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VIABILITY OF GRAYWATER REUSE IN LESOTHO'S LOWLAND AGRICULTURAL DISTRICT

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VIABILITY OF GRAYWATER REUSE IN LESOTHO'S LOWLAND AGRICULTURAL DISTRICT

By

Ryan Wagner

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Civil Engineering

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2018

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This report has been approved in partial fulfillment of the requirements for the Degree of
MASTER OF SCIENCE in Civil Engineering.

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DEFINITIONS

Basotho - The people of Lesotho.

Mosotho – Person from Lesotho.

Rand – South African unit of currency.

Loti / Maloti (plural) – Lesotho unit of currency.

Herd boy – Mosotho shepherd

JoJo – Prefabricated plastic water tanks common in Lesotho and South Africa.

Great Escarpment – Large geologic formation in southern Africa characterized by high cliffs and mountains.

Field – refers to large agricultural lands located away from a village but within walking distance (1 to 5 miles). The main purpose of the field is to grow corn for household storage through the dry months and create a revenue stream with any excess corn produced.

Garden – refers to agricultural land that is located within the homestead area. Often surrounded with a fence and able to be watered with a nearby spigot. The main purpose a garden is to supplement the diet of the household; however, some gardens are large enough to create a revenue stream for a household.

Improved water sources – water from an improved water source is located on premises, available when needed, and free from fecal and priority chemical contamination (JMP, 2017)

Sample variance, s_1^2 – the measure of how far any observation is from the average for treatment 1

Pooled estimated variance, s_{pool}^2 – A method of weighing the average of two treatment variances, where the degrees of freedom act as weights. Assuming both treatment variances are of the same magnitude.

Estimated variance of the difference, $V(\bar{y}_g - \bar{y}_t)$ – Estimates the variance between treatment 1 and treatment 2 averages.

Standard error, $s_{\bar{y}_g - \bar{y}_t}$ – a measure of accuracy of the estimate for the difference between treatment averages. The greater the standard error, the smaller the size of the sample. Larger sample sizes reduce the standard error.

Sample standard deviation, s_1 – a measurement how spread out the treatment 1 sample set is. A higher standard deviation indicates more distance between the measurements of a sample set.

Number of measurements, n_1 – the number of measurements in treatment 1 set.

Treatment average, $\bar{y}_1$ – represents the central value of a set of data for treatment 1.

95% confidence interval – a degree of confidence used to express uncertainty associated with a sample statistic. If sampling were done and an interval estimate computed the expected population parameter would fall within the interval 95% of the time.

T-distribution table – used for small sample sizes when sample variance is unknown.

$t_{n-2, \alpha/2}$ – t-value at $n - 2$ degrees of freedom and alpha, which is computed as 1 subtracted by the desired confidence interval in decimal format.

LIST OF ABBREVIATIONS

BMP	Best Management Practice
CMA	Common Monetary Area
IMF	International Monetary Fund
HDPE	High Density Polyethylene
JMP	WHO/UNICEF Joint Monitoring Programme for water supply, sanitation, and hygiene
LEWA	Lesotho Electricity and Water Authority
LHWP	Lesotho Highlands Water Project
NEPAD	New Partnership for Africa's Development
NGO	Non-Governmental Organization
PPCPs	Pharmaceuticals and personal care products
UN	United Nations
WASCO	Lesotho Water and Sewage Company
WHO	World Health Organization

ABSTRACT

Water security has become a large issue with populations rising and weather patterns changing to drier and hotter conditions in southern Africa. Lesotho, a mountainous country landlocked by South Africa, is responsible for a large amount of the rainfall in southern Africa. As such, Lesotho provides water to South Africa in exchange for national economic growth. Lesotho, however, is also prone to droughts and with water reserves being sold to South Africa, water security has become a national issue. This study looked at Lesotho's current water use habits and found that graywater reuse could lead to much more available water. The purpose of this study was to determine if recycled graywater would be a suitable replacement for improved water when irrigating edible gardens in Lesotho.

A typical garden was constructed as well as a graywater collection system. The study was conducted using baby spinach plants that were treated with graywater irrigation or improved water irrigation. The garden was divided into separate treatment rows that were randomly assigned. The study garden went through a single growing season and then plants were measured for physical characteristics.

It was found that there was no statistical difference between the two treatments in any of the measurement types. The results of the study suggest that there is no difference in the physical growth of spinach plants when graywater is used as an irrigation source.

1.0 INTRODUCTION

As populations in South Africa continue to rise, economic centers such as Johannesburg and Pretoria in Gauteng Province, along with Capetown in the Western Cape, are having difficulties meeting the growing water demand (BusinessTech, 2015). The water supply available for meeting this demand is limited due to central and western South Africa's low annual rainfalls (Figure 1.1). In addition, there are also weather patterns that can create severe droughts, and climate changes are expected to lead to less winter rains and drier, hotter weather overall (Geographic, 2018).

Figure 1.1 - Average annual precipitation for South Africa and Lesotho (Stewart, 2003)

The challenges associated with meeting the growing water demand, have resulted in water security becoming a major issue for South Africa. This in turn has impacted Lesotho, a small mountainous country that is landlocked by South Africa (Figure 1.1). Lesotho, which on average is a water rich country, has created national economic growth by selling water to South Africa. However, Lesotho, like South Africa, is prone to severe droughts. Drought conditions negatively impact Lesotho's ability to meet the water supply terms it has with South Africa, and in turn create nation-wide water shortages within Lesotho.

