting System for an Apartment Complex

EPANET 2 was used to model the collection and distribution of rainwater for use in a 180-unit apartment building housing approximately 300 people. The apartment utilizes rainwater collected from the roof and stored in a below-ground cistern for toilet flushing and laundry. The hydraulic modeling capabilities of EPANET 2 were used to properly size the rainwater distribution system as well as the underground rainwater collection system. Figure 3.10 displays the floor plan of the 1st floor.



Note: Each floor of the apartment has 60 units (for a total of 180 units). The figure above displays the floor plan of the first floor. The 2nd and 3rd floors are identical to the 1st floor.

Figure 3.10 Apartment Floor Plan – 1st Floor

3.4.2 Design of the Rainwater Cistern

The cistern for each apartment building was designed using the same methods as described in Section 3.3. Rainfall data for each city was used as an input to the Rainwater Harvester Model. Past rainfall data was compared to the average precipitation in each city. A representative year was chosen for each city. The year chosen was recent (less than 10 years old), and the cumulative precipitation was within 1-2 inches of the average annual precipitation in each of the cities.

The apartment building has a roof area of approximately 82,015 square feet. The downspouts and rainwater collection pipes were sized for a 10-year event. Thus, water would overflow the gutters and downspouts in all storms with intensities in excess of a 10-year storm. Consequently, a capture efficiency of 85% was used compared to the 90% capture efficiency used in Section 3.3 for the hybrid system for the single family house.

The daily water uses (laundry and toilet flushing) were the only outputs from the cistern. Eight separate cistern storage volumes were evaluated (10, 20, 30, 40, 50, 60, 80, and 100 kgal). The same method was used to determine the optimal cistern size as described in Section 3.3.2.1. The percentage of water captured and the payback period of the rainwater capture system were tabulated for each cistern volume in each city. The two values were normalized and weighted equally. The optimal cistern for each apartment building was determined to be the cistern with the highest score considering both the percentage of rainwater captured and the payback of the rainwater system.

The optimal cistern size was 50 kgal for Scottsdale, Omaha, and Tampa. However, a tank size of 30 kgal was optimal in the city of Seattle. Figures B.5-B.8 in Appendix B display the water levels in the cistern for each city using the site-specific rainfall data as obtained in Section 3.3. These figures were generated using the Rainwater Harvesting Program from North Carolina State University (2010).

3.4.3 Materials for Rainwater Catchment System in Seattle

After sizing the cistern, the rainwater collection and distribution system was designed and modeled using the EPANET model (Killion, 2011). The resulting materials are shown in Tables 3.41-44 for Seattle, Scottsdale, Omaha, and Tampa, respectively.

Table 3.41 – Materials for the Rainwater Catchment System in Seattle

Materials	Unit Price	Unit	Quantity	Total Price	Sector
2" PVC Schedule 40 Pipe	$2.30	LF	5163	$11,874.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" T Connection (PVC)	$1.68	EA	174	$292.32	326122 Plastics Pipe and Pipe Fitting Manufacturing
Manifold - 2 effluent lines	$18.35	EA	72	$1,321.20	33142 Copper Rolling, Drawing, Extruding, and Alloying
Manifold - 3 effluent lines	$18.35	EA	108	$1,981.80	33142 Copper Rolling, Drawing, Extruding, and Alloying
RW control system	$125.25	EA	1	$125.25	334512 Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use
Motor for the pump	$2,600.00	EA	1	$2,600.00	335312 Motor and Generator Manufacturing
15 HP Grundfos Pump (230S150-5B)	$2,882.00	EA	1	$2,882.00	333911 Pump and Pumping Equipment Manufacturing
Pressure Tank	$730.00	EA	1	$730.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Storage tank	$22,700.00	EA	1	$22,700.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
3" PVC Schedule 40 Pipe	$3.77	LF	199	$750.23	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC Schedule 40 Pipe	$4.76	LF	360	$1,713.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" PVC Schedule 40	$8.10	LF	2010	$16,281.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

Pipe					
8" PVC Schedule 40 Pipe	$8.10	LF	116	$939.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
12" PVC for diverters	$34.00	LF	141	$4,794.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" T PVC Schedule 40	$54.50	EA	30	$1,635.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" 90d elbows PVC-40	$35.00	EA	36	$1,260.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" to 6" reducer	$36.50	EA	2	$73.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" T PVC Schedule 40	$56.50	EA	2	$113.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 45d elbows PVC-40	$8.25	EA	60	$495.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" x 3" Reducer	$22.60	EA	60	$1,356.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" x 2" Reducer	$1.48	EA	6	$8.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" T PVC Schedule 40	$13.55	EA	5	$67.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 90d elbows PVC-40	$6.10	EA	8	$48.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
1" PVC Schedule 40 Pipe	$1.66	LF	53	$87.98	326122 Plastics Pipe and Pipe Fitting Manufacturing
Downspout filter	$34.95	EA	60	$2,097.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
First flush diverters	$100.00	EA	4	$400.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

Note: Prices listed in Table 3.41 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

Table 3.42 – Materials for the Rainwater Catchment System in Scottsdale

Materials	Unit Price	Unit	Quantity	Total Price	Sector
2" PVC Schedule 40 Pipe	$2.30	LF	5163	$11,874.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" T Connection (PVC)	$1.68	EA	174	$292.32	326122 Plastics Pipe and Pipe Fitting Manufacturing
Manifold - 2 effluent lines	$18.35	EA	72	$1,321.20	33142 Copper Rolling, Drawing, Extruding, and Alloying
Manifold - 3 effluent lines	$18.35	EA	108	$1,981.80	33142 Copper Rolling, Drawing, Extruding, and Alloying
RW control system	$125.25	EA	1	$125.25	334512 Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use

Motor for the pump	$2,600.00	EA	1	$2,600.00	335312 Motor and Generator Manufacturing
15 HP Grundfos Pump (230S150-5B)	$2,882.00	EA	1	$2,882.00	333911 Pump and Pumping Equipment Manufacturing
Pressure Tank	$730.00	EA	1	$730.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Storage tank	$38,300.00	EA	1	$38,300.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
3" PVC Schedule 40 Pipe	$3.77	LF	202	$761.54	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC Schedule 40 Pipe	$4.76	LF	372	$1,770.72	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" PVC Schedule 40 Pipe	$8.10	LF	2010	$16,281.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" PVC Schedule 40 Pipe	$8.10	LF	116	$939.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
12" PVC for diverters	$34.00	LF	141	$4,794.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" T PVC Schedule 40	$54.50	EA	30	$1,635.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" 90d elbows PVC-40	$35.00	EA	36	$1,260.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" to 6" reducer	$36.50	EA	2	$73.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" T PVC Schedule 40	$56.50	EA	2	$113.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 45d elbows PVC-40	$8.25	EA	62	$511.50	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" x 3" Reducer	$22.60	EA	62	$1,401.20	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" x 2" Reducer	$1.48	EA	6	$8.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" T PVC Schedule 40	$13.55	EA	5	$67.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 90d elbows PVC-40	$6.10	EA	8	$48.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
1" PVC Schedule 40 Pipe	$1.66	LF	53	$87.98	326122 Plastics Pipe and Pipe Fitting Manufacturing
Downspout filter	$34.95	EA	62	$2,166.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
First flush diverters	$100.00	EA	4	$400.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

Note: Prices listed in Table 3.42 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

Table 3.43 – Materials for the Rainwater Catchment System in Omaha

Materials	Unit Price	Unit	Quantity	Total Price	Sector
2" PVC Schedule 40 Pipe	$2.30	LF	5163	$11,874.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" T Connection (PVC)	$1.68	EA	174	$292.32	326122 Plastics Pipe and Pipe Fitting Manufacturing
Manifold - 2 effluent lines	$18.35	EA	72	$1,321.20	33142 Copper Rolling, Drawing, Extruding, and Alloying
Manifold - 3 effluent lines	$18.35	EA	108	$1,981.80	33142 Copper Rolling, Drawing, Extruding, and Alloying
RW control system	$125.25	EA	1	$125.25	334512 Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use
Motor for the pump	$2,600.00	EA	1	$2,600.00	335312 Motor and Generator Manufacturing
15 HP Grundfos Pump (230S150-5B)	$2,882.00	EA	1	$2,882.00	333911 Pump and Pumping Equipment Manufacturing
Pressure Tank	$730.00	EA	1	$730.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Storage tank	$38,300.00	EA	1	$38,300.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
3" PVC Schedule 40 Pipe	$3.77	LF	94	$354.38	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC Schedule 40 Pipe	$4.76	LF	448	$2,132.48	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" PVC Schedule 40 Pipe	$8.10	LF	2010	$16,281.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" PVC Schedule 40 Pipe	$8.10	LF	116	$939.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
12" PVC for diverters	$34.00	LF	141	$4,794.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" T PVC Schedule 40	$54.50	EA	30	$1,635.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

6" 90d elbows PVC-40	$35.00	EA	36	$1,260.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" to 6" reducer	$36.50	EA	2	$73.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" T PVC Schedule 40	$56.50	EA	2	$113.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" 45d elbows PVC-40	$14.25	EA	58	$826.50	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" x 4" Reducer	$18.20	EA	58	$1,055.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" x 2" Reducer	$1.48	EA	6	$8.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" T PVC Schedule 40	$13.55	EA	5	$67.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 90d elbows PVC-40	$6.10	EA	8	$48.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
1" PVC Schedule 40 Pipe	$1.66	LF	53	$87.98	326122 Plastics Pipe and Pipe Fitting Manufacturing
Downspout filter	$34.95	EA	58	$2,027.10	326122 Plastics Pipe and Pipe Fitting Manufacturing
First flush diverters	$100.00	EA	4	$400.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

Note: Prices listed in Table 3.43 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

Table 3.44 – Materials for the Rainwater Catchment System in Tampa

Materials	Unit Price	Unit	Quantity	Total Price	Sector
2" PVC Schedule 40 Pipe	$2.30	LF	5163	$11,874.90	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" T Connection (PVC)	$1.68	EA	174	$292.32	326122 Plastics Pipe and Pipe Fitting Manufacturing
Manifold - 2 effluent lines	$18.35	EA	72	$1,321.20	33142 Copper Rolling, Drawing, Extruding, and Alloying
Manifold - 3 effluent lines	$18.35	EA	108	$1,981.80	33142 Copper Rolling, Drawing, Extruding, and Alloying
RW control system	$125.25	EA	1	$125.25	334512 Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use
Motor for the pump	$2,600.00	EA	1	$2,600.00	335312 Motor and Generator Manufacturing
15 HP Grundfos Pump (230S150-5B)	$2,882.00	EA	1	$2,882.00	333911 Pump and Pumping Equipment Manufacturing

Pressure Tank	$730.00	EA	1	$730.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
Storage tank	$38,300.00	EA	1	$38,300.00	33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing
3" PVC Schedule 40 Pipe	$3.77	LF	94	$354.38	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC Schedule 40 Pipe	$4.76	LF	465	$2,213.40	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" PVC Schedule 40 Pipe	$8.10	LF	2010	$16,281.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" PVC Schedule 40 Pipe	$8.10	LF	116	$939.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
12" PVC for diverters	$34.00	LF	141	$4,794.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" T PVC Schedule 40	$54.50	EA	30	$1,635.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" 90d elbows PVC-40	$35.00	EA	36	$1,260.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" to 6" reducer	$36.50	EA	2	$73.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" T PVC Schedule 40	$56.50	EA	2	$113.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" 45d elbows PVC-40	$14.25	EA	60	$855.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
6" x 4" Reducer	$18.20	EA	60	$1,092.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" x 2" Reducer	$1.48	EA	6	$8.88	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" T PVC Schedule 40	$13.55	EA	5	$67.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
3" 90d elbows PVC-40	$6.10	EA	8	$48.80	326122 Plastics Pipe and Pipe Fitting Manufacturing
1" PVC Schedule 40 Pipe	$1.66	LF	53	$87.98	326122 Plastics Pipe and Pipe Fitting Manufacturing
Downspout filter	$34.95	EA	60	$2,097.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
First flush diverters	$100.00	EA	4	$400.00	326122 Plastics Pipe and Pipe Fitting Manufacturing

Note: Prices listed in Table 3.44 are taken from RSMeans Plumbing Cost Data (Reed Construction Data 2004), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

Table 3.45 displays the total amount (for 50 apartment buildings) used as an input to each sector in the EIO-LCA model after adjusting for inflation to 2002 U.S. dollars, and after backing out the mark-up value from the retail price to arrive at the producer prices of the materials.

Table 3.45 – Materials Totals for All Sites

Sector	Seattle	Scottsdale	Omaha	Tampa
326122 Plastics Pipe and Pipe Fitting Manufacturing	$1.5728	$1.5796	$1.5725	$1.5799
33243 Metal Can, Box, and Other Metal Container (Light Gauge) Manufacturing	$0.9201	$1.5351	$1.5351	$1.5351
333911 Pump and Pumping Equipment Manufacturing	$0.0843	$0.0843	$0.0843	$0.0843
33142 Copper Rolling, Drawing, Extruding, and Alloying	$0.1275	$0.1275	$0.1275	$0.1275
334512 Automatic Environmental Control Manufacturing for Residential, Commercial, and Appliance Use	$0.0039	$0.0039	$0.0039	$0.0039
335312 Motor and Generator Manufacturing	$0.0793	$0.0793	$0.0793	$0.0793
Total	$2.79	$3.41	$3.40	$3.41

Note: Values shown in Table 3.45 are in millions of 2002 U.S. dollars

3.4.3 Water Savings

The Rainwater Harvester program was then used to calculate the amount of water reused in each city. Using current water rates (for multi-family residential users), the monetary value of the saved water was calculated in each city on an annual basis. Since the sewer rates are calculated based on the homeowner's potable water usage, the sewer charges would also be reduced from using rainwater. The sewer savings were calculated as part of this analysis for use in the economic analysis of this system. However, sewer savings were not included in the EIO-LCA because the same amount of water is treated at the wastewater treatment plant with a rainwater reuse system. The actual savings are only on the supply side.

3.4.3.1 Water Savings in Seattle

In Seattle, the general service commodity charge is $4.68 per kgal for potable water between September 16 and May 16. During peak usage (May 16 - September 16), the rate is $6.00 per kgal. The sewer rates are $12.01 per kgal for apartment buildings. The Rainwater Harvester program was used to calculate the water saved through the entire year. The results of the model indicate that approximately 798 kgal would be saved from a 30 kgal cistern in Seattle. This results in water and sewer savings of $3,900 and $9,600, respectively. The owner will save this amount on the sewer fees due to the fact that sewer rates are tied to potable water usage. However, only potable water savings will be included in the EIO-LCA because the wastewater treatment plant will still need to treat the same amount of wastewater.

Thus, after adjusting for inflation, 50 apartment buildings discounted over the 50-year design life of the project results in $4.19 million which was used as an input to the Water and Wastewater Treatment sector.

3.4.3.2 Water Savings in Scottsdale

In Scottsdale, the general service commodity charge is $4.60 per kgal for potable water. The sewer rates are $2.23 per kgal for apartment buildings. The Rainwater Harvester program was used to calculate the water saved through the entire year. The results of the model indicate that approximately 275 kgal would be saved from a 50 kgal cistern in Scottsdale. This results in water and sewer savings of $1,300 and $600, respectively. The owner will save this amount on the sewer fees due to the fact that sewer rates are tied to potable water usage. However, only potable water savings will be included in the EIO-LCA because the wastewater treatment plant will still need to treat the same amount of wastewater.

Thus, after adjusting for inflation, 50 apartment buildings discounted over the 50-year design life of the project results in $1.37 million which was used as an input to the Water and Wastewater Treatment sector.

3.4.3.3 Water Savings in Omaha

In Omaha, the general service commodity charge is $1.11 per kgal for potable water. The sewer rates are $2.23 per kgal for apartment buildings. The Rainwater Harvester program was used to calculate the water saved through the entire year. The results of the model indicate that approximately 897 kgal would be saved from a 50 kgal cistern in Omaha. This results in annual water and sewer savings of $1,173 and $2,001, respectively. The owner will save this amount on the sewer fees due to the fact that sewer rates are tied to potable water usage. However, only potable water savings will be included in the EIO-LCA because the wastewater treatment plant will still need to treat the same amount of wastewater.

Thus, after adjusting for inflation, 50 apartment buildings discounted over the 50-year design life of the project results in $1.27 million which was used as an input to the Water and Wastewater Treatment sector.

3.4.3.4 Water Savings in Tampa

In Tampa, the general service commodity charge is $2.47 per kgal for potable water. The sewer rates are $5.23 per kgal for apartment buildings. The Rainwater Harvester program was then used to calculate the water saved through the entire year. The results of the model indicate that approximately 903 kgal would be saved from a 50 kgal cistern in Scottsdale. This results in water and sewer savings of $2,230 and $4,721, respectively. The owner will save this amount on the sewer fees due to the fact that sewer rates are tied to potable water usage. However, only potable water savings will be included in the EIO-LCA because the wastewater treatment plant will still need to treat the same amount of wastewater.

Thus, after adjusting for inflation, 50 apartment buildings discounted over the 50-year design life of the project results in $2.41 million which was used as an input to the Water and Wastewater Treatment sector.

3.4.4 Pumping Energy

The rainwater collection and distribution systems were modeled using EPANET. For all 4 sites, the required energy to pump the water to its end uses was found to be approximately 846.16 kWh/Mgal. In 2002, the average wholesale price for electricity was 3.56 cents per kWh. The producer prices for pumping costs are included in Table 3.46. The values shown in Table 3.46 were used as inputs to the Power Generation and Supply EIO-LCA sector.