2.0 PROBLEM STATEMENT, PROJECT GOAL, AND OBJECTIVES

The purpose of this study is to find and evaluate a way to increase water availability in Lesotho. Sources of agricultural irrigation include, rainfall and rainwater storage, improved water, and graywater recycling; of these sources graywater recycling is the least explored and has the most potential for promotion. The goal of this study is to determine if graywater is, at a minimum, an effective substitute for improved water (a water source that is available, in close proximity to user, and free of contaminants) when used as an irrigation source for edible gardens in Lesotho.

The objectives for evaluating graywater as a potential substitute for improved water when irrigating edible garden were as follows:

- Design and construct an experimental Basotho style garden with randomized test beds for evaluation via improved water and graywater;
- Design and construct a graywater collection system;
- Plant, maintain, and irrigate the experimental garden during one growing season;
- Collect and analyze data on plant productivity including size, weight, and robustness;
- Estimate the project costs and feasibility in Lesotho; and
- Perform a risk assessment on graywater use.

3.0 BACKGROUND

3.1 LESOTHO

Lesotho is a small country that is completely surrounded by South Africa (Figure 3.1). As a result, Lesotho's economy is closely linked to that of South Africa. The Lesotho currency, the Loti, is valued at a 1:1 ratio to South Africa's currency, the Rand. Both currencies are part of the Common Monetary Area (CMA), which includes Lesotho, South Africa, Swaziland, and Namibia. The CMA was formed to advance less-developed participating members (Jian-Ye Wang, 2007).

Figure 3.1 – Lesotho, Southern Africa (Wagner, 2018b)

There is one major tar road that connects Lesotho's 10 districts and their largest towns. Beginning in the capital of Maseru the northern road connects Berea, Leribe, Butha Buthe, and Mokhotlong and ends in Mokhotlong town. The southern road extends from Maseru to Mafetang, Mochale's Hoek, Quthing, and Qacha's Nek, ending in Qacha's Nek town. The road system is illustrated in Figure 3.3.

The study described in this report was conducted within the town of Peka, Lesotho, in a village called Ha Pululu. Figure 3.2 shows Peka in the northwestern part (Leribe district) of Lesotho. The largest populations in Lesotho are in the lowlands, which are in the western areas of the country. The interior and eastern parts of the country are mainly highlands and sparse in population. Figure 3.4 shows the population densities for Lesotho's districts.

3.2 AGRICULTURAL AND GARDENING PRACTICES IN LESOTHO

The majority of Basotho are subsistence farmers. However, different types of agriculture predominate in different regions of the country.

3.2.1 AGRICULTURAL PRACTICES IN THE LOWLANDS

The lowlands are characterized by rich soils and account for much of the agricultural crop production in Lesotho. Most of the agriculture households in this region maintain fields and gardens. Corn is grown in fields to use within the household and for sale to neighbors and, if the farmer has large land holdings, neighboring villages and towns. In years with excess corn production, households with corn fields will act as the local corn supply for the village for the dry season. Fields are typically no further than a few miles from a farmer's household; except for large agricultural producers, who may have employees and holdings across the district or country. In addition to fields, households will often plant gardens within the household's fenced area. Gardens are typically used for the household exclusively and have more crop variety. Common crops include, spinach, cabbage, beets, onions, pumpkins and squash, and melons.

Figure 3.2 – Peka, Leribe, Lesotho (Wagner, 2018a)

Figure 3.3 - Lesotho Road System (Leseli, 2017)

Figure 3.4 - Lesotho population density by district (Geo-Ref, 2015)

3.2.2 AGRICULTURAL PRACTICES IN THE HIGHLANDS

Fenced in areas are less common in the highlands than in the lowlands. Consequently, the highlands are used for grazing livestock. Herd boys are given large flocks of goats and sheep to manage. Herd boys are usually school dropouts who are employed by farmers or work for family

farms. In the highlands, herd boys may be away from the village for months at a time. There is a system of cattle posts that accommodate herd boys and livestock as herds move through the highlands each year. In addition to goats and sheep, cattle are common, but are raised only near villages. Cattle are taken out daily to graze and are corralled on the farmer's land upon their return.

3.3 CLIMATE AND CULTURAL FACTORS CONTRIBUTING TO WATER SCARCITY

Lesotho has four ecological regions: lowlands, foothills, Senqu River Valley, and highlands (NEPAD, 2005). In the eastern portion of the country, which comprises mostly Highlands and the headwaters of the Senqu river, the Great Escarpment forms the border with the KwaZulu-Natal Province of South Africa. Warm moist air from the Indian Ocean is forced up and over the escarpment, and precipitates as rain and snow across the highlands of Lesotho (Dedekind, Engelbrecht, & van der Merwe, 2016). Rainfall then drains through the Senqu River Valley to the lowlands of Lesotho. The mountains of Lesotho receive an average of 100 cm of rain annually (Review, 2015).

Water is culturally celebrated in Lesotho. The national motto, "Khotso, Pula, Nala", means "Peace, Rain, Prosperity" when translated from Sesotho, the national language of Lesotho. Four out of five Basotho have a livelihood directly related to agriculture (Mutizwa, 2016). Therefore, most of the conversations between the author and Basotho were centered around weather and rainfall. This was reinforced in Sesotho language training provided by Peace Corps Lesotho, where weather vocabulary was an early focus. Basotho, especially older farmers, were observed by the author to be surprisingly accurate with rainfall predictions.

Basotho place a high value on appearance and cleanliness. Much of the daily household water is used in washing and cleaning tasks. It was observed that some students washed their school uniforms daily, and having a dirty uniform could often lead to expulsion from school. This emphasis on cleanliness and appearance created a type of social hierarchy within the student population. Laundry was done for the entire household multiple times per week. Household cleaning was observed as well. Women, who are often managers of the households, were commonly observed sweeping exposed soil around the entryway of the household. The amount of time, energy, and water resources placed on washing and cleanliness made it a centerpiece of daily life.

Based on observations, there were few water conservation practices in the author's village. If water was available, it was often observed to be used in excess and epitomized the tragedy of the commons. Similar attitudes toward food and money prevailed. Because of this emphasis on short term consumption of resources and lack of long-term planning, there are several non-profit organizations operating within Lesotho that promote long term planning education. The African Capacity Building Foundation (ACBF) and the European Union (EU) both have current projects focused on building economic capacity in Lesotho (LCN, 2018). Though most long-term planning education is focused on monetary security, there is hope that long-term resource planning will also be promoted culturally.

3.4 THE LESOTHO HIGHLANDS WATER PROJECT

Lesotho has one of the largest annual rainfalls in southern Africa, which is otherwise arid. The Lesotho Highlands Water Project (LHWP) was originally proposed in the 1950s to address concerns about water security in South Africa. The purpose of LHWP was to take water from Lesotho and the Senqu River and deliver it to the Vaal River System. The Vaal River system provides water to several large population areas in South Africa, including Johannesburg and Pretoria. Spurred on by a drought in the mid 1980's that left Gauteng Province in need of water for mining and a growing population (Mwangi, 2007), South Africa and Lesotho reached an

agreement that led to a signed treaty in 1986. Phase 1A and 1B of the LHWP began in 1986 and were completed in 2008, and resulted in two large dams, the Katse Dam and Mohale Dam, in Lesotho (Rivers, 2005).

In 2015, Lesotho experienced its largest drought in 35 years. This was also the first drought after the dams had been constructed. During this drought, serious concerns regarding Lesotho's water security arose. A drought assessment that was performed by the government of Lesotho during the 2015 drought showed that as many as 56% of Basotho were consuming water from sources that were not regulated or protected by the government water code (Mutizwa, 2016). In comparison, during normal weather patterns, 87 percent of urban and 66 percent of rural populations, which is equivalent to approximately 72 percent of the total population, have access to improved water sources (Figure 3.5), which is water that is available on premises, available when needed, and free of contaminants (JMP, 2017).

Figure 3.5 - Basic water coverage for Lesotho populations (JMP, 2015)

There were also concerns about food security. It is estimated that during the 2015 drought, there was a 47 percent drop in corn production. As a result, it was predicted that nearly half of the population of Lesotho would need food assistance through April of 2017, due to the lack of water available for farming (Haynie, 2016).

3.5 POTENTIAL SOURCES OF IRRIGATION

Irrigation systems are not widely practiced in Lesotho, using approximately one percent of total country-wide water withdraw for agricultural (FOA, 2005). Instead, crop production relies on natural rainfall, which makes harvests entirely dependent on the amount of rainfall during the growing season. However, watering of household gardens is supplemented with improved water because of the proximity of water spigots to the gardens. Other possible sources of water that could be used for watering gardens in Lesotho include collected rainwater and graywater.

The Water and Sewage Company (WASCO) of Lesotho was established in 2010 and is the only water utility in Lesotho (LEWA, 2013). Approximately 60 percent of water produced by WASCO is used in commerce and industry, and the remainder is consumed in agriculture and by residences/institutions (WASCO, 2017). According to Lesotho water regulations, water is treated

by WASCO to the World Health Organization (WHO) water quality standards or the National Standards. No documentation was found on the National Standards, but WHO describes Lesotho's national water regulation standards as less strict than the current WHO water quality standards (WHO, 2000). The reason for compliance with varying water quality standards across the country was the logistics of WASCO services. WASCO provides water to approximately 60 percent of urban populations in Lesotho and approximately 13 percent of the total population (WASCO, 2017). This leaves approximately 87 percent of the population receiving water from nonregulated sources, including improved water sources. Of the 87 percent of the population that does not have water delivered by WASCO, 59 percent have access to improved water sources (JMP, 2015).

Because WASCO did not provide water at all volunteer sites, Peace Corps Lesotho provided instructions for water treatment for all Peace Corps volunteers in Lesotho. The instructions were that improved water should be boiled and filtered with a Peace Corps-issued ceramic filter system. Based on the author's observations, the Basotho people did not treat improved water, even in areas where water was not provided by WASCO, thus having potentially lower water quality. In Peka where the current study was conducted, water was supplied by WASCO. There were no observable fields that had modified irrigation. Though several fields did implement land modifications using berms and swales to retain and channel water.

Lesotho experiences wet and dry seasons. The wet season begins in November and ends in January. The dry season takes place over the winter months (May through August). Figure 3.6 shows the average monthly rainfall in Teyateyaneng, which is approximately 20 kilometers from Peka. Rainfall is often the only moisture fields receive in Lesotho. There were no observed fields that employed irrigation systems. Though there were small green house operations that used irrigation.