Table 3.46 – Pumping Energy Costs

Site	Amount
Seattle	$30,900
Scottsdale	$10,700
Omaha	$34,800
Tampa	$35,000

3.4.5 Excavation

The excavation costs for the underground rainwater cistern were also estimated. The underground storage tank in Seattle was 30,000 gal. For all tanks, it was assumed that 3' of cover would be needed to prevent freezing of the tank. In addition, the tank depth would be over-excavated by 1' in depth, and 3' on each side. Thus, the overall excavation volume for a 30,000 gal tank is approximately 333 cubic yards. The Means Construction Cost data book estimates excavation costs at $1.73 per cubic yard which results in an overall excavation cost of $28,800 for 50 apartments in 2002 U.S. dollars. This amount was applied to the Construction of Non-residential structures sector in the EIO-LCA.

The same assumptions were used to calculate the excavation volume for a 50,000 gal tank in Scottsdale, Omaha, and Tampa. The result was approximately 505 cubic yards of excavation for the tank, and an excavation cost of $43,700 for 50 apartments in 2002 U.S. dollars.

3.4.5 Disposal Phase

The final phase in this LCA is the disposal of materials. It is assumed that all materials used in the LCA are placed in a landfill even though materials such as the underground steel tank could be recycled. The environmental impacts of this phase are relatively small compared to the other phases of the study, so this assumption will have minor impacts on the results of this analysis. Table 3.47 displays the amount of materials that will be disposed of in each of the four sites as well as their corresponding landfill prices. These prices were adjusted for inflation to 2002 U.S. dollars and multiplied by 50 to include impacts associated with a 50 apartment buildings. These prices were then used as an input in the EIO-LCA model in the Waste Management and Remediation services sector.

Table 3.47 – Disposal Cost Calculation

Site	2009 Consumer Price for Landfill fees (per ton)	2009 Producer Price for Landfill fees (per ton)	2002 Producer Price for Landfill fees (per ton)	Disposal Amount for 50 apartments (tons)	Total for 50 apartments (2002 U.S. dollars)
Seattle	$102.05	$89.91	$75.42	9,440	$712,100
Scottsdale	$37.00	$32.60	$27.34	13,550	$370,500
Omaha	$23.12	$20.37	$17.09	13,550	$231,500
Tampa	$41.00	$36.12	$30.30	13,560	$410,800

3.5 Model 5 - Development of an EIO-LCA for a Water Reuse Design for a Community

The final design analyzed is a community-wide water reclamation system in which treated wastewater is distributed in a separate pipe network and used for non-potable uses (i.e., toilet flushing, landscape irrigation, laundry washing, fireflow, etc.). the community covers approximately one square mile and has a population of approximately 6,732 (3,357 in residential houses assuming 2.8 people per household and the rest living in apartments) as well as various commercial buildings. A more detailed description of the community-wide distribution system can be found in Killion (2011). Figures 3.11-3.13 display the pipe networks for the conventional, potable, and non-potable or reclaimed water distribution systems, respectively.

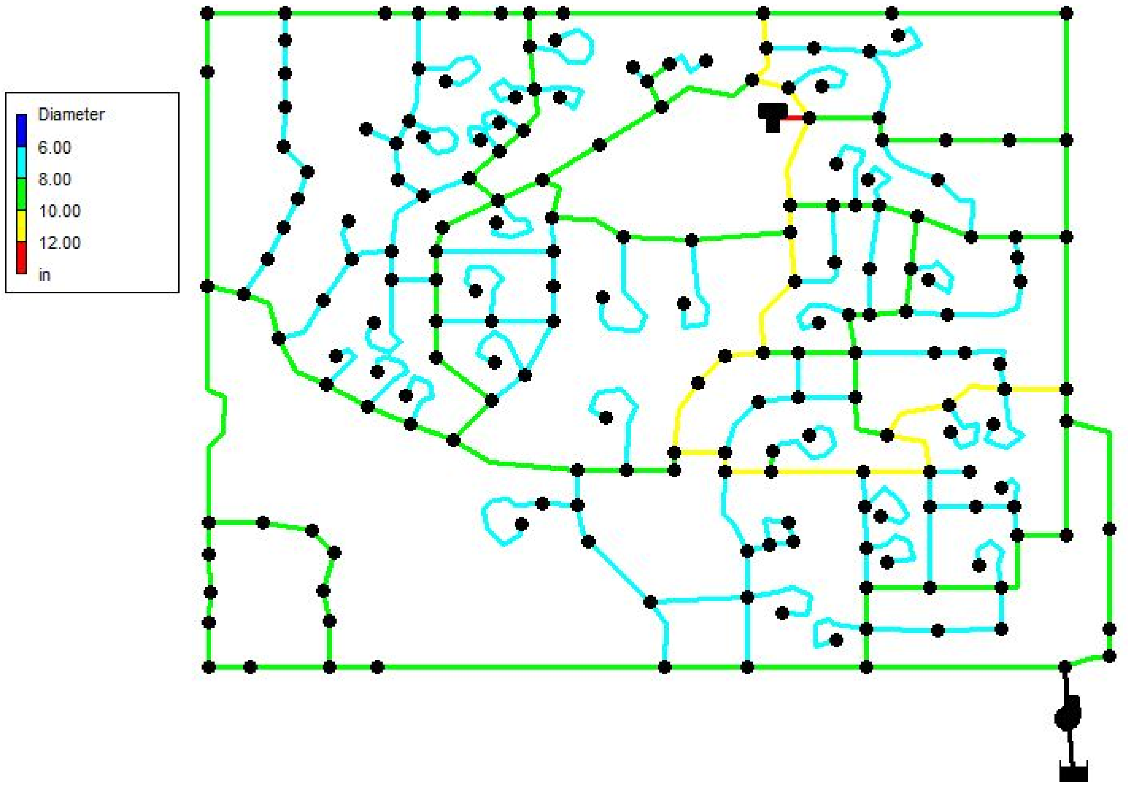


Figure 3.11 – EPANET 2 Model for the Conventional System

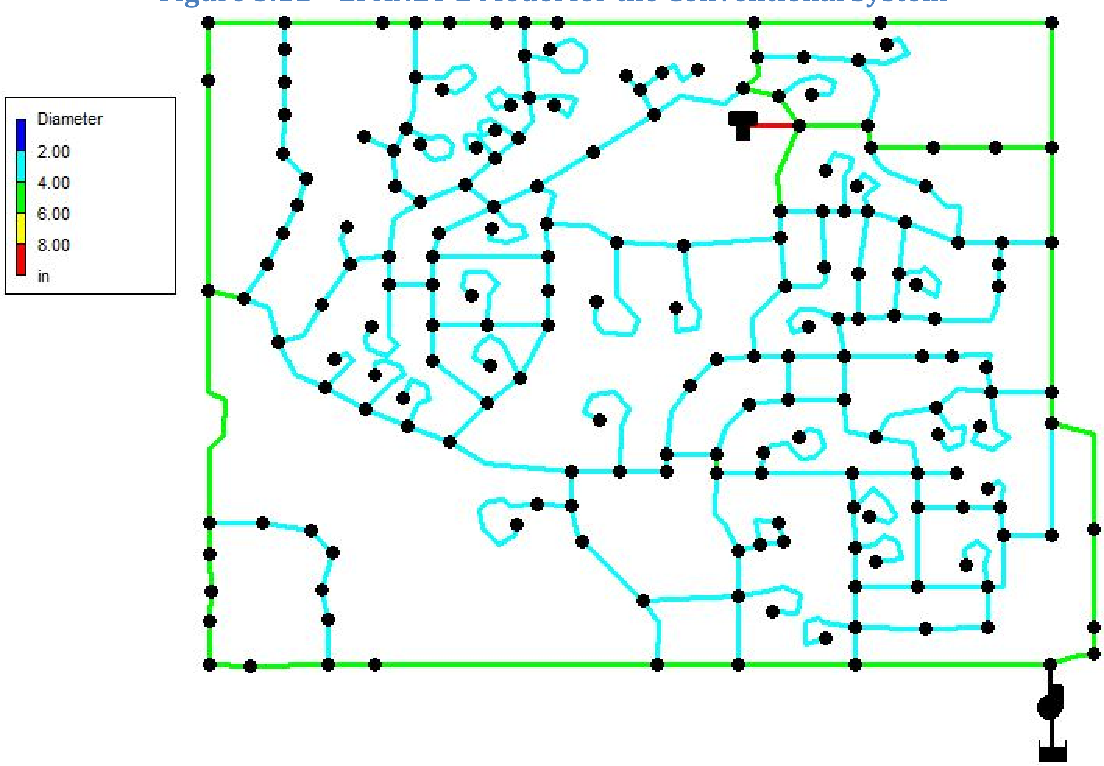


Figure 3.12 – EPANET 2 Model for the Potable Water Distribution System

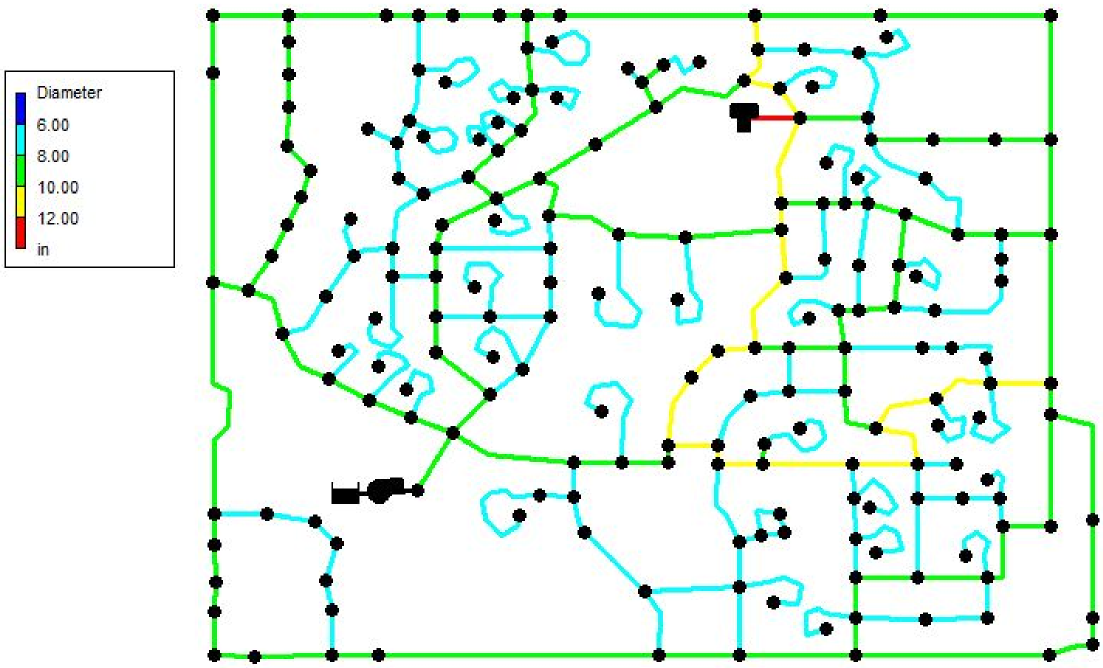


Figure 3.13 – EPANET 2 Model for the Reclaimed Water Distribution System

The pump and "reservoir" in the southeast corners of Figures 3.11-13 represent the municipal water supply. The elevated storage tank for the community is in the north-central area of each figure. Each node, shown by a dot in the model represents approximately ten houses or a commercial or apartment building. Commercial businesses and apartment buildings are primarily along the western edge of the community.

The water distributed in the non-potable or reclaimed system would require higher levels of treatment than is provided by a conventional activated sludge plant due to the fact that reclaimed water is brought into the house for toilet flushing and other indoor, non-potable uses. In order to meet the respective standards (which vary by state), an additional treatment step (tertiary treatment) or a membrane bioreactor (MBR) would be necessary to meet these water quality standards. However, a detailed comparison between an LCA of a conventional activated sludge plant and of a MBR plant would be very complex. Process data would be needed to analyze the differences between these two plants. In addition, wastewater treatment plants have intricate electrical, instrumentation, control, and mechanical systems, which would need some level of design to be quantified in order to address the life cycle impacts of this study.

An adequate life cycle comparison of these two treatment systems would require a process LCA as distinct sectors are not available in the EIO-LCA model for many of the materials needed in a wastewater treatment plant. Many of these materials are specific to the wastewater industry. Using an EIO-LCA model on wastewater treatment plants would introduce a high level of variability and uncertainty into the analysis, for the reasons stated previously. For example, each plant has varying discharge permit requirements depending on the location and receiving water body. The wastewater characteristics vary on a site by site basis as well depending on a variety of factors including climate, infiltration rates, percentage of and type of industries, and other factors. In addition, there are multiple treatment technologies available and this study looked at two of the available options. Thus, it was determined that differences in treatment would be excluded from this study, and noted. Finally, planning level cost comparisons of the two treatment systems show that the overall costs are similar for moderately sized installations such as this.

3.5.1 Materials Phase

Killion (2011) modeled the community using EPANET 2. The existing water distribution network was sized for fireflow demands, and in this paper is referred to as the conventional system. The community scenario modifies the conventional system by treating the wastewater to reuse water standards and delivering it back to the community for non-potable uses such as toilet flushing, laundry washing, fireflow, and landscape irrigation. Thus, this scenario requires an additional water distribution network, one for non-potable water, and the other for potable water. The non-potable water distribution network is essentially equivalent to the existing or conventional distribution network because both water distribution networks are sized for fire flow demands. There are potential minor differences due to location of valves and other small design details, but minor details such as these were considered in this analysis.

The community scenario, however, requires an additional potable water distribution system which was sized to deliver only the potable water demand. Table 3.48 displays the materials included for the potable water distribution network.

Table 3.48 – Materials Required for Community Scenario

Materials	Unit Price	Unit	Quantity	Total Price	EIO-LCA Sector
2" PVC C900 Pipe	$1.08	LF	69570	$75,135.60	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" PVC C900 Pipe	$3.77	LF	25431	$95,874.87	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" PVC C900 Pipe	$13.80	LF	129	$1,780.20	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" Long Radius Elbow	$4.30	EA	38	$163.40	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" Long Radius Elbow	$20.50	EA	4	$82.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 45d Elbow	$8.15	EA	165	$1,344.75	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" Tee	$18.15	EA	1179	$21,398.85	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" Tee	$33.00	EA	93	$3,069.00	326122 Plastics Pipe and Pipe Fitting Manufacturing
2" 4way	$10.67	EA	11	$117.37	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" 4way	$41.12	EA	1	$41.12	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" to 2" Reducer	$31.78	EA	19	$603.82	326122 Plastics Pipe and Pipe Fitting Manufacturing
8" to 4" Reducer	$100.32	EA	1	$100.32	326122 Plastics Pipe and Pipe

					Fitting Manufacturing
2" PVC Gate Valves	$37.59	EA	155	$5,826.45	326122 Plastics Pipe and Pipe Fitting Manufacturing
4" Water Distribution Gate valves	$266.00	EA	32	$8,512.00	33291 Metal Valve Manufacturing
Motor (60 HP)	$11,206	EA	1	$11,206.00	335312 Motor and Generator Manufacturing
Grundfos Pump 625S600-3A (60 HP)	$6,467	EA	1	$6,467.00	333911 Pump and Pumping Equipment Manufacturing
TOTAL				**$231,722.75**	

Note: Prices listed in Table 3.48 are taken from RSMeans Building Construction Data (Reed Construction Data 2009), local suppliers (Ferguson Plumbing in Omaha), and price quotes from other suppliers.

Table 3.49 displays the total amount used as inputs to each sector in the EIO-LCA model after adjusting for inflation to 2002 U.S. dollars, and after backing out the mark-up value from the retail price to arrive at the producer prices of the materials.

Table 3.49 – Producer Prices of Materials in Community Scenario

EIO-LCA Sector	2002 Producer Price
326122 Plastics Pipe and Pipe Fitting Manufacturing	$154,012.97
33291 Metal Valve Manufacturing	$6,494.66
335312 Motor and Generator Manufacturing	$6,918.58
333911 Pump and Pumping Equipment Manufacturing	$3,829.76
TOTAL	**$171,255.97**

Note: Values listed are in 2002 U.S. Dollars

As can be seen from Tables 3.48 and 3.49, storage tanks and upgrades at the wastewater treatment plant are not included in the analysis. Storage tanks were sized for the conventional, non-potable, and potable systems. The analysis resulted in tanks with a high water elevation of 129 feet above ground surface with storage volumes of 1,291 kgal, 922 kgal, and 369 kgal for the conventional, non-potable, and potable systems, respectively (Killion, 2011). These design requirements necessitate tanks with volumes of 1,500 kgal (material cost was quoted at $1,720,000), 1,000 kgal (material cost was quoted at $1,190,000), and 400 kgal ($390,000). Thus, the cost of the elevated storage tank for the conventional system is very similar (within 10%) to the cost for materials of the 2 smaller tanks in the water reclamation system. In additional, it was decided that the impacts due to the storage volumes would greatly depend on the design specifics (i.e., controls, foundations, etc.). There is also great uncertainty in quantifying the environmental impacts of concern for the construction of the elevated tanks. Thus, due to the small differences in material cost between the two sectors, it was determined that the materials required for storage were essentially equal for the two systems, and the differences were not considered as part of this study.

As can be seen in Table 3.48, gate valves were included in this analysis. However, depending on the design, the number and placement of valves could vary significantly, depending on the needs and protocols of the utility. There may be a difference in the number of valves between the conventional and non-potable systems. However, since the two systems were identical in terms of pipe size and lengths, it was assumed that the number of valves in each of these systems would be equivalent. The gate valves on the potable distribution system were counted and included in the analysis, but check valves and other valves were not included in the design. The cost for these minor design details would be small since the valves would be small and relatively inexpensive (on 2” and 4” PVC pipes). These valves would have a negligible impact on the overall analysis, and were not considered.

3.5.2 Use Phase – Water Savings

In order to calculate the savings from the water reclamation system within the community, average water rates were needed. Since the majority of municipalities have block rate structures in which rates increase with increasing use, an average use was also needed. Using the results from the EPANET 2 model (Killion, 2011), the average end user uses approximately 6.48 kgal/month in this community. To determine the water costs, this usage rate was applied to each of the 12 sites in the Residential End Uses of Water Study (Mayer et al. 1999). The result is a 12-site average water rate of $1.66 per kgal.