Figure 3.6 – Rainfall data for Teyateyaneng (Climate-Data, 2015)

Rainwater collection is common throughout Lesotho. The majority of government buildings, mostly schools, have large prefabricated water collection tanks, called Jojos, that capture roof runoff. Built-in-place tanks are common in households, because the use of locally gathered stone keeps construction costs low. The Lesotho government, with aid from the United Nations (UN) and the New Partnership for Africa's Development (NEPAD) program, has a development program through the Lesotho Ministry of Agriculture and Food Security that aids Basotho, through

education and supervision, in constructing stone and mortar rainwater collection tanks. This program also installed surface ponds for use within households and small dams for larger fields (NEPAD, 2005). Rainwater collection systems implemented through the NEPAD program were observed to be designed in proximity to gardens with the ability to gravity irrigate gardens.

Although rainwater collection systems are prevalent throughout Lesotho, the author observed many instances in which these systems are misused or underutilized. This was especially true for Jojo systems, usually found on government buildings, and much less common for household collection tanks. Students were observed drinking directly from rainwater collection tanks with no water treatment in place. A lack of maintenance was also observed in these systems. There was also no designated use for collected rainwater. For example, tanks were often placed far away from garden areas or in low lying areas on the property, which increased difficulty in irrigating the gardens. Based on observations, government buildings and complexes were outfitted with rainwater collection systems without design input from the education of the building administration, unlike the NEPAD program, which focused on small-scale gardens and promoted owner inputs. Rainwater collection tanks continue to be installed on new construction; however, current use patterns have left large quantities of collected rainwater unused or wasted.

The majority of graywater in Lesotho is disposed of in areas designated by the household. Graywater is viewed by Basotho as unclean, and often designated disposal areas are located away from daily activities. The author observed one graywater system during his time in Lesotho; that system diverted the water that drained from a kitchen sink to a garden near the household. There were no additional swales or berms to disperse water throughout the garden. There was also no graywater storage involved in this system.

3.6 GRAYWATER AND GRAYWATER RECYCLING

Residential wastewater can be separated into two categories, graywater and blackwater. Graywater streams include wastewater from bathtubs, showers, hand-wash basins, laundry facilities, and kitchen sinks (Lubbe, Rodda, & Sershen, 2016). Blackwater is the water flushed from toilets, which contains urine and fecal matter. Typical western households have plumbing systems that combine blackwater and graywater to create larger volumes of black water. Because most building codes and water quality codes are adapted from western organizations like WHO, households that contain plumbing in Lesotho also employ combined plumbing systems. Compared to greywater, blackwater requires more extensive treatment to protect human health and the environment from harmful constituents. In developed countries, this is accomplished via a septic system (or other onsite treatment system) or a centralized wastewater treatment facility.

Graywater recycling is the practice of collecting graywater from a household or institution for reuse. The requirements for treatment of graywater depends on its intended use. For example, treating graywater for consumption as potable water would require more extensive treatment compared with the treatments required for different agricultural uses. In developed countries, graywater for use as an irrigation source for non-food crops would need to be treated using primary and secondary wastewater treatments, which reduce total suspended solids and biochemical oxygen demand. The resulting effluent from primary and secondary wastewater treatment would need to be applied as surface irrigation to reduce possible pathogen spread (EPA). Graywater intended for reuse in food crop irrigation needs an additional tertiary treatment, which focuses on removing nitrogen and phosphorus to prevent eutrophication (Malik, 2014). The city of Sydney's tertiary treatment uses alum to remove phosphorus particles and coagulate remaining suspending solids, gravity fed sand filters are then employed, and finally a chlorine disinfectant is administered to remove remaining pathogens. Chlorine is removed using sodium bisulphite to reduce the impact to discharge waters (Sydney Water, 2010). Graywater that does not come into contact with blackwater can often still contain fecal coliforms, enterococci, and bacteriophages at levels nearly equal to blackwater (Finley, 2009). Depending on personal care and cleaning products used, graywater can also have increased salts, nutrients, and chemicals

when compared to potable water sources. Because of these characteristics, it is recommended to limit graywater storage times to 24 hours or less, to reduce biological activity and odor, and use environmentally friendly detergents and products (Rand Water, 2013). Additionally, kitchen sinks are often not included in graywater recycling streams do to further possible issues with contamination.

3.7 GRAYWATER RECYCLING IN LESOTHO AND OTHER SOUTHERN AFRICAN COUNTRIES

Large portions of southern Africa are arid and drought prone. As such, South Africa's water regulations promote ease of water reuse and decreasing water use. Specific to graywater recycling, South Africa's minimum treatment requirements for water used for agricultural irrigation are stated in the *Water Quality Guidelines Vol. 4* and are presented in Appendix D (Forestry, 1996). There is no legislation that prohibits the use of graywater, once treated, for agricultural irrigation (Rand Water, 2013). Researchers at the University of South Africa evaluated the effectiveness of several different graywater treatment methods at treating residential graywater to the level specified by the water quality standards for agricultural use in South Africa (Rand Water, 2013). Of the treatment methods evaluated, it was found that treatment via a filter sock was suitable to meet standards for agriculture reuse.

South Africa's water quality standards use WHO guidelines as a reference, guidelines are presented in Appendices D and E (Africa, 1996). Lesotho's standards will then be equal or less strict for graywater recycling compared to South Africa and WHO guidelines. However, there are no known large-scale graywater recycling projects in Lesotho.

The regulations or guidelines related to water quality standards for agricultural use did not explicitly state that the regulations apply to edible garden crops. However, rosemary and olives are given as examples of good crops to irrigate with treated graywater (Rand Water, 2013). The production of edible foods does fall under agriculture and because there is no specific mention of graywater, it is assumed that edible foods are an acceptable use of treated graywater irrigation.

3.8 POTENTIAL CHALLENGES AND CONCERNS ASSOCIATED WITH GRAYWATER IRRIGATION

Implementation of graywater recycling in the irrigation of household gardens in Lesotho would have to overcome several challenges. Some of these challenges are related to the challenges associated with maintaining household gardens themselves. The author observed that the Basotho families that would benefit the most from having small edible household gardens generally did not have them. Some of the potential factors that may be contributing to this phenomenon, include:

- Approximately 33% of children living in Lesotho are orphans, and 50% of households are caring for at least one orphan (USAID, 2014), which places a significant amount of time and monetary pressure on households that are often managed by young women;
- The overall population of Lesotho is young with 51.6 percent under the age of 25 (CIA, 2017). Increasing the number of young Basotho who are managing households with little or no experience with agriculture. Young women often drop out of school to manage their family households due to family illnesses in a small, aging, adult population;
- Basotho who are knowledgeable in agriculture do not have the capital or are unwilling to allocate money to gardening, which can take months to see a harvest; and
- Capital for building a graywater storage system or graywater distribution system can be too high for households with small surpluses of capital that are focused on daily food security.

In addition to household implementation issues, there is a need to actively educate the public regarding the BMPs for graywater storage and handling. Basotho with the desire and means to begin using graywater would have to actively research BMPs because there are no current government or non-government organization (NGOs) programs tasked with graywater reuse education.

4.0 EXPERIMENTAL APPROACH AND METHODS

4.1 OVERALL EXPERIMENTAL APPROACH

A fenced in garden plot (5m wide x 6m long) was constructed for this study in the Basotho Style following the Ministry of Agriculture and Food Security guidelines (Kruger, 2008). The area was divided into ten test rows that were assigned either graywater or improved water for an irrigation treatment. Each row was randomly given an irrigation method. Figure 4.1 is a diagram of the garden plots and includes the treatments assigned to each row, and shows the row spacing separated by berms. Measurements were then taken for each plant and the results were analyzed for statistical differences.

Figure 4.1 – Layout of the garden plot used in graywater irrigation study

4.2 MATERIALS

4.2.1 SEEDS

Spinach plants were evaluated in this study because this is a vegetable commonly grown in Lesotho gardens, and the plants were grown from seeds. Baby spinach seeds used in this study were packaged by Starke Ayres of South Africa. One package containing approximately 230

spinach seeds was used in this study. Table 4.1 summarizes the planting information provided on the packet.

Table 4.1 - Planting Information for Starke Ayres Baby Spinach

Seed Type	Plant Spacing (cm)	Row Spacing (cm)	Depth (cm)	Direct/Planter	Germination (Days)	Harvest (Days)	Planting Season
Spinach	10	10	1	Both	7-14	35-45	August to April

The seeds were sown according to the instructions indicated in Table 4.1. All seeds were sown in the garden plots in groups of 2-3 seeds in case some seeds did not germinate, a common practice in Lesotho. Germination for most of plants began on day 7 of the study. By day 9 the plants were sprouting and many seedlings had two leaves, except for five plants that failed to germinate. On day 26, planting troughs that had multiple plants growing were thinned, and the excess plants were transplanted to plots where the seeds did not germinate. Seedlings were transplanted between plots receiving the same treatment. For example, seedlings removed from plots receiving graywater were transferred to another plot receiving graywater. Transplants were understandably stressed, and one transplanted seedling (1A) did not survive. The remaining transplants never recovered to full robustness.

4.2.2 GARDEN CONSTRUCTION

Garden construction was done by hand and local materials were gathered whenever possible. Tools were borrowed from neighbors and host family. The garden area required a fence due to free-roaming cattle, sheep, and chickens that are large numbers of plants in other gardens that were not enclosed with a fence. The fencing material selected was a square-wire mesh, which kept out all large animals; however, chickens were found within the fence on several occasions. It was observed that the chickens did not harm study plants for the most part, but were attracted to the area by the compost bin that was located inside the fenced-in area. Locals were employed to help gather branches that served as fence posts and install the posts. The costs associated with construction of the fenced-in garden are summarized in Table 4.2.

Table 4.2 – Garden Construction Costs

Item	Cost / Unit (Loti / Unit)	Number of Units	Cost (Loti)
Fence Posts (Labor for gathering)	R3 ea	10	30
Fencing	R21.67 / m	30	650
Pallet	R30 ea	1	30
Hinges	R25 ea	2	50
Nails	R50 pack	1	50
Rain Gauge	-	-	-
Total			810

4.2.3 SHOWER AND GRAYWATER COLLECTION

This project took several months to prepare and was dependent largely on finances and transportation. The entire project was completed with Peace Corps salary. Table 4.3 shows an itemized list of costs associated with construction of the loft, graywater collection system, and shower. No cost for labor was calculated as it was done without help, other than transportation. Transportation was largely scheduled with coworkers that had previous plans to make the same trip.