The results of the EPANET 2 model indicate that approximately 371 kgal per day will be re-used via the water reclamation system. Thus, the present value of the water savings over 50 years is $6.25 million after adjusting to 2002 dollars.

3.5.3 Use Phase – Additional Energy Costs for Pumping

As modeled, the conventional system would convey 579.5 kgal per day. The EPANET 2 model for the conventional system shows that the energy requirements for the community (as designed) are 831 kWh per million gallons of water conveyed. Thus, the conventional system would use 175,770 kWh annually.

The community reuse design requires 812.8 kWh per million gallons in the non-potable distribution network and 1,545 kWh per million gallons in the potable distribution network. The daily distribution of water in the non-potable and potable systems is 371 kgal and 208.6 kgal, respectively. Thus, the reuse design would require 227,700 kWh annually, which exceeds the conventional system by 51,929 kWh.

In 2002, the average wholesale price of electricity in the United States was 3.56 cents per kWh. Thus, the pumping energy costs for distribution for the water in the reuse design would exceed the conventional system by $1,850 on an annual basis. For the 50-

year design life of the system, the present value of these costs is $47,600, which is used as an input into the Power Generation and Distribution sector in the EIO-LCA model.

3.5.4 Disposal Phase

As with the previous scenarios, the materials in this design were assumed to be placed in a landfill. The total weight of the materials shown in Table 3.49 and 3.50 was estimated to be 118,000 lbs. From Section 3.2, the 4-city average (Omaha, Seattle, Scottsdale, and Tampa) price for landfills was $50.79 per ton. Thus, the total used as an input in the EIO-LCA model is approximately $3000 in the Waste Management and Remediation Services sector.

4.0 Chapter 4 Results and Discussion

4.1 Feasibility of Designs: Benefit/Cost Analysis

A benefit/cost analysis was performed for each of the designs at the given sites. In terms of economic benefits and costs, an individual investment or project in this case is considered worthwhile and feasible if its benefits/cost ratio is greater than 1.0.

4.1.1 Simple Greywater Reuse System for Residential House

The first analysis only considers the cost for materials. The analysis was first done considering no labor costs (i.e., the homeowner completes the installation). This analysis was done for each of the four study sites, and the results are in Table 4.1.

Table 4.1 – Benefit/Cost Analysis of Simple Greywater Reuse System with no Labor Costs

	Seattle	Scottsdale	Omaha	Tampa
First Cost	$644.64	$506.01	$718.69	$644.64
Project life (years)	50	50	50	50
Annual receipts or savings	$56.64	$37.09	$33.35	$36.49
Annual O & M costs	$10	$10	$10	$10
Salvage value	$0	$0	$0	$0
MARR	3%	3%	3%	3%
B/C	**1.88**	**1.40**	**0.93**	**1.07**

At an interest rate of 3%, which is approximately the rate of inflation, all of the study sites were feasible or cost effective with the exception of Omaha. Omaha's benefit/cost ratio is 0.93 which is slightly less than 1.0. The main reason for this was the low cost for water and sewer in Omaha.

The analysis was then repeated considering labor costs of contractors completing the installation. The amount for labor depends on the size and slope of your lot, as well as the design. For a new home, the difference in the amount of labor between a typical plumbing system and a simple greywater reuse system is negligible inside the home. However, substantial labor outdoors is necessary to lay the pipe. The cost for the outdoor labor is assumed to be $10 per hour.

Table 4.2 – Benefit/Cost Analysis of Simple Greywater Reuse System including Labor Costs

	Seattle	**Scottsdale**	**Omaha**	**Tampa**
First Cost	$644.64	$506.01	$718.69	$644.64
Labor	$250	$200	$300	$250
Project life (years)	50	50	50	50
Annual receipts or savings	$56.64	$37.09	$33.35	$36.49
Annual O & M costs	$10	$10	$10	$10
Salvage value	$0	$0	$0	$0
MARR	3%	3%	3%	3%
B/C	**1.35**	**1.0**	**0.65**	**0.77**

Even considering labor costs, it is still economical to install a greywater system in both Seattle and Scottsdale. However, it is not economical in either Tampa or Omaha. The amount of greywater reused over a given year is relatively similar across the sites with the exception of Scottsdale which has a longer growing season. The main difference is the variance in water prices, as prices for potable water are much higher in Seattle than Omaha or Tampa.

Cost, however, is not the only consideration. There may be other drivers for water reuse including water shortages or wet weather programs looking to reduce sanitary flows. Water prices are also likely to rise, which would have a significant impact on this analysis.

4.1.2 Feasibility of Indoor Greywater Reuse System for Residential House

As the indoor greywater reuse system is designed, the first cost for the materials is $1809.40. In addition, this design requires electricity to run the pumps. These pumps require 513.5 kWh of electricity, which amounts to $54.12 per year in electricity costs. This system, on average, saves $52.24 per year for the reduced water costs. Consequently, the homeowner would have a net cost of $1.88 each year in addition to the first cost of the system. Thus, the benefit to cost ratio is 0.42. From the benefit/cost perspective, this design is clearly not feasible unless you have a larger than average household and save more water than the designed system.

However, if more greywater can be reused than is considered under the current design without increasing infrastructure costs, the benefit/cost ratio may change significantly. The indoor treatment system has a capacity of 83.4 gallons per day. If a reuse efficiency of 95% is assumed as in Section 3.2, it is possible to re-use 79.2 gallons of greywater per day. If the homeowner uses these 79.2 gallons per day (e.g., for the current indoor uses plus landscape irrigation via a hose), it is possible to reuse 28,919 gallons per year. This water could be applied to the landscape via a sprinkler because it has been treated. Assuming a site-average of $1.81 per kgal for water, and $2.67 per kgal for wastewater (same as Section 3.2), it is possible to save approximately $129.56 per year with this system.

In this case, the energy costs would also be higher. The energy for aeration would remain the same, as the aerator pump runs all of the time anyway. However, the energy required for the supply pumps would increase, and the total required for electricity would be approximately $55.11, leaving a savings of $74.45 per year. The benefit/cost ratio would be 1.06 in this case, slightly above what is considered economically feasible. This would be a justifiable investment if 95% of the water was reused.

The difference between the actual design system and the hypothetical scenario is the amount of greywater produced and reused. In Section 3.2, it was assumed that a homeowner who employs a water reuse system would also have water efficient appliances. This may or may not be the case. However, it would take more than the average household (approximately 2.8 people) to produce enough greywater for this system to make economic sense. Improvements either need to be made to reduce the amount of energy required for aeration, or in the materials needed to collect and supply the water to its end uses. Higher water prices could also tip the scales in favor of this design, if they increase faster than electricity and material prices.

4.1.3 Feasibility of Hybrid Greywater and Rainwater Reuse System for Residential House

Table 4.3 displays the benefit/cost analysis for Model 3 (the hybrid greywater and rainwater reuse system).

Table 4.3 – Benefit/Cost Analysis of Hybrid Greywater and Rainwater Reuse System

	Seattle	**Scottsdale**	**Omaha**	**Tampa**
First Cost	$5398.52	$5382.51	$5663.36	$5914.33
Project life (years)	50	50	50	50
Annual receipts or savings	$156.46	$51.83	$51.26	$179.34
Annual O & M costs	$10	$10	$10	$10
Salvage value	$0	$0	$0	$0
MARR	3%	3%	3%	3%
B/C	**0.70**	**0.20**	**0.19**	**0.74**

Note: Annual O & M costs include costs for electricity to run pumps. Average retail cost of electricity in U.S. in 2010 is 10.54 cents/kWh (www.eia.gov).

As currently designed, none of the sites were financially feasible. The main driver is the extensive materials required for this design scenario. A large amount of water has to be saved in order to pay off a system that costs a homeowner over $5000. At current water prices, no system that costs this much will be economically feasible.

4.1.4 Feasibility of Rainwater Reuse System for Apartment Building

Table 4.4 displays the benefit/cost analysis for Model 4 (the rainwater reuse system for an apartment building).

Table 4.4 – Benefit/Cost Analysis of Rainwater Reuse System for an Apartment Building

	Seattle	Scottsdale	Omaha	Tampa
First Cost	$77,204.00	$93,302.00	$93,087.00	$93,302.00
Project life (years)	50	50	50	50
Annual receipts or savings	$13,457.00	$1877.00	$3,174.00	$6,951.00
Annual O & M costs	$171	$125	$180	$181
Salvage value	$0	$0	$0	$0
MARR	3%	3%	3%	3%
B/C	**4.43**	**0.48**	**0.83**	**1.87**

Note: First cost includes cost of materials and the cost of excavation. It does not include the cost of labor for the construction of the associated system. Annual O & M costs include costs for electricity to run pumps plus $100 per year for maintenance of diverters, filters, and other system parts. Average retail cost of electricity in U.S. in 2010 is 10.54 cents/kWh (www.eia.gov).

As currently designed, this design is financially feasible in Tampa and Seattle. It is actually an attractive financial investment in Seattle as the benefit/cost ratio is very high. It is nearly feasible in Omaha with water rates at $1.11 per kgal (which is well below the cost of water in the other sites). Holding sewer rates constant at $2.23 per kgal, this system would become feasible with water rates above $2.00 per kgal which is still substantially below the water rates in Seattle and Tampa.

The main reasons for differences in this analysis are the availability of rainwater and the cost of water. In Seattle, the rainfall patterns were such that a smaller tank was optimal as compared to the other sites. The smaller tank greatly reduced the price of materials. In addition, Seattle also had the highest water and sewer rates, which is the other reason for the large difference.

4.1.5 Feasibility of Community Water Reclamation System

A conventional activated sludge plant's capital and operational and maintenance costs were calculated using equations from Qasim (1999). Using these equations, it was determined that a conventional activated sludge treatment plant (sized for 250,000 gpd) would cost approximately $1.485 million in capital costs and approximately $179,000 in operation and maintenance costs.

A price quote was obtained from GE for a MBR treatment plant sized for a daily load of 250,000 gpd. The capital costs were estimated at $995,000 which includes packaged membrane system, chemical cleaning systems, process blowers, RAS pumps, anoxic mixers, aeration blower and diffusers, turbidity meters, and TP reduction. The annual power consumption was estimated to be 178,000 kWh. At 10.54 cents per kWh, this amounts to just under $19,000 per year in electricity costs. It was also estimated that the MBR plant would require 298 gal of NaOCL and 180 gal of Citric Acid annually. In addition, there would be additional annual expenses for replacement parts and maintenance (Higgins 2011).

Although the capital costs for the MBR plant are slightly lower, it was estimated that the operation and maintenance costs would be slightly greater with the MBR plant. It was determined that the costs of the two plants are essentially equivalent, and would depend greatly on site-specific conditions and the characteristics of the wastewater. Thus, cost differences between the two treatment plants were considered equivalent, and excluded from the economic analysis of Model 5.

Although the community reclamation system would require an additional elevated water storage tank, the conventional tank (1,500,000 gallon tank quoted at $1,720,000 for materials cost) for this design actually costs slightly more than the two required tanks for the potable (400,000 gallon tank quoted at $390,000 for materials cost) and non-potable (1,000,000 gallon tank quoted at $1,190,000 for materials cost) water distribution systems. The total costs for the tanks could depend on a number of factors including the cost of land for the tank, elevation head required, and size of foundation needed. For this study, it is assumed that the costs of the tanks will be nearly equivalent on average. Thus, these costs are excluded from this analysis.

Using the quantities of materials listed in Table 3.48, the additional capital costs for construction were estimated to be $485,000. From the 2002 Means Costbook, the estimated construction price per linear foot for 2", 4", and 8" pipe is $2.84, $7.15, and $19.50, respectively. The cost of the rest of the materials was included as recorded in Table 3.48. In addition, a 10% contingency was added for the construction related to the additional pump, motor and other ancillary materials. The additional electricity required (for pumping) for the water reclamations system would cost an additional $1850 per year. However, the savings from the utility costs would be approximately $225,000 at $1.66 per kgal. No adjustments for inflation are needed for the utility cost savings or the construction costs as both figures are in 2002 U.S. dollars. Thus, the benefit/cost ratio is 11.8, and the simple economic payback for the community water reclamation system would be approximately 2.2 years. Therefore, from an economic perspective, this is an option that deserves consideration from municipal supply planners.

4.2 EIO-LCAs of Water Reuse Strategies

Using the methods discussed in Section 3, the greenhouse gas emissions, energy use, toxic releases, and water use were calculated using the EIO-LCA model (Hendrickson et al. 2006). The results of the analysis are shown in Tables 4.5 - 4.8. These same results are shown graphically in Appendix A. Results with values below zero represent a decrease in environmental impacts (i.e., greenhouse gas emissions, energy use, toxic releases, or water consumption) as compared to the conventional plumbing system. Results with values above zero indicate an increase in environmental impacts as compared to the conventional system.

Table 4.5 – EIO-LCA Results in Terms of Greenhouse Gas Emissions (Mtons of CO_2 eq.)

	Materials Phase	Use Phase		Disposal Phase	**Net Total[c]**
		Utility Cost Savings[a]	Pumping Energy		
Model 1-Seattle	550	-2,600	n/a	46	**-2,000**
Model 1-Scottsdale	430	-1,700	n/a	15	**-1,300**
Model 1-Omaha	620	-1,300	n/a	11	**-640**
Model 1-Tampa	550	-1,700	n/a	18	**-1,100**
Model 2-site average	1,100	-2,400	4,400	14	**3,100**
Model 2-best case[b]	*1,100*	*-6,400*	*4,500*	*14*	***-830***
Model 3-Seattle	4,700	-3,600	31	140	**1,200**
Model 3-Scottsdale	4,700	-2,100	17	53	**2,700**
Model 3-Omaha	4,800	-1,400	57	35	**3,500**
Model 3-Tampa	5,100	-1,700	62	65	**3,600**
Model 4-Seattle	3600	-7500	290	1800	**-1,700**
Model 4-Scottsdale	4400	-2400	100	950	**3,000**
Model 4-Omaha	4400	-2300	330	600	**3,000**
Model 4-Tampa	4400	-4300	330	1100	**1,500**

Model 5-site average	230	-11,000	450	8	**-10,000**

Note: (a) Savings in this column are due to reductions in demand to the water and sewer utility providers. These savings represent a reduction in treatment and conveyance of the water/wastewater. (b) These results were approximated by scaling the results from Model 2, as detailed in Section 3.2.3. Since the EIO-LCA model is linear, scaling the results is reasonable. Since the amount of water saved is 2.67 times greater than the amount in Model 2, the utility cost savings are scaled by 2.67 while the energy costs for pumps are scaled by 1.018. (c) The totals displayed in this table are not meant to be quantitatively compared from model to model. The purpose of the results is show an improvement or decline as compared to the standard system.

Table 4.6 – EIO-LCA Results in Terms of Energy Consumption (TJ)

	Materials Phase	Use Phase		Disposal Phase	**Net Total[c]**
		Utility Cost Savings[a]	Pumping Energy		
Model 1-Seattle	8.8	-30	n/a	0.1	**-21**
Model 1-Scottsdale	6.7	-20	n/a	0.0	**-13**
Model 1-Omaha	9.9	-13	n/a	0.0	**-3.4**
Model 1-Tampa	8.8	-19	n/a	0.0	**-10**
Model 2-site average	17	-25	52	0.0	**45**
Model 2-best case[b]	17	-67	53	0.0	**3.6**
Model 3-Seattle	71	-38	0.4	0.3	**34**
Model 3-Scottsdale	72	-22	0.2	0.1	**51**
Model 3-Omaha	75	-15	0.7	0.1	**61**
Model 3-Tampa	79	-31	0.7	0.1	**49**
Model 4-Seattle	57	-78	3	4	**-14**
Model 4-Scottsdale	69	-25	1	2	**46**
Model 4-Omaha	69	-24	4	1	**50**
Model 4-Tampa	69	-45	4	2	**30**
Model 5-site average	3.8	-120	5.3	0.02	**-108**

Note: (a) Savings in this column are due to reductions in demand to the water and sewer utility providers. These savings represent a reduction in treatment and conveyance of the water/wastewater. (b) These results were approximated by scaling the results from Model 2, as detailed in Section 3.2.3. Since the EIO-LCA model is linear, scaling the results is reasonable. Since the amount of water saved is 2.67 times greater than the amount in Model 2, the utility cost savings are scaled by 2.67 while the energy costs for pumps are scaled by 1.018. (c) The totals displayed in this table are not meant to be quantitatively compared from model to model. The purpose of the results is show an improvement or decline as compared to the standard system.

Table 4.7 – EIO-LCA Results in Terms of Toxic Releases (Mg C2H3Cl eq)

	Materials Phase	Use Phase		Disposal Phase	**Net Total[c]**
		Utility Cost Savings[a]	Pumping Energy		
Model 1-Seattle	110	-210	n/a	6.4	**-95**
Model 1-Scottsdale	86	-140	n/a	2.1	**-51**
Model 1-Omaha	120	-96	n/a	1.5	**30**
Model 1-Tampa	110	-140	n/a	2.6	**-22**
Model 2-site average	480	-180	90	1.7	**390**
Model 2-best case[b]	480	-480	90	1.7	**90**
Model 3-Seattle	71	-38	0.37	0.29	**34**
Model 3-Scottsdale	72	-22	0.21	0.11	**51**
Model 3-Omaha	75	-15	0.67	0.07	**61**
Model 3-Tampa	79	-31	0.74	0.13	**49**
Model 4-Seattle	2,000	-560	5.9	220	**1,700**
Model 4-Scottsdale	2,600	-180	2.0	110	**2,500**
Model 4-Omaha	2,600	-170	6.6	71	**2,500**
Model 4-Tampa	2,600	-330	6.7	130	**2,400**
Model 5-site average	53	-840	9.1	0.92	**-780**

Note: (a) Savings in this column are due to reductions in demand to the water and sewer utility providers. These savings represent a reduction in treatment and conveyance of the water/wastewater. (b) These results were approximated by scaling the results from Model 2, as detailed in Section 3.2.3. Since the EIO-LCA model is linear, scaling the results is reasonable. Since the amount of water saved is 2.67 times greater than the amount in Model 2, the utility cost savings are scaled by 2.67 while the energy costs for pumps are scaled by 1.018. (c) The totals displayed in this table are not meant to be quantitatively compared from model to model. The purpose of the results is show an improvement or decline as compared to the standard system.

Table 4.8 – EIO-LCA Results in Terms of Water Consumption (kgal)

	Materials Phase	Use Phase			Disposal Phase	**Net Total[c]**
		Utility Cost Savings[a]	Energy	Water Volume Savings		
Model 1-Seattle	6,900	-66,000	n/a	-340,000	170	**-400,000**
Model 1-Scottsdale	5,300	-43,000	n/a	-600,000	55	**-640,000**
Model 1-Omaha	7,800	-15,000	n/a	-600,000	40	**-610,000**
Model 1-Tampa	6,900	-42,000	n/a	-370,000	68	**-410,000**
Model 2-site average	15,000	-28,000	120,000	-540,000	28	**-430,000**

Model 2-best case[b]	15,000	-75,000	120,000	-1,400,000	28	**-1,400,000**
Model 3-Seattle	62,000	-42,000	1,000	-1,100,000	820	**-1,100,000**
Model 3-Scottsdale	63,000	-24,000	460	-950,000	110	**-920,000**
Model 3-Omaha	65,000	-17,000	1,500	-1,900,000	70	**-1,900,000**
Model 3-Tampa	68,000	-35,000	1,700	-1,900,000	130	**-1,900,000**
Model 4-Seattle	48,000	-87,000	7,800	-2,000,000	3,700	**-2,000,000**
Model 4-Scottsdale	58,000	-29,000	2,700	-690,000	1,900	**-650,000**
Model 4-Omaha	58,000	-27,000	8,700	-2,200,000	1,200	**-2,200,000**
Model 4-Tampa	58,000	-50,000	8,800	-2,300,000	2,100	**-2,200,000**
Model 5-site average	3,000	-130,000	12,000	15	-6,800,000	**-6,900,000**

Note: (a) Savings in this column are due to reductions in demand to the water and sewer utility providers. These savings represent a reduction in treatment and conveyance of the water/wastewater. (b) These results were approximated by scaling the results from Model 2, as detailed in Section 3.2.3. Since the EIO-LCA model is linear, scaling the results is reasonable. Since the amount of water saved is 2.67 times greater than the amount in Model 2, the utility cost savings are scaled by 2.67 while the energy costs for pumps are scaled by 1.018. (c) The totals displayed in this table are not meant to be quantitatively compared from model to model. The purpose of the results is show an improvement or decline as compared to the standard system.

4.3 Discussion of Results

As can be seen in Tables 4.5-4.8, Models 1 and 5 performed the best from an environmental standpoint. Model 1 (Simple Greywater Reuse System) resulted in reductions due to environmental impacts compared to the conventional system in all categories except for the toxic releases in Omaha where there was a slight increase. The reductions in greenhouse gas emissions, energy consumption, and water consumption were due largely to the reductions in water use which reduces the amount of potable water and wastewater that utilities have to treat. Model 1 also does not require any pumping energy to supply the water to the landscape which also adds to the reductions in environmental impacts. The Omaha design had slightly higher toxic releases because it irrigated a larger area, and thus required more materials.

Model 5 (Community Wastewater Reuse) also performed very favorably compared to the conventional distribution system in terms of environmental impacts with substantial decreases in all four categories. This is largely because of the substantial amount of water that could be saved by implementing the water reclamation system. In addition, the potable supply was so small that the distribution sizes for the potable supply were very small (2" and 4" pipes). The costs for 2" and 4" pipes is very low compared to larger pipes which helped the economics side of the analysis considerably. In addition, the environmental impacts from manufacturing the smaller pipes and fittings (2" and 4") is also reduced because there very little material is required, relatively, for pipes of this size.

As designed, Model 2 (Indoor Greywater Reuse) performed unfavorably in terms of environmental sustainability and economic feasibility. However, there were many variables to consider. If the household is larger than average, and produces more than the average amount of greywater, this system could make environmental and economic sense. However, any additional uses for the greywater would most likely require additional materials. Even under the hypothetical best-case, this system still results in a slight increase in energy consumption over the life cycle. Thus, unless changes are made to the design, the system saves a great amount of water but consumes some energy in the process.

Models 3 (Greywater and Rainwater Reuse in a Single Family House) and 4 (Rainwater Harvesting in an Apartment Building) had mixed results. These three models all resulted in substantial water savings. However, these three models also resulted in an increase in greenhouse gas emissions, energy consumption, and toxic releases (with the exception of Model 4 in Seattle) as compared to the conventional system.

When comparing the designs of the systems, it needs to be noted that the baseline changed between the simple greywater reuse system (Model 1) and the other two single family residential water reuse designs (Models 2 and 3). Model 1 is geared more for a retrofit of an existing house whereas the next two are designs for new construction. Models 2 and 3 assume that water conservation strategies (e.g., low-flow fixtures) are already being used by the homeowner, which means less water is being reused. Since less water is reused, the results of the EIO-LCA and economic analysis are less favorable for these designs than the first greywater reuse design. If the baseline comparison was changed so that conservation measures (water efficient appliances from USGBC LEED for Homes) were not taken prior to implementation of these water reuse designs, the analysis would show greater reductions in environmental impacts in the use phase (utility cost savings). However, the greater reuse volumes would also require greater amounts of energy to treat and supply the treated greywater or rainwater. In Model 2, the energy required to treat and supply the greywater was more expensive than the savings realized from the water reuse system on a per gallon basis. This would hold true no matter how much greywater is reused. Thus, changing the baseline would not alter the results in the analysis for Model 2 in any significant way.

Model 3 would have different results if the baseline was changed to exclude the implementation of conservation measures. In addition, there are several site-specific variables that would impact the overall results of the analysis in Model 3. They include the price of water, precipitation pattern of the city/region, amount of residents in home, and amount of water needed for non-potable uses. The purpose of this study was to determine the environmental sustainability and financial feasibility of these water reuse designs for the average homeowner. So, there may be locations where this model would perform favorably compared to the conventional system, but on average, this system is not an improvement to the conventional system.

For Models 1-4 (simple greywater system, indoor reuse system, hybrid system, and the rainwater reuse system for the apartment), the external impacts to the distribution network were ignored. For example, one could argue that the harvesting of rainwater would reduce the peak flows coming off of the lot in Models 3 and 4. However, these reductions cannot be relied upon from the utility's standpoint, due to the fact that there is zero storage available if the homeowner does not continue to pump the tank down between rains. There is also nothing preventing the homeowner from disconnecting the downspouts to the cistern. So, even though reductions in stormwater runoff could be realized by these systems, these impacts were not quantified in the study.

Also, in general, prices are higher in Seattle, Washington than Omaha, Nebraska. For example, the rates for water, sewer, and landfill fees are much higher in Seattle than Omaha. In the EIO-LCA, these higher prices translate into additional environmental impacts/savings. However, just because one ton of waste costs more for disposal in Seattle, in reality it probably does not mean more emissions will result from disposing into the higher-priced landfill. Less land is available for landfilling in Seattle than Omaha. Consequently, we do not believe that the result from any site specific analysis gives a complete answer to the sustainability question (Does the proposed design have an overall positive effect on the environment?). The results from this study should be looked at considering all four sites at the same time. If all four sites show a consensus, conclusions can be made in regards to the level of sustainability of each design. However, if there is not a consensus between the sites, it is difficult to make conclusive statements about the level of sustainability of the design across the United States.

Another issue in this analysis is the time value of money. The environmental savings resulting from the reuse of greywater or rainwater is discounted using a net present value analysis. This allows us to put one value into the EIO-LCA model and compare the environmental savings on an annual basis to the one-time impacts resulting from the purchase of various materials. Ideally, a dynamic model would be used for this analysis. However, currently nothing like this is available.

The markup percentage also can be calculated in a variety of ways. In our analysis, capital expenditures were included whereas many exclude this in the calculation of a markup percentage. The reason for this is that capital expenditures are usually considered fixed costs (i.e. sunk costs that cannot be recovered). Thus, if a company is looking at profitability moving forward, they would not consider the capital expenditures because that money has already been spent and cannot be recovered. However, the EIO-LCA model uses producer prices as an input. The model uses the amount that it costs producers to produce one unit of output in the given sector. For this reason, capital expenditures were included in order to give the actual price to the producer to produce a unit of output. The markup percentage in this study is lower than it would be if you left the capital expenditures out of the analysis.

Another large issue in this study is the value of water. Several of the designs are currently not economically feasible. However, it is possible that this is due to the current value of water. Water as a commodity is under-valued. If the price of water were to increase, these systems could become financially attractive investments very quickly.

4.4 Uncertainty Discussion

In any LCA or EIO-LCA, an uncertainty analysis is important to identify the level of variability in the results. There are two sources of uncertainty in this study which include uncertainty in the EIO-LCA model in estimating impacts and the uncertainty in the methodology used to calculate the producer prices used as inputs to the various EIO-LCA sectors. The following parameters are the main sources of uncertainty within the EIO-LCA model (Hendrickson 2006):

1. Survey errors: Some industrial plants may produce in multiple sectors which could introduce some error into the analysis.
2. Old data: The 2002 model, the model used in this study, is 8 years old. Some things may have changed since the 2002 data were published. For example, the average energy generation mix likely includes slightly more renewable energy generation which could reduce the emissions from the electricity generation sector. However, according to the Energy Information Administration (EIA), renewable energy generation is only projected to increase from 9.8% of the total electricity generated in 2010 to 12.7% of the total in 2035 (which would be the midpoint of this analysis). Even if it is conservatively assumed that all of this added renewable energy generation will be wind or solar (no emissions), the greenhouse gas emissions from the production of the materials would be reduced by approximately 3.2% (http://www.eia.gov/oiaf/aeo/tablebrowser/).

3. Incomplete and missing data: Hendrickson (2006) states that some small industries (e.g., auto repair shops, etc.) are not required to report toxic releases.
4. Aggregation: The EIO-LCA lumps the water and wastewater treatment into one sector. Since the processes are different, this introduces some error into the analysis.
5. Imports: The EIO-LCA does not recognize some imports within some sectors.

Lenzen (2000) estimated the total relative standard error of input-output coefficients in the EIO-LCA to be approximately 85%. Lenzen (2000) also stated that the relative standard errors of economic requirements are only 10-20%; however, because many of the errors in the individual coefficients cancel each other out (Hendrickson 2006). Thus, the overall uncertainty for this study for the above 5 factors is 10-20%.

There is also uncertainty in developing the producer prices used as inputs into the various sectors. For example, the following parameters, and the relative levels of uncertainty that they contribute to the overall assessment are:

- Evapotranspiration: The evapotranspiration data used in Models 1 and 3 was calculated from local measured data for wind speed, humidity and other parameters using the Penman-Monteith method. However, these data were just used to size the irrigated area, and did not impact the overall amount of water saved. This calculation only impacts the amount of materials needed to convey the water to these irrigated areas.
- Precipitation: The variability of precipitation would have minimal impacts on the outdoor greywater reuse systems (Models 1 and 3) due to the same reasons stated

for evapotranspiration. However, for the rainwater collection systems (Models 3 and 4) the precipitation data would have a slightly greater impact. Due to the fact that water is wasted due to overflow in large rain events, it is expected that the variability in precipitation data will have a small impact on the overall result of the study.

- Irrigation efficiency: This parameter adds a small amount of uncertainty.
- Retail prices of materials: In this study, the Means Costbooks were used for retail prices wherever possible. However, some materials were not included in this Costbook and were determined through contacting suppliers, or finding a supplier on the web. The variability of this parameter likely has a larger impact on the overall results than the other parameters.
- CPI Index: This parameter adds a very small amount of uncertainty.
- Calculation of markup factor : This parameter adds a very small amount of uncertainty.
- Pump energy calculations (Models 2-5): This parameter adds some uncertainty to the analysis as the energy required for the pumps was a major contributor on the overall result, especially for Model 2. In Model 2, a small aerator pump was needed to aerate greywater in the tank for the MBR. This calculation has some variability in it, as it was assumed that the aerator would need to run continuously. Thus, this parameter adds moderate uncertainty to the overall results.

4.5 Evaluation of Contributing Sectors

In this section, areas with the potential for significant improvement are highlighted as well as the major contributors the environmental burden of the five water reuse designs (models). In Model 1, the sectors with the greatest contribution to greenhouse gas emissions and energy consumption for all sites were the “Power Generation and Supply” and the “Plastic Material and Resin Manufacturing” sectors. This shows that significant electricity and energy is required for the manufacturing of materials necessary for the design, particularly PVC pipe. Since PVC pipe was used for the collection and distribution of the greywater, it makes sense that this was the largest contributor. Other materials could be explored for this function (i.e. collection and distribution of greywater), but further savings in environmental impacts through use of another pipe material is not expected.

With a few exceptions, the “Power Generation and Supply”, “Plastic Material and Resin Manufacturing”, and “Iron and Steel Mills” were the top three contributors in terms of greenhouse gas emissions and energy consumption for the materials phase of the EIO-LCA. This means that the manufacturing of the materials included in all models is very energy intensive. Improvements in the energy generation mix (i.e. more renewable energy) could reduce the overall impact of manufacturing the required materials. As stated in the previous section, the impact of additional renewable energy is expected to have a minimal impact on the overall analysis. Improvements to the efficiency and emissions of thermoelectric generation could also reduce the impact of the manufacturing of materials.

Other areas for improvement include the selection of materials in the water reuse designs. More sustainable materials for the collection and storage of greywater and rainwater offer opportunities for improvement on the overall result. For example, the underground steel tank for Model 4 contributed much of the environmental impacts of that design. A new, more sustainable, material could reduce those impacts.

Sizing the MBR treatment system specifically for the water production rates at a given house has the potential to significantly improve the results for Model 2, as was discussed in Section 4.1.2. Another potential improvement to this system would be to look at ways to reduce the energy requirements of the greywater treatment. Reducing the amount of time that the aerator pump has to run would reduce the environmental burden of the overall system.

5.0 Chapter 5 Conclusions and Recommendations

5.1 Conclusions

In general, it was determined that there are no solutions without tradeoffs or system complications. Even Models 1 and 5 that were environmentally preferable to the conventional system have some disadvantages. Both of these models would require additional systems to operate and maintain. There are also potentially additional health risks with these systems due to the use and potential exposure to non-potable water.

Some of the models were better suited for certain regions. For example, the models that included rainwater harvesting (Models 3 and 4) did not work particularly well in Scottsdale where there was little available rainwater. The designs required large cisterns in Scottsdale, and the water was used quickly. However, in Seattle and Tampa, the rainwater harvesting was determined to be a good idea. Rainwater harvesting also seemed to be particularly beneficial in Omaha where the months with the greatest available water from rainfall were also the months with greatest potable water demand

(June and July) due to landscape irrigation demands. Stormwater reductions would also be very beneficial in this city, as the City of Omaha is investing in infrastructure to reduce combined sewer overflows. The one caveat to rainwater harvesting in Omaha is the current low price of water making economic investments in rainwater harvesting or any form of water reuse difficult to justify from a financial point of view. However, rates are expected to increase greatly in the next few years.

The results of the analysis indicate that the simple greywater reuse system (Model 1) is most likely a good idea in terms of environmental sustainability and economic feasibility in most locations. There are some tradeoffs as mentioned previously, but in general, this model should be recommended. This water reuse system will become more attractive as the price of water increases. This system does not require any energy inputs, so it is independent of increases in energy costs.

The study pointed out that the overall results for the decentralized treatment of greywater for indoor reuse at the household level (Model 2) depend largely on the amount of water reused and the price of water in the given area. On average, this model is most likely not a good idea from an environmental or financial perspective unless improvements are made to the system, especially with respect to the aerator pump. The treatment process is energy intensive, and does not make financial sense at current prices of water and electricity. However, in certain circumstances, the system may make sense as noted by the best-case scenario evaluation. This treatment system may work better in a multi-family or multi-unit dwelling where more greywater is produced and treated. It is estimated that there may be some economies of scale at play with this system, as the price would decrease as the volume of treated greywater increases. In addition, this analysis was done on an average basis only. It is likely that in areas with high water and sewer fees like Seattle, this model would be more economically justifiable than the economic results presented in Section 4.1.2. Ultimately, the results greatly depend on the amount of water used by the homeowner, on average, and the price for water and sewer fees in that City. There are likely Cities where an indoor reuse system similar to Model 2 should be implemented. However, on average, there are better ways to reduce water consumption.

Models 3 and 4 are most likely site-specific and have mixed results. Rainwater harvesting is most likely a good idea wherever the price of water is high and where adequate rainfall is available like Seattle or Tampa. Metal or steel tanks were used for this analysis and they were placed underground. Improvements to this system could include environmentally friendly tank materials. In addition, there are several benefits to these systems that are not accounted for in this analysis. They include the capture of nitrogen in the rainwater that reduces nutrient loadings to receiving water bodies. Another benefit is the reduction in stormwater runoff from the site. Thus, it was determined that these two models should be evaluated on a site by site basis, but an overall conclusion cannot be made for all sites in the United States.

The analysis of Model 5 was very positive in terms of environmental sustainability and financially feasibility. The results of this study indicate that wastewater reclamation is a good idea, and should be further explored as a potential alternative in many areas.

5.2 Recommendations for Future Projects and Studies

This study has pointed out that Wastewater reclamation (Model 5) has potential to reduce greenhouse gas emissions, energy consumption, and water consumption. A more detailed analysis of the water quality requirements in each state and a more thorough comparison of the level of treatment needed to meet these regulations as compared to conventional wastewater treatment plants would be very beneficial.