Table 4.3 – House Modification Costs

	Item	Cost / Unit (Loti / Unit)	Number of Units	Cost (Loti)
Loft Construction	Cement	80 ea	5	400
	Sand	900 / ton	0.5	450
	Bricks	Recycled from School		
	Glass Cutter	20 ea	1	20
	Tape	20	1	20
	Lumber	65 ea	2	130
	Pallet	30 ea	5	150
	Branch (Ladder)	3 ea	1	3
	Paint	100	2	200
	Screws	25	2	50
	Nails	30	1	30
Graywater Collection	Drain	50	1	50
	PVC Pipe	30	1	30
	Collection Bucket	50	1	50
	Watering Can	80	1	80
Shower Construction	Boiler Tank	Recycled from School		
	Heating Element	180	1	180
	HDPE Pipe	9 / meter	16	144
	Thread Seal	3	2	6
	Pipe Elbows	25	3	75
	Male Elbow	30	3	90
	Pipe Fittings	101	1	101
	Pipe Valve	30	1	30
	Total			2,289

Figure 4.4 and Figure 4.6 show the original house plan prior to construction of graywater collection system and the modified layout of the house with the graywater collection system.

4.3 EXPERIMENTAL SYSTEM AND PROCEDURES

4.3.1 BASOTHO GARDEN CONSTRUCTION

Soil in the garden was removed to a depth of approximately eight inches. The removed soil was then used to build up the berms and a planting bed, which was used for growing seedlings outside the scope of the study (Figure 4.1). Each berm was approximately 1½ feet wide and 6½ feet long. Berms are an essential part of Basotho style gardens reducing the number of seeds washed away from storm runoff and erosion. Berms were then amended with manure and covered with mulch, following recommended procedures (Kruger, 2008); for five square meters approximately one wheelbarrow of manure is added to improve the soil. This resulted in approximately 1 ½ wheelbarrow loads of manure that was applied with a shovel and garden hoe and mixed with garden soil. The manure used was gathered from the household manure pile. The pile included cattle, sheep, and chicken manure and was dry at the time of application.

Lesotho's soil erosion issues were documented as far back as the late 19th century. Erosion largely began, in Lesotho, with the adoption of European methods of agriculture and land use and moving away from traditional use land practices (Showers, 1989). In Peka, wherever there was a drainage pathway there were deep crevasses, called dongas, many over 20 feet deep due to agricultural practices in the area. Because of the erosion issue and the propensity for heavy short rainfall events, mulch was added to the berms in the form of dried grass. Mulch not only decreased erosion in the garden but also limited evaporation from the sun. South Africa has one of the largest solar radiation averages in the world; in Lesotho, this lead to villagers watering in the late afternoon and use rocks and grasses to keep moisture in the plant root system (Energy). A trough was also formed around each plant to keep water within the plants root system. Figure 4.2 shows the berms after construction was completed.

Figure 4.2 – Typical berm construction (Row 7)

Fence posts were installed on the east and south elevations of the garden. The existing barbed wire fence posts were used for the remainder of the fence. A trench was dug around the perimeter of the garden and fencing was placed into the trench and attached to the posts with fencing nails. The trench was then filled in to prevent animals from digging under the fence, especially pigs. The gate was made from a wooden pallet and hinges. The garden is shown in Figure 4.3.

Figure 4.3 - Fenced-in garden prior to row construction

4.3.2 GRAYWATER SYSTEM DESIGN AND CONSTRUCTION

The graywater recycling system constructed for this study was designed to collect the water generated from an indoor shower. Only graywater from the shower and laundry was collected. This ensured that graywater was generated at regular intervals and had consistent properties. Laundry products that were used and thus present in the graywater included several brands of powdered soap that were locally available. Baking soda, apple cider vinegar, and Dr. Bronner's brand soaps were used in the shower.

Figure 4.4 - Original House Floor Plan

The original house floor plan is shown in Figure 4.4. The first step in constructing the shower was to remove the bed and wardrobe from the floor plan. Next, an interior masonry wall was constructed with a loft built above the wall for sleeping. This was accomplished using recycled bricks from Peka High School and recycled glass bottles found at the village bar, which were fashioned into glass bricks to allow more natural light into the shower. The loft was built by chiseling 2 x 6 beams into the exterior masonry wall then notching them around the interior wall. The decking for the loft was gathered from dismantled wooden pallets and attached to beams with 3 in nails. The walled-in area accommodated a closet and shower. The completed wall is shown in Figure 4.5; along with a handmade ladder for loft access.

Figure 4.5 - Completed Loft and Shower Project

Water then had to be plumbed into the house. 20 mm high-density polyethylene (HDPE) piping was used to bring the water from the outside spigot into a tank located in the loft. The tank was a refurbished 50-liter water boiler that was retired from use by Peka High School. The heating element of the water boiler was replaced and used to heat the water. A drain was installed in the sloped concrete shower floor and the graywater effluent was diverted to a 20-liter bucket located outside the house. The storage bucket was kept inside a makeshift rock-walled shelter that incorporated a piece of tin to cover and keep animals and rain out. All wash water, shower and laundry, was disposed of in the shower drain and stored in the graywater storage bucket. Kitchen graywater was not used due to a high concentration of food particles and nutrients. The completed floor plan and elevation of the house is shown in Figure 4.6 and Figure 4.7, respectively.

Figure 4.6 - Completed House Floor Plan

Figure 4.7 - Completed House Elevation with Graywater System

4.3.3 TREATMENT

Graywater and improved water treatments were assigned to rows using a typical playing card deck. Ten cards were selected from the deck; five black and five red. Graywater treatment was represented by black cards and improved water treatment was represented by red cards. The selected cards were shuffled by hand, and then cards were dealt out to each row. Row 1 was the first row to be dealt and that progressed to the next subsequent row (Row 2) until all ten rows were assigned treatments. The results of the assigned treatments are shown in Table 4.4.