A health risk assessment of the reuse of greywater and rainwater would help to address the social aspect of sustainability and the roadblocks to implementation of more water reuse systems. This risk assessment could help to more correctly quantify the actual health risks with each of these systems, and would address whether the current codes should be adjusted.

Other potential opportunities for further research include observing whether long term use of greywater and rainwater for landscape irrigation has any positive or negative impacts to plant health. Rainwater has nitrogen in it, so it would be interesting to see if using rainwater or greywater reduces the amount of fertilizer needed for turfgrass and landscape plants.

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Appendix A

Appendix A includes graphs or figures of the data presented in Section 4.2 (Tables 4.5-4.8). These figures are intended to give a graphical representation of the data, and visually display the relative impacts of each phase of the analysis. As can be seen from Figure A.1, the Use Phase was the largest contributor to greenhouse gas emissions for Model 1 (Simple Greywater Reuse System).

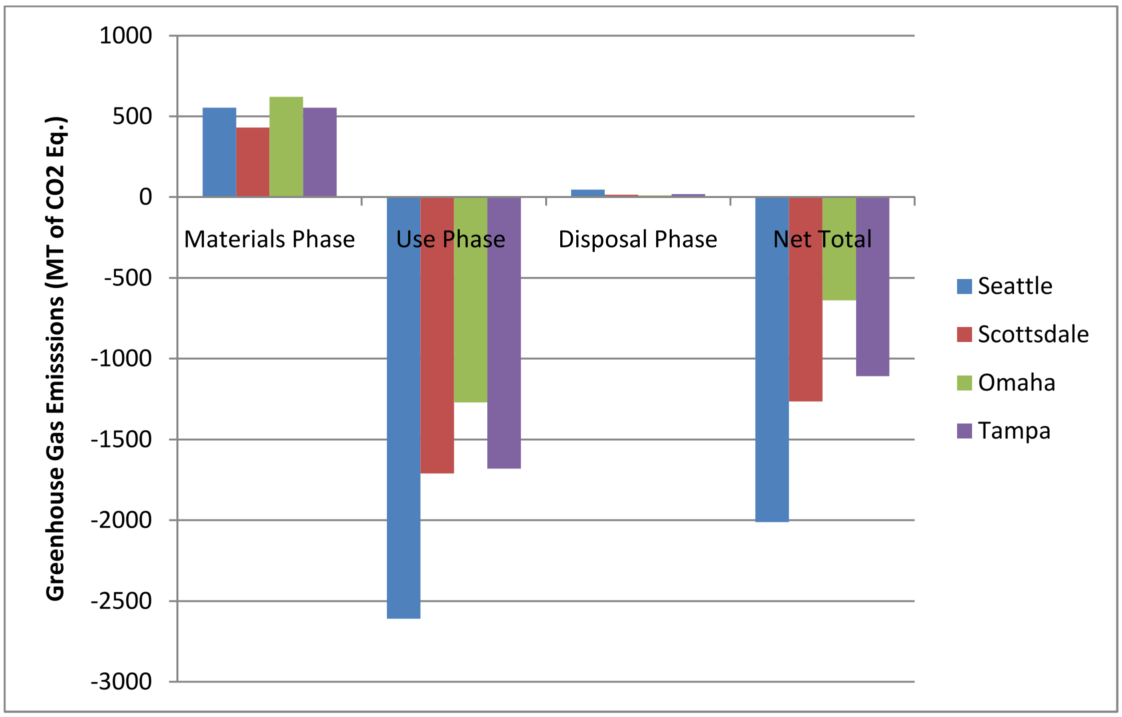


Figure A.1 – EIO-LCA of Simple Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Greenhouse Gas Emissions

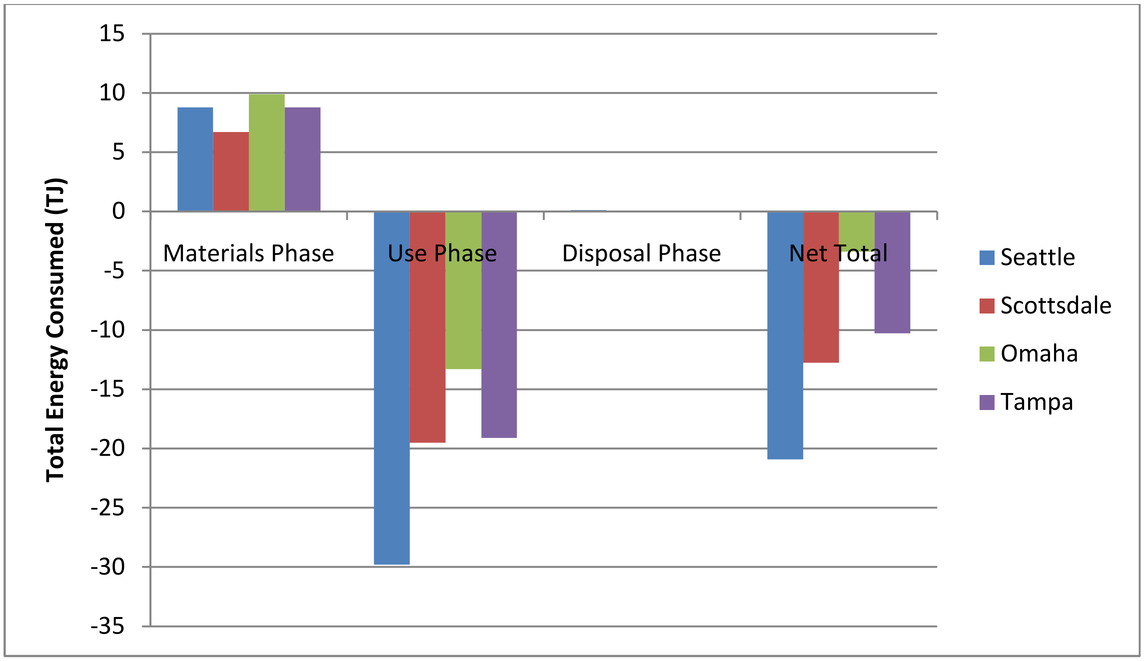


Figure A.2 – EIO-LCA of the Simple Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Energy Use

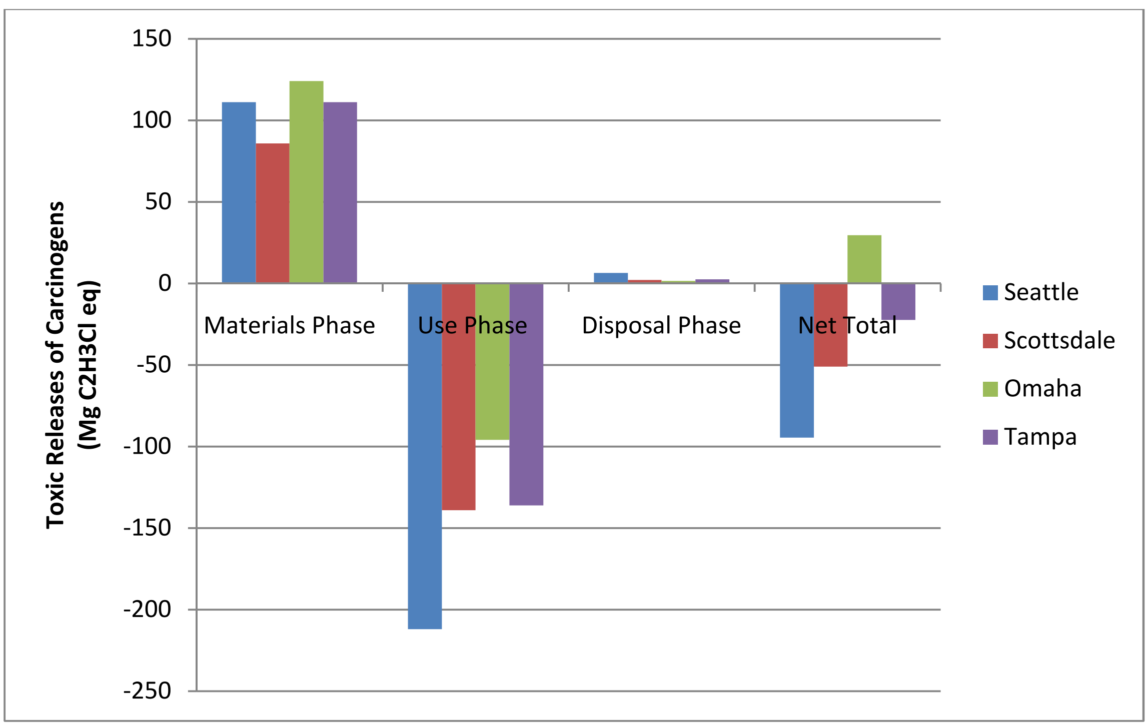


Figure A.3 – EIO-LCA of the Simple Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Toxic Releases

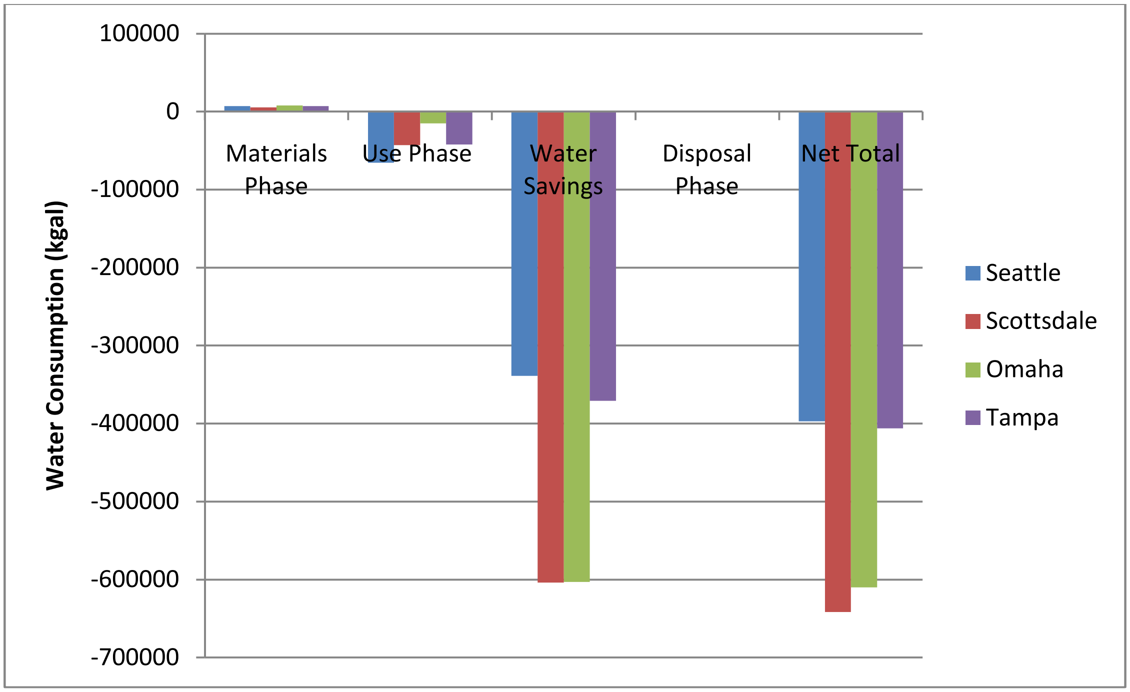


Figure A.4 – EIO-LCA of the Simple Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Water Consumption

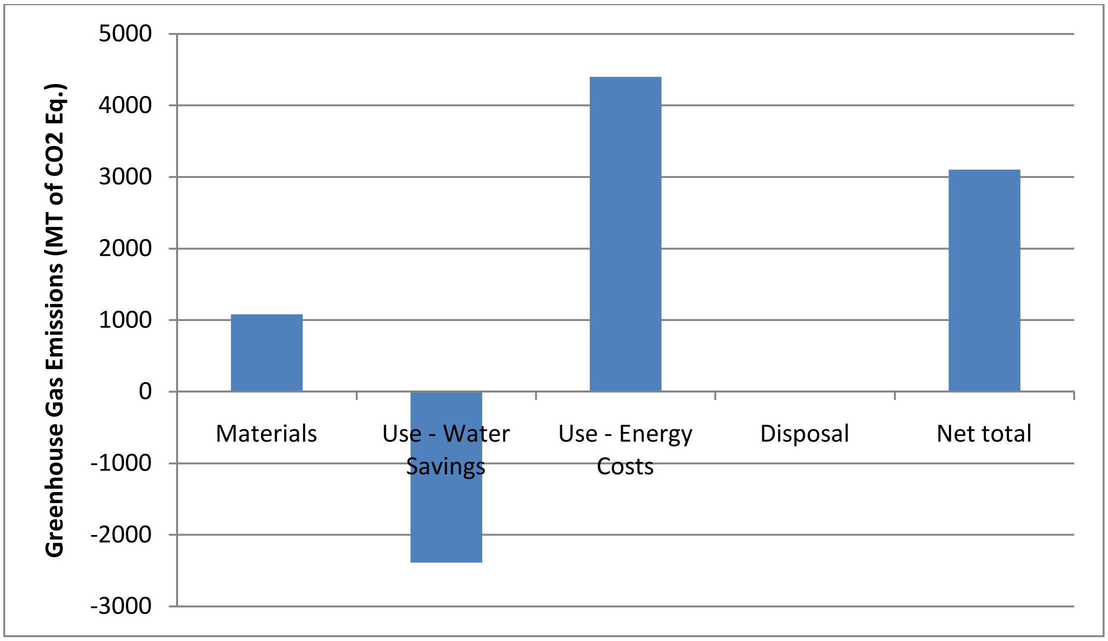


Figure A.5 – EIO-LCA of Indoor Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Greenhouse Gas Emissions

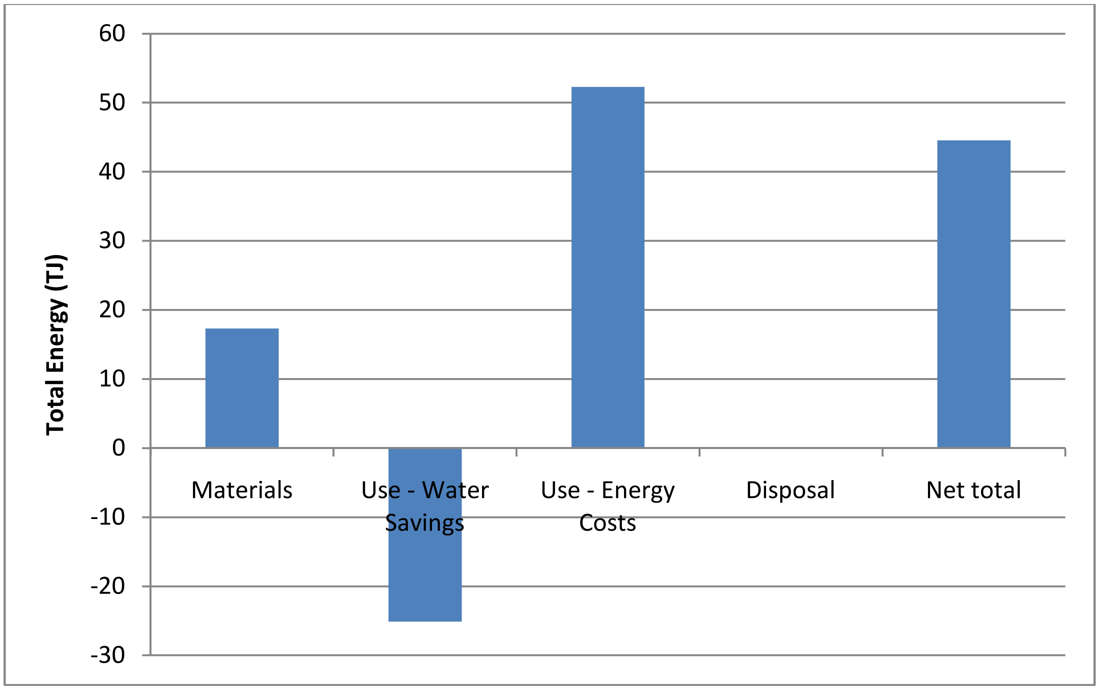


Figure A.6 – EIO-LCA of Indoor Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Energy Use

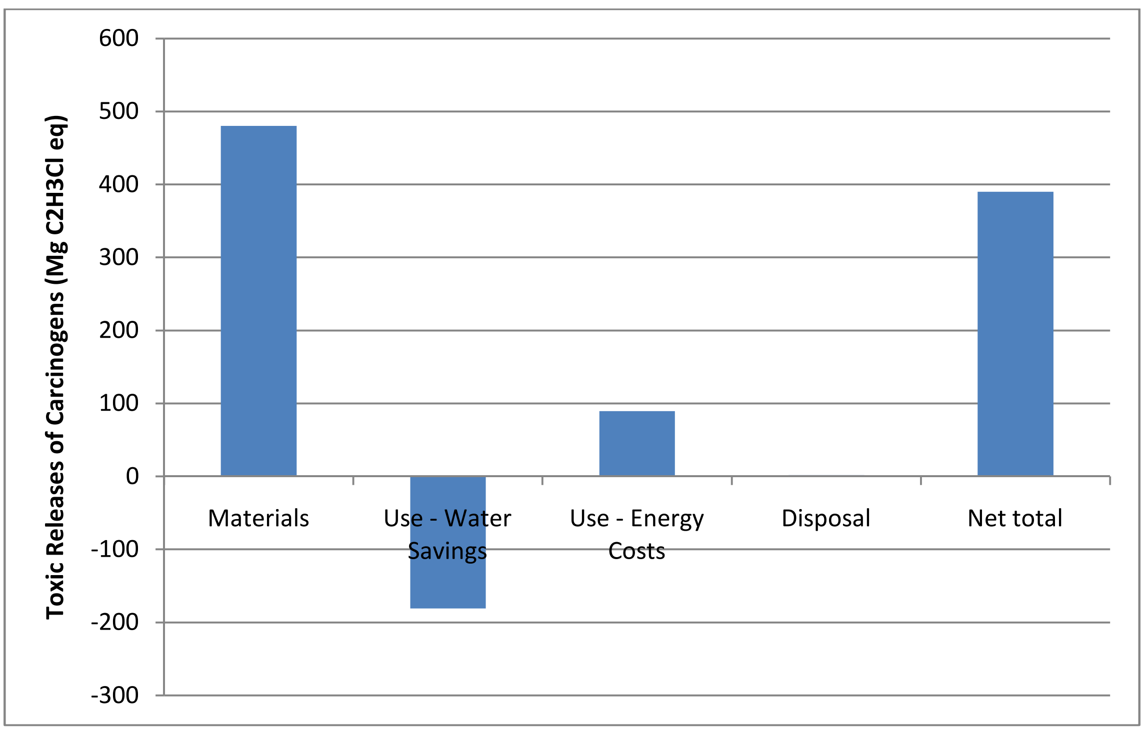


Figure A.7 – EIO-LCA of Indoor Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Toxic Releases