Table 4.4 - Treatment Assignments

Row Number	Treatment
1	Graywater
2	Graywater
3	Graywater
4	Improved water
5	Graywater
6	Improved water
7	Graywater
8	Improved water
9	Improved water
10	Improved water

4.3.4 WATERING SCHEDULE

The garden was watered in late afternoon to minimize evaporation. Each plant received approximately the same amount of water. A 10-liter watering can was used for all watering activities. Each row received approximately 3 liters of water per day, for a total of 15 liters applied for each treatment, on 29 out of 47 days, as summarized in Figure 4.8. On days when either improved water or graywater were unavailable, the rows were not watered to ensure that they were watered on the same schedule.

Figure 4.8 - Amount of water applied between September 22, 2017 (Day 1) and November 8, 2017 (Day 47)

Improved water was unavailable for a total of seven days during the study. Graywater was unavailable for three days during the study. On five days, the garden was not watered because of damp soil, e.g., due to rainfall. On three days, the garden was not watered due to being away from site. Table 4.5 provides a summary of the rain events that were recorded during the study. All rain events were measured at the study garden with a handmade rain gauge.

Table 4.5 – Storm Event Data During Study

Storm Date	Storm Duration (min)	Precipitation (cm)
September 23, 2017	< 30	< 0.5
October 2, 2017	N/A	N/A
October 4, 2017	Overnight	2
October 7, 2017	< 30	0.75
October 30, 2017	< 30	< 0.25

4.4 PLANT MEASUREMENTS

The plants growing in the plots were labeled with identification tags, according to the diagram in

Figure 4.1. The number on each tag corresponded to the row and the letter indicated the position of the plant within the row. Each plant was measured at the time of harvest for the following attributes:

- Number of leaves;
- Leaf size;
- Plant height;
- Plant canopy width;
- Robustness;
- Root length;
- Root system width;

- Plant length;
- Plant weight; and
- Plant dry weight.

Only leaves that were clearly formed were counted. Stems with immature leaves were not counted. Leaf size was measured at the widest and longest points of the largest leaves of the plant. Plant height was measured from soil level to top of canopy. Plant canopy width was measured at the largest width of the plant canopy. Plants were assigned a robustness score of poor, poor/fair, fair, fair/good, or good, based on visual inspection. A description of each measure of plant robustness is provided below.

Table 4.6 - Explanation of robustness scale

Poor	Plant is stunted in size and/or leaf development. The majority of leaves are dead or wilting severely.
Poor/Fair	Plant is stunted in size and/or leaf development. The majority of leaves are wilting, but not severely.
Fair	Plant has majority healthy leaves and stems are robust. Some leaves are wilting, but there is no severe wilting.
Fair/Good	Small amount or no wilting on leaves and stems are robust. Plants may be small or stunted.
Good	Large plants with small or no amount of wilting present on leaves. Stems are thick and healthy, promoting tall strong plants.

Each plant was photographed before (Figure 4.9) and after (Figure 4.10) they were dug out of the garden for root measurements. Root length was measured based on the main root, which was extended as much as possible. Root system width was measured at the widest point (Figure 17). Plant length was measured after extracting the plant from the soil and includes the root system length. Plant weight was measured with an electronic food scale after removing all loose dirt and debris from the plant. Plant dry weight was determined by dehydrating plants and reweighing them with the electronic scale. To dehydrate the plants, two sheets of plastic were used and plants were placed between the sheets. The plants were left in the sun for two days. Plants were observed to have little or no condensation print on the plastic before taking weights.

Figure 4.9 - Plant 7C during in place measurements

Figure 4.10 - Plant 7C during extracted root measurements

5.0 RESULTS

All plant measurements, except dry weight measurements, were made on November 8, 2017. The complete set of measurements is tabulated in Appendix A. In Figure 5.1, the averages of the properties of plants watered with graywater and improved water treatments are shown. Plants watered with graywater were larger than those watered with improved water with respect to leaf width, plant height, and total plant length, and they also developed greater numbers of leaves, in contrast, the plants watered with improved water exhibited larger average canopy widths, root lengths, root widths, wet weights, and dry weights.

As shown in Figure 5.1, these differences in the average plant measurements for graywater and improved water treatments did not appear to be statistically significant. Therefore, to determine the significance of the difference between the two treatments' averages, the results were analyzed using the independent t-test (Brown & Berthouex, 2002). Example calculations are summarized below for the number of leaves measurement.

Figure 5.1 - Average of measurements made on plants watered with graywater and improved water. (Error bars represent $\pm$ one standard deviation from the average.)

To use the independent t-test method, the variance must be calculated. Then, if the two treatments have variances of the same magnitude, the variances are combined and the pooled estimate is calculated for the two variances. Next the variance between the differences in the treatment averages is calculated. The standard error is calculated and used along with a *t*-distribution table to calculate the difference between the treatment averages.

The sample variance is calculated according to

$$s_1^2 = \frac{\sum (y_{1i} - \bar{y}_1)^2}{n_1 - 1} \quad [\text{Equation 5.1}]$$

where s_1^2 is the sample variance for treatment 1, y_{1i} is the treatment 1 value for the i th specimen, $\bar{y}_1$ is the treatment 1 average, and n_1 is the number of measurements in treatment 1.