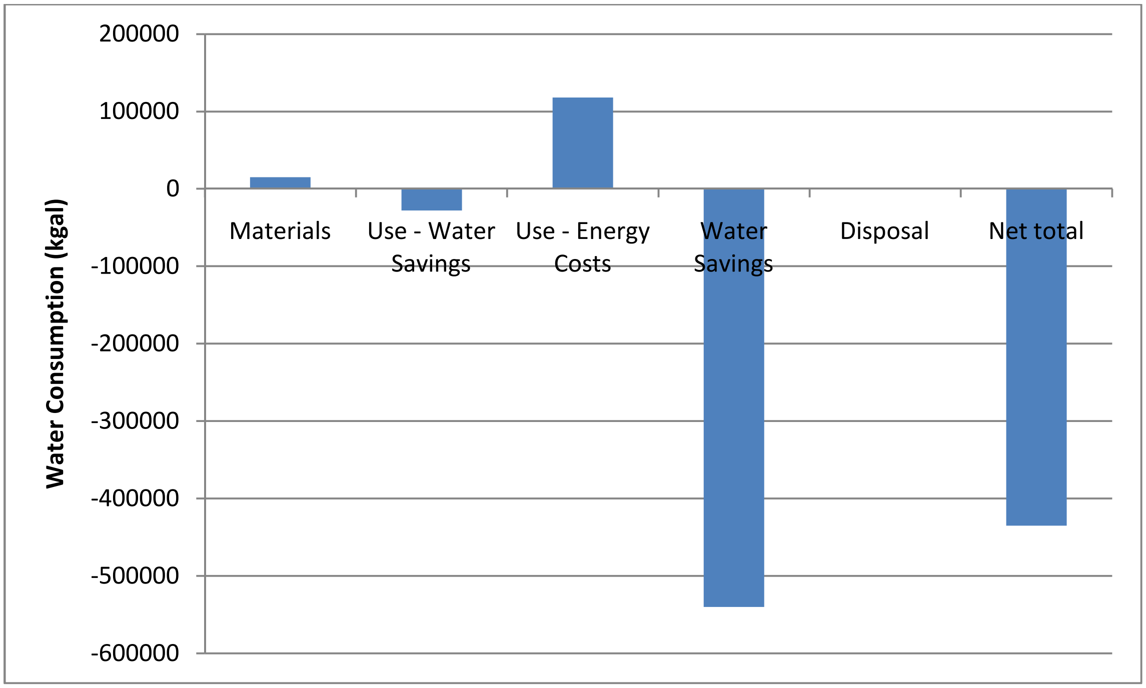


Figure A.8 – EIO-LCA of Indoor Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Water Consumption

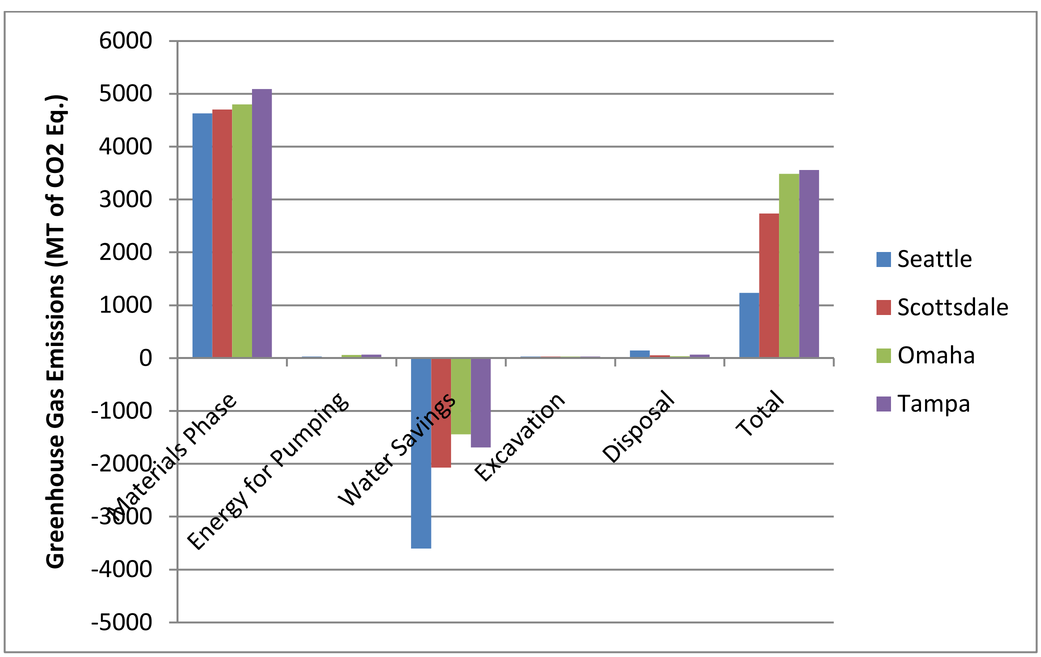


Figure A.9 – EIO-LCA of Hybrid Rainwater and Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Greenhouse Gas Emissions

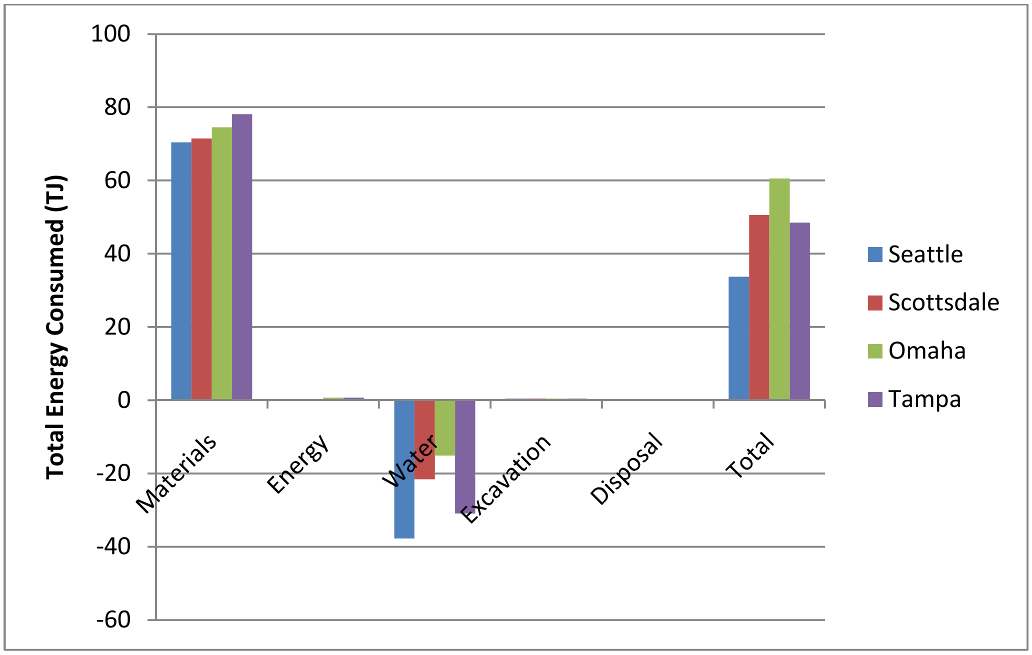


Figure A.10 – EIO-LCA of Hybrid Rainwater and Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Energy Consumption

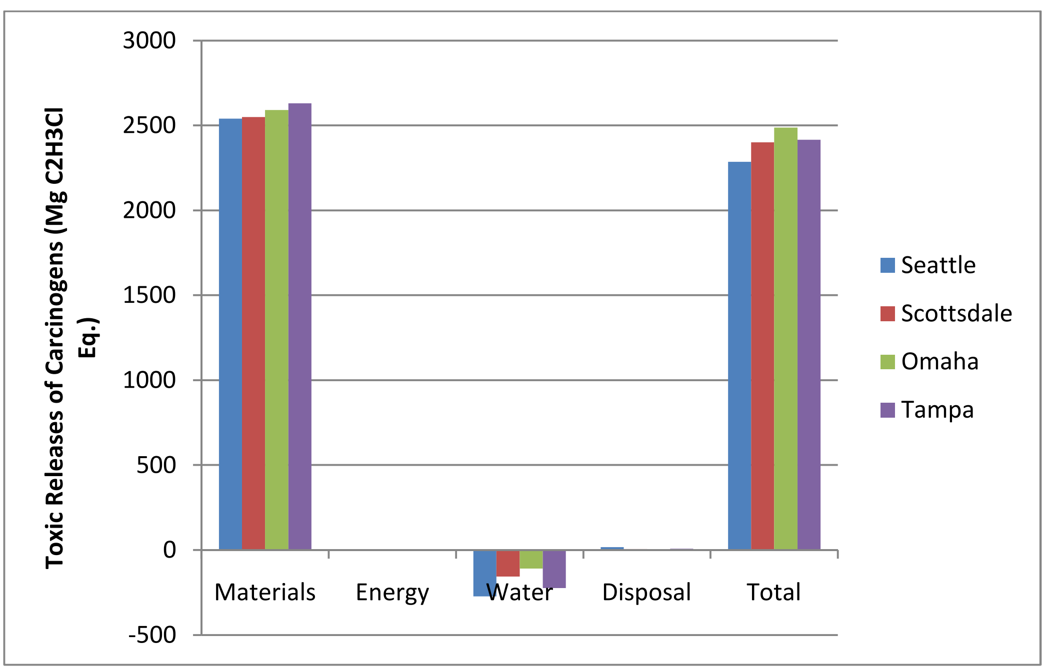


Figure A.11 – EIO-LCA of Hybrid Rainwater and Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Toxic Releases

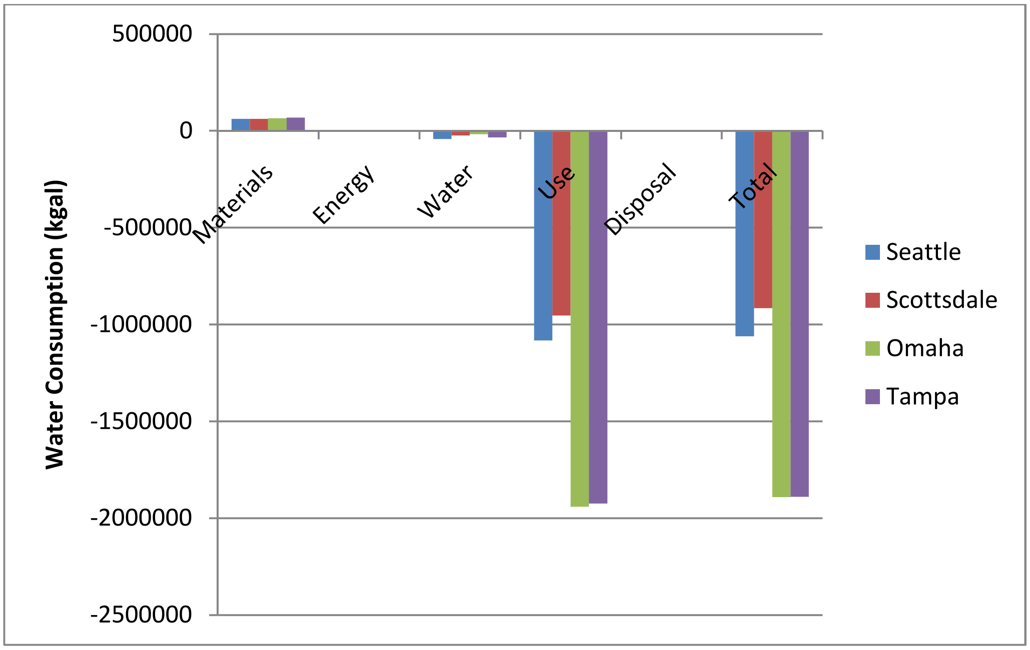


Figure A.12 – EIO-LCA of Hybrid Rainwater and Greywater Reuse System for 1000 Residential Houses over a 50-year Design Life in Terms of Water Consumption

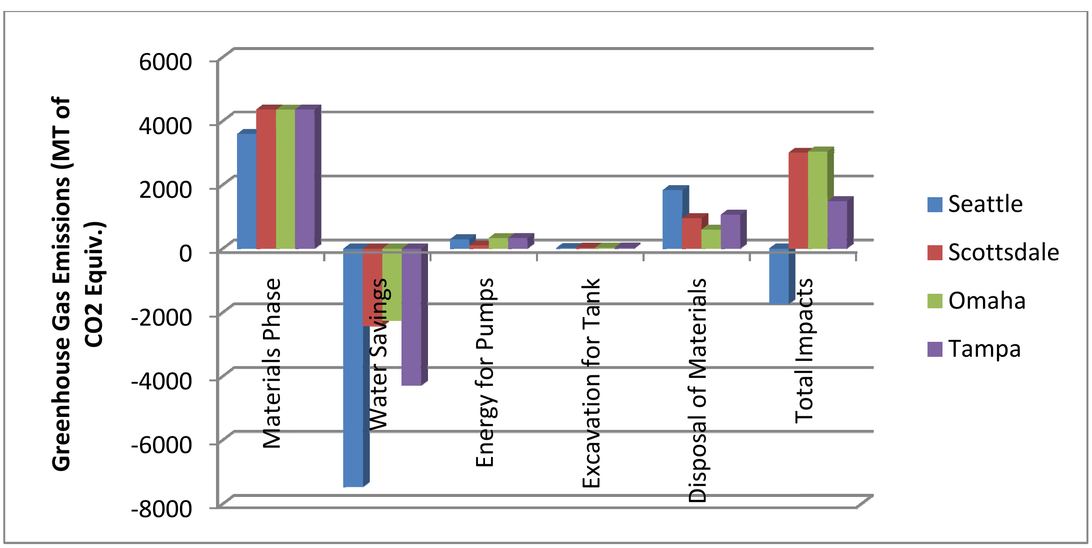


Figure A.13 – EIO-LCA of Rainwater Harvesting System on 50 Apartment Buildings over a 50-year Design Life in Terms of Greenhouse Gas Emissions

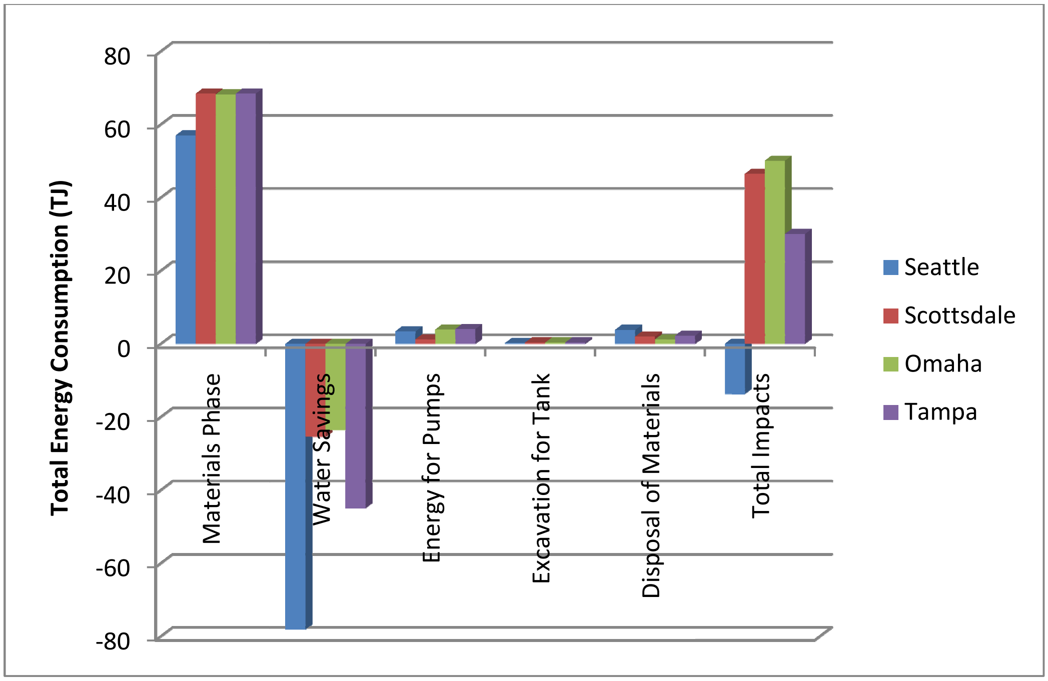


Figure A.14 – EIO-LCA of Rainwater Harvesting System on 50 Apartment Buildings over a 50-year Design Life in Terms of Energy Consumption

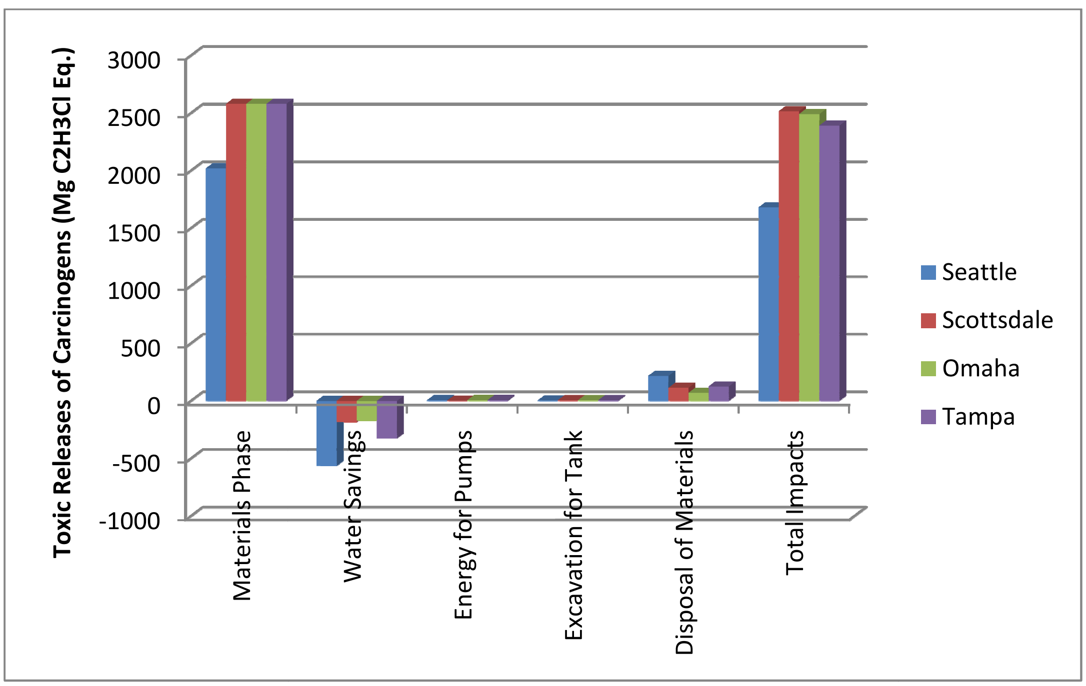


Figure A.15 – EIO-LCA of Rainwater Harvesting System on 50 Apartment Buildings over a 50-year Design Life in Terms of Toxic Releases

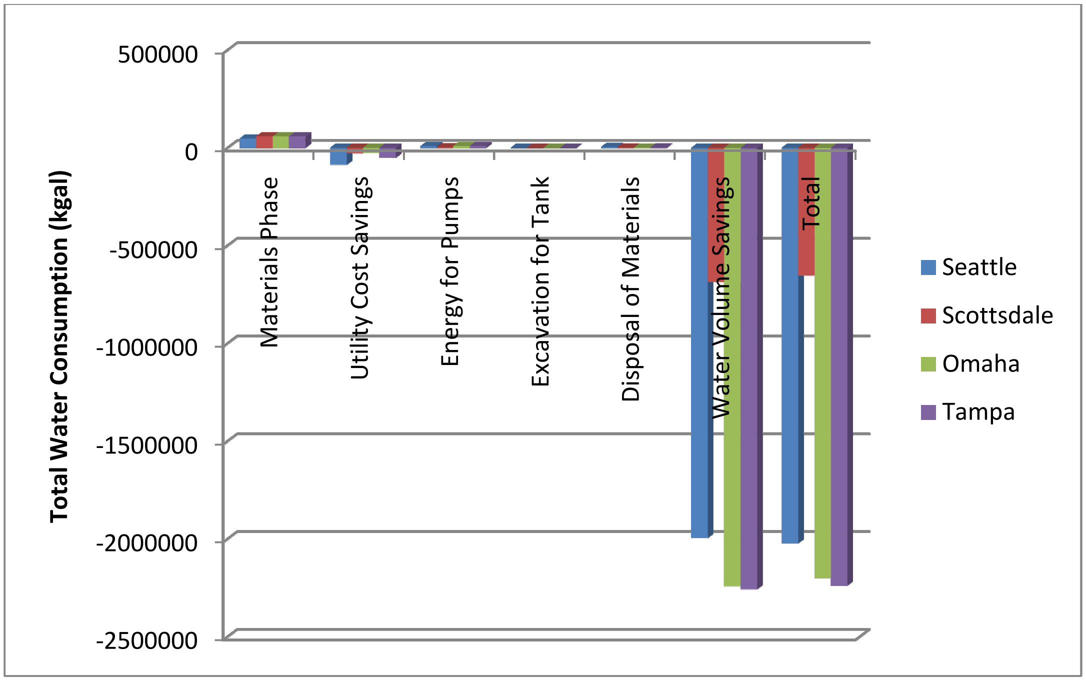


Figure A.16 – EIO-LCA of Rainwater Harvesting System on 50 Apartment Buildings over a 50-year Design Life in Terms of Water Consumption

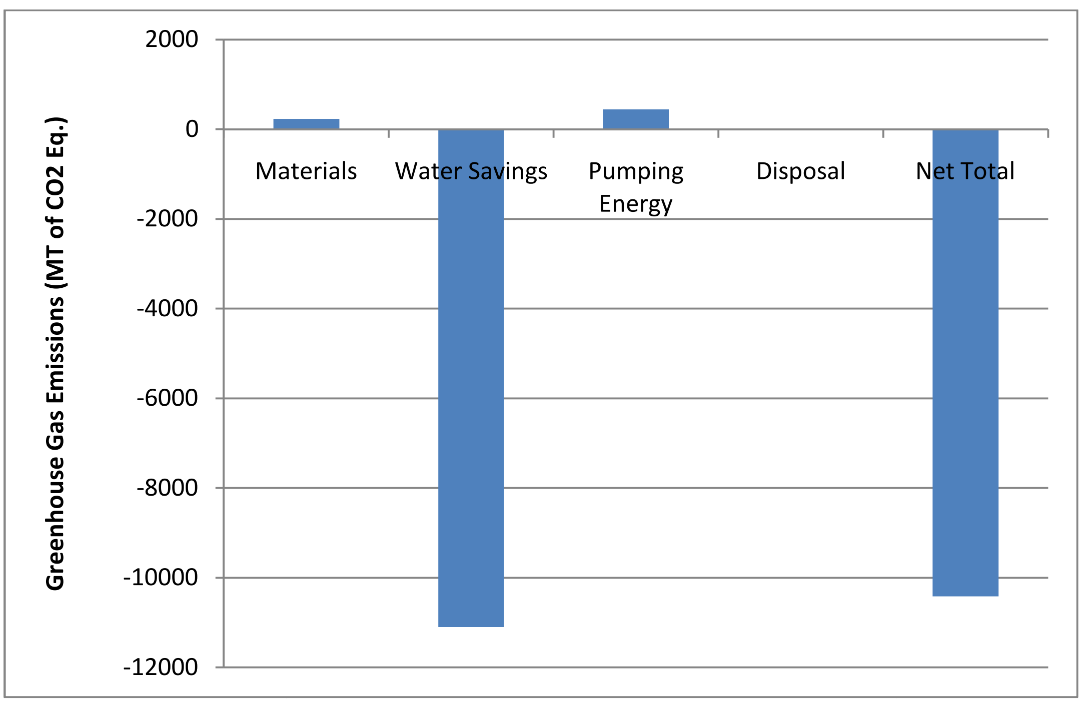


Figure A.17 – EIO-LCA of Community Water Reclamation System over a 50-year Design Life in Terms of Greenhouse Gas Emissions

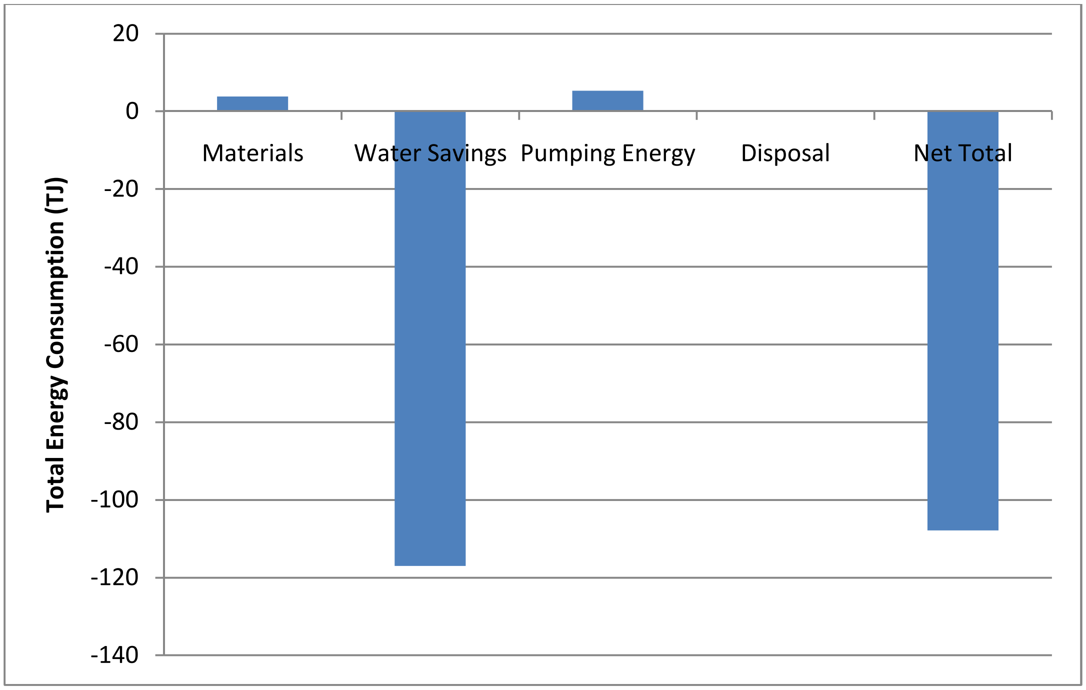


Figure A.18 – EIO-LCA of Community Water Reclamation System over a 50-year Design Life in Terms of Energy Consumption

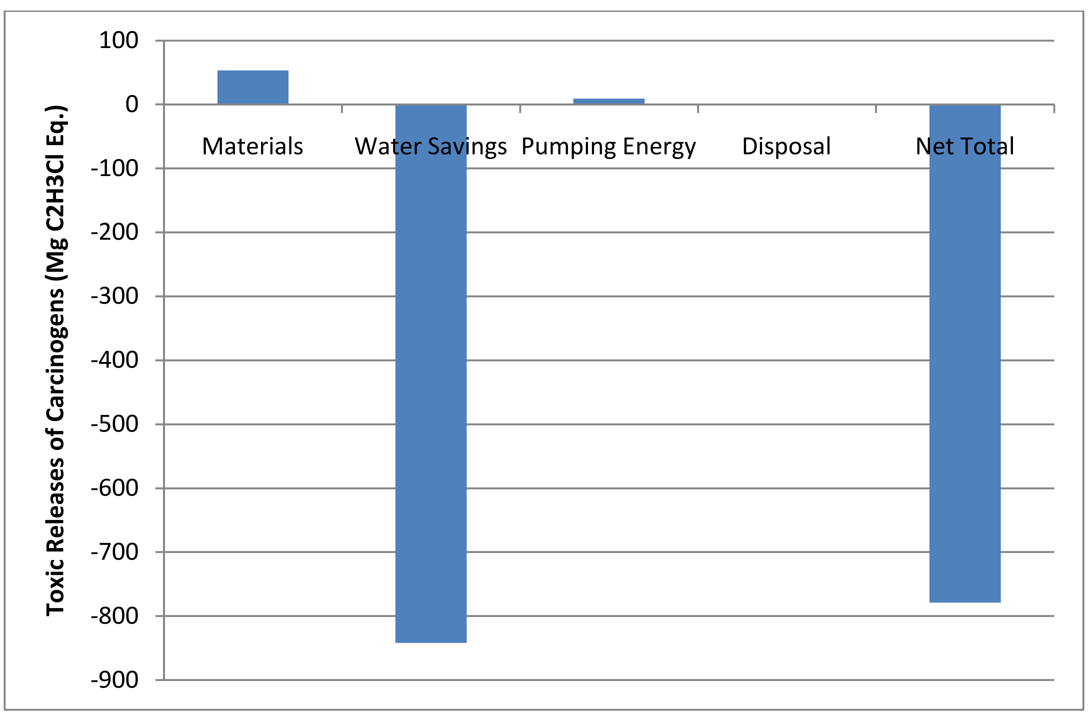


Figure A.19 – EIO-LCA of Community Water Reclamation System over a 50-year Design Life in Terms of Toxic Releases

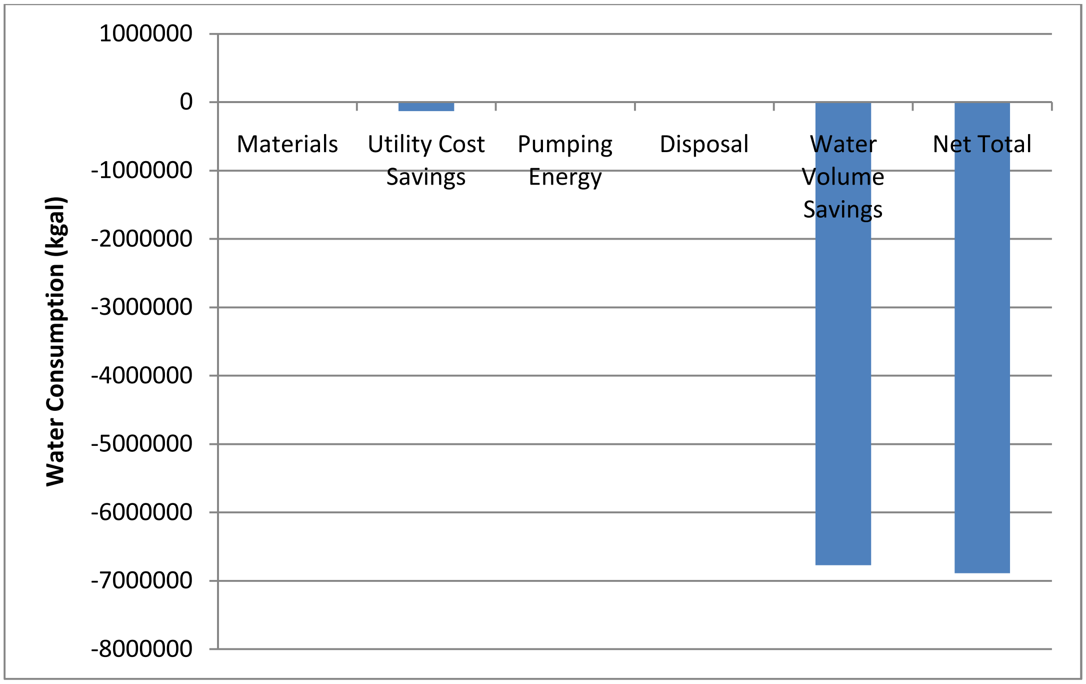
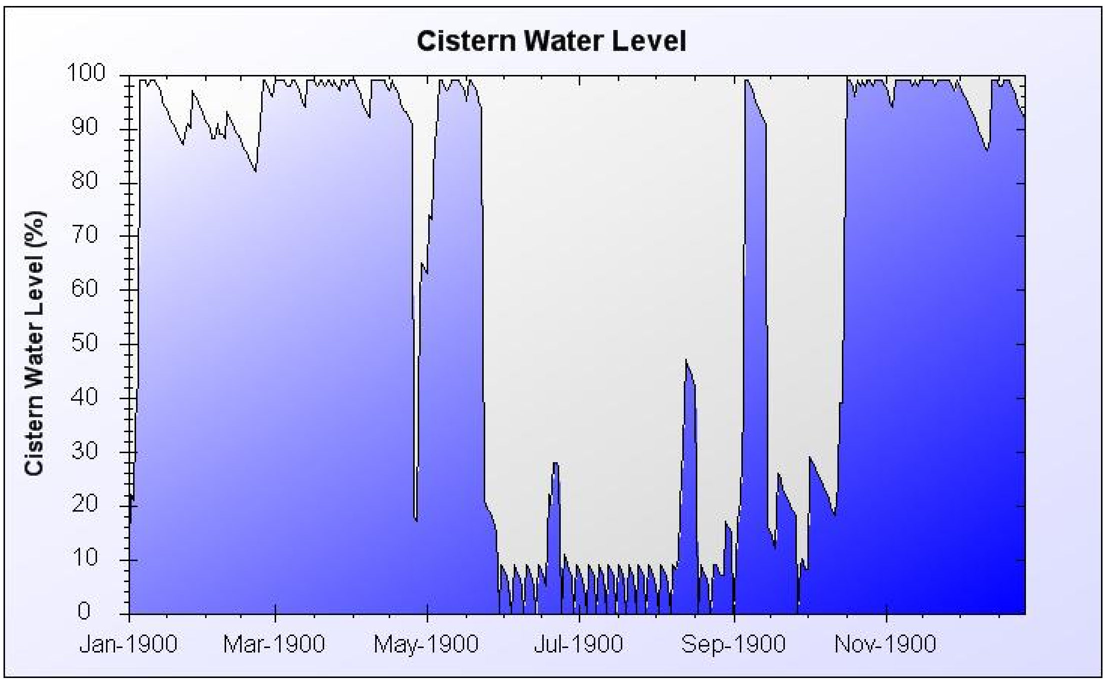


Figure A.20 – EIO-LCA of Community Water Reclamation System over a 50-year Design Life in Terms of Water Consumption

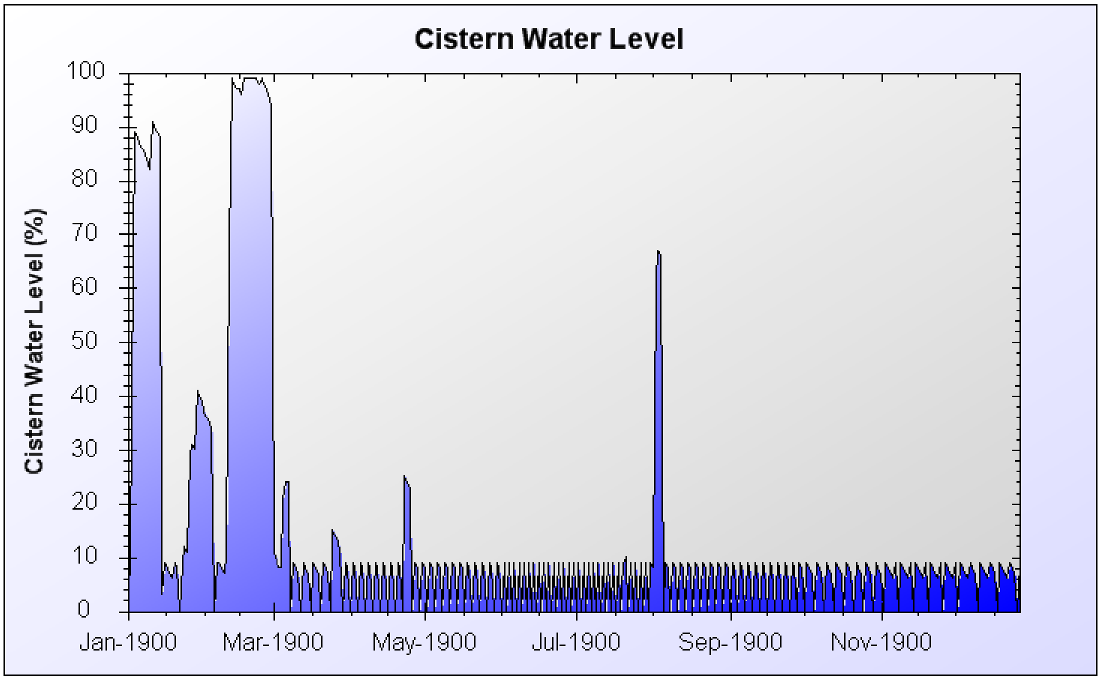
Appendix B

Appendix B includes figures which display a visual representation of the water level in each of the cisterns over the design year. As can be seen from Figure B.1, sufficient rainwater is available in the fall, winter, and spring months for non-potable uses, but the system requires supplemental potable water in the summer when the irrigation demand is high in Seattle.



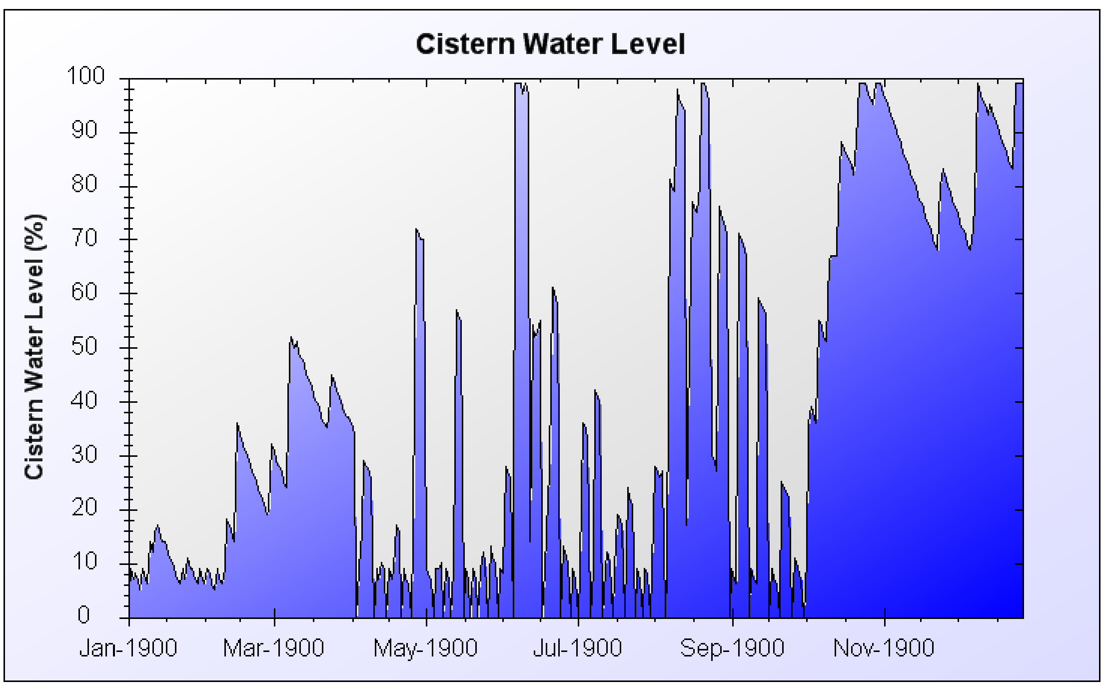
Note: Historic Daily Rainfall taken from AgWeather station from Washington State University

Figure B.1 – Water Level in 2500 gallon Cistern in Seattle for Model 3



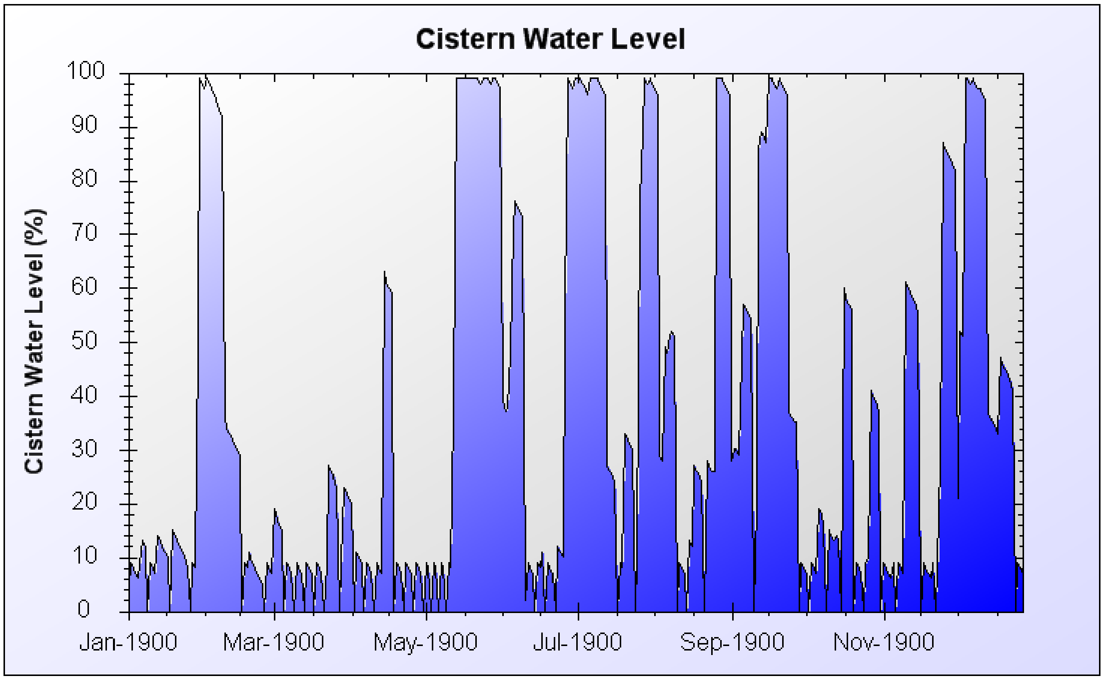
Note: Historic Daily Rainfall taken from AZMET

Figure B.2 – Water Level in 2500 gallon Cistern in Scottsdale for Model 3



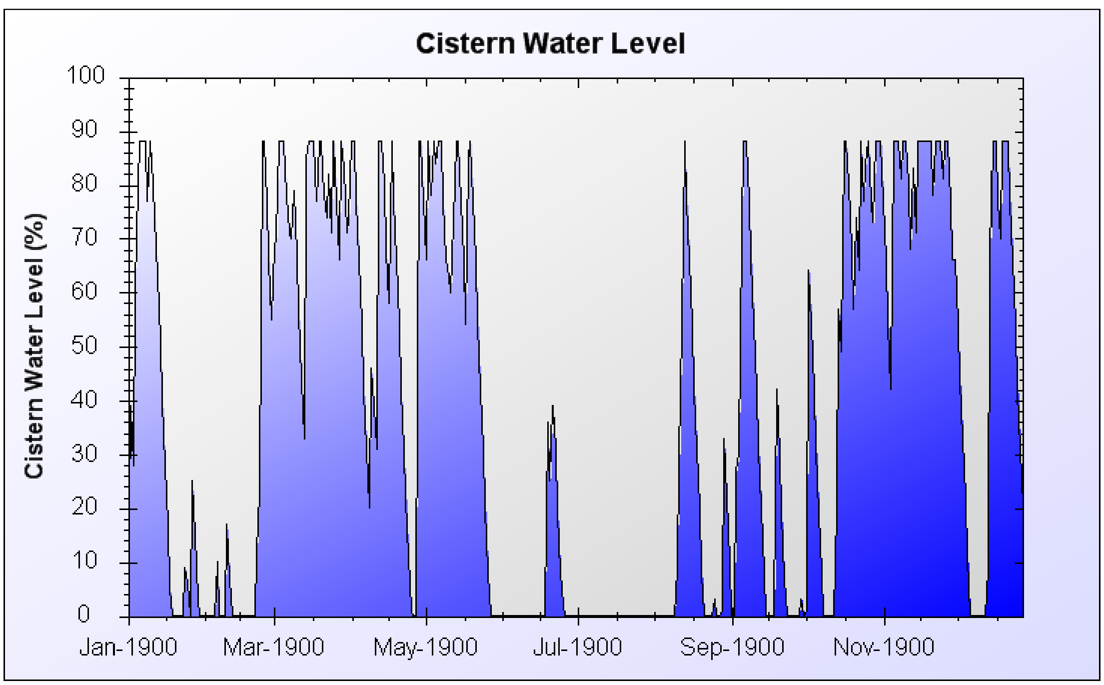
Note: Historic Daily Rainfall taken from High Plains Regional Climate Center

Figure B.3 – Water Level in 2500 gallon Cistern in Omaha for Model 3



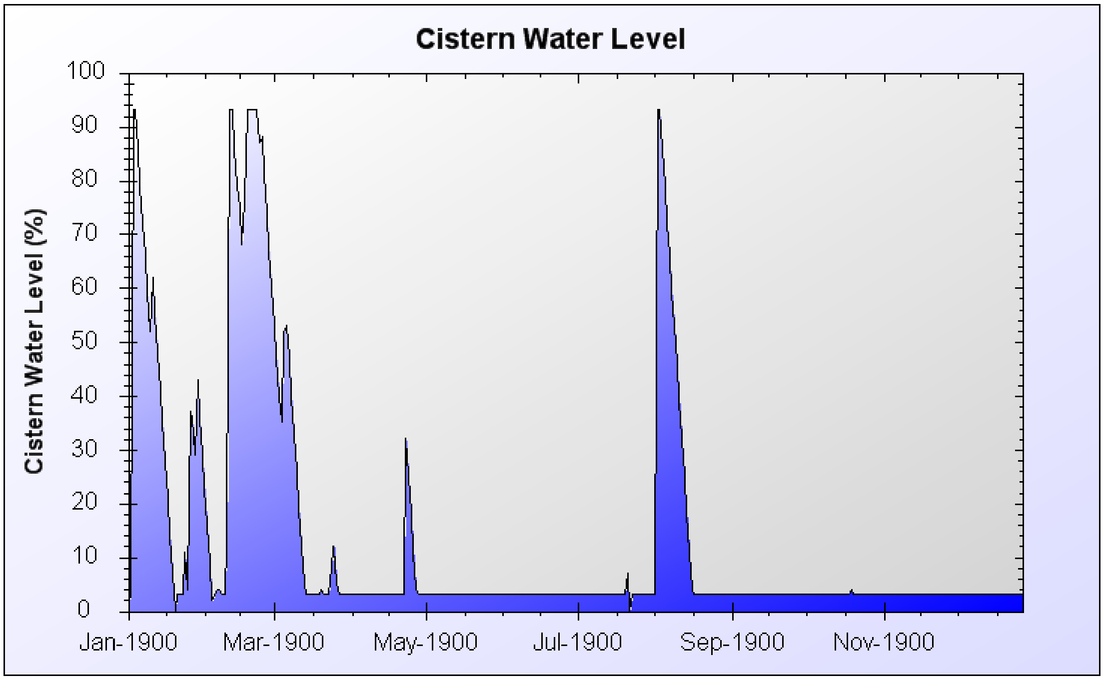
Note: Historic Daily Rainfall taken from the Florida Climate Center

Figure B.4 – Water Level in 2500 gallon Cistern in Tampa for Model 3



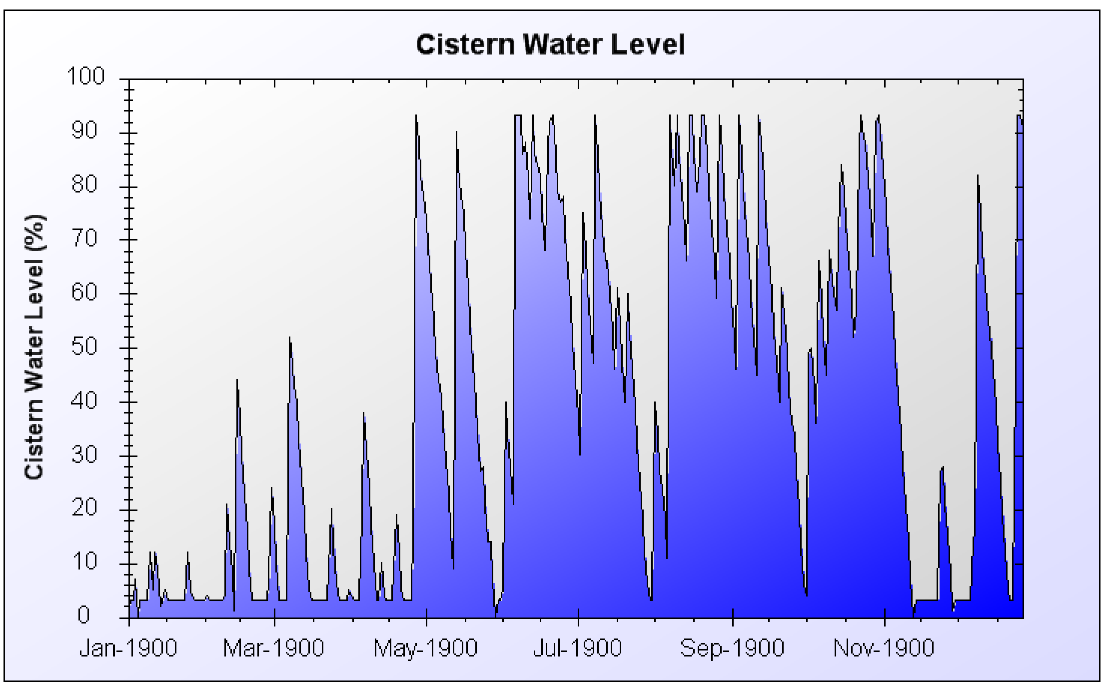
Note: Historic Daily Rainfall taken from AgWeather station from Washington State University

Figure B.5 – Water Level in 30,000 gallon Cistern in Seattle for Model 4



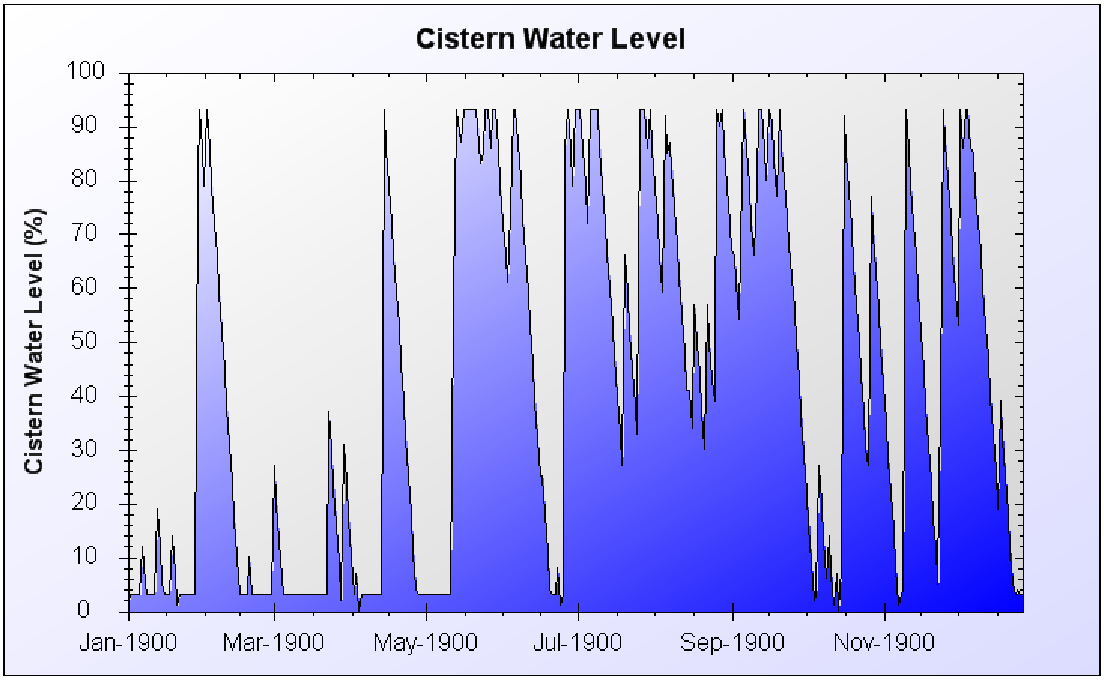
Note: Historic Daily Rainfall taken from AZMET

Figure B.6 – Water Level in 50,000 gallon Cistern in Scottsdale for Model 4



Note: Historic Daily Rainfall taken from High Plains Regional Climate Center

Figure B.7 – Water Level in 50,000 gallon Cistern in Omaha for Model 4



Note: Historic Daily Rainfall taken from the Florida Climate Center

Figure B.8 – Water Level in 50,000 gallon Cistern in Tampa for Model 4