The summary of y_{1i} and the calculation of $\bar{y}_1$ values for number of leaves are shown in Appendix C and can be used to calculate the variance for the graywater treatment (g) and improved water treatment (w) for 40 measurements, according to

$$s_g^2 = \frac{\sum (y_{gi} - \bar{y}_g)^2}{n_g - 1} = \frac{1551.5}{40 - 1} = 39.8 \text{ leaves}$$

$$s_t^2 = \frac{\sum (y_{wi} - \bar{y}_t)^2}{n_w - 1} = \frac{931.1}{40 - 1} = 23.9 \text{ leaves}$$

As discussed previously, because the sample variances for graywater and improved water are of the same magnitude, the variances of the two treatments can be combined to make a single pooled estimate of the variance (s_{pool}^2) and is calculated according to

$$s_{pool}^2 = \frac{(n_g - 1)s_g^2 + (n_w - 1)s_w^2}{n_g + n_w - 2} \quad [\text{Equation 5.2}]$$

where s_g^2 is variance for the graywater sample, s_w^2 is the variance for the improved water sample, and n_g and n_w are the number of measurements for graywater and improved water treatments, respectively. Then, for the number of leaves measurement, s_{pool}^2 is calculated according to

$$s_{pool}^2 = \frac{(n_g - 1)s_g^2 + (n_w - 1)s_w^2}{n_g + n_w - 2} = \frac{(40 - 1)39.8 + (40 - 1)23.9}{40 + 40 - 2} = 24.3 \text{ leaves}$$

The pooled variance estimate was then used to estimate the variance of the treatment difference, according to

$$V(\bar{y}_g - \bar{y}_w) = s_{pool}^2 \left(\frac{1}{n_g} + \frac{1}{n_w} \right) \quad [\text{Equation 5.3}]$$

where V is the variance between graywater and improved water treatment averages, $\bar{y}_g$ is the graywater treatment average, $\bar{y}_w$ is the improved water treatment average, s_{pool}^2 is the pooled variance estimate for the two treatments, and n_g and n_w are the number of measurements for graywater and improved water, respectively.

$$V(\bar{y}_g - \bar{y}_w) = s_{pool}^2 \left(\frac{1}{n_g} + \frac{1}{n_w} \right) = (24.3) \left(\frac{1}{40} + \frac{1}{40} \right) = 1.2 \text{ leaves}$$

The standard error between graywater and improved water treatments, was then calculated taking the square root of the estimated variance of the difference, $s_{\bar{y}_g - \bar{y}_w}$, was then calculated as the square root of the estimated variance of the difference, according to

$$s_{\bar{y}_g - \bar{y}_w} = \sqrt{V(\bar{y}_g - \bar{y}_w)} \quad [\text{Equation 5.4}]$$

For the example of the number of leaves measurement $s_{\bar{y}_g - \bar{y}_w}$ was calculated as follows:

$$s_{\bar{y}_g - \bar{y}_w} = \sqrt{V(\bar{y}_g - \bar{y}_w)} = \sqrt{1.2} = 1.1 \text{ leaves}$$

The standard error was then used to determine the confidence intervals according to

$$95\% \text{ confidence interval} = (\bar{y}_g - \bar{y}_w) \pm t_{n-2, \alpha/2} \times s_{\bar{y}_g - \bar{y}_w} \quad [\text{Equation 5.5}]$$

where $\bar{y}_g - \bar{y}_w$ is the difference of the treatment averages as shown in Figure 5.1, α is the two-tailed area probability, $t_{n-2, \alpha/2}$ is the t-value for the single-tailed t-distribution for a given $n - 2$ degrees of freedom and alpha, and $s_{\bar{y}_g - \bar{y}_w}$ is the standard error between graywater and improved water treatments. For the example of the number of leaves measurement, there were $n = 80$ total specimens and therefore 78 degrees of freedom. For the 95 percent confidence interval, $\alpha =$

$1.00 - 0.95 = 0.05$, therefore the single-tail area probability will be $\alpha/2 = 0.025$. The corresponding single-tailed t-distribution value ($t_{78,0.025} = 1.9908$) was obtained from Brown and Berthouex (2002). The values for the example of the number of leaves were calculated by substituting these values in equation 5.5, according to:

$$(\bar{y}_g - \bar{y}_w) \pm t_{78,0.025} \times s_{\bar{y}_g - \bar{y}_w} \rightarrow (0.4) \pm (1.9908) \times (1.1) \rightarrow 0.4 \pm 2.2 \text{ leaves}$$

The minimum is thus -1.8 leaves, and the maximum is 2.6 leaves. The resulting interval includes zero, which indicates that there is not a significant difference in the average number of leaves per specimen of plants watered with improved water versus graywater. Had the interval not included zero, then there would be significant statistical difference, at the 95 percent confidence interval, between the number of leaves per specimen in the two treatments.

The above calculations were repeated for the remaining measurements. The results of these confidence interval calculations are summarized in Table 5.1.

Table 5.1 – 95 Percent Confidence Intervals for Plant Measurements

	Minimum	Maximum
Number of Leaves	-1.80	2.60
Leaf Length (cm)	-0.48	1.28
Leaf Width (cm)	-0.31	1.11
Plant Height (cm)	-1.02	1.82
Plant Canopy Width (cm)	-2.03	2.83
Root Length (cm)	-1.25	2.05
Root System Width (cm)	-1.87	2.67
Plant Length (cm)	-2.48	3.28
Weight (g)	-4.50	5.30
Dry Weight (g)	-1.05	1.85

The calculated confidence intervals for all treatments include zero. As with the number of leaves, it can be said with a high degree of confidence that there is no significant statistical difference in any of the average measurements made on plants irrigated with graywater versus those receiving improved water.

6.0 DISCUSSION AND RECOMMENDATIONS

As stated above, this study focused on evaluating whether graywater could be used as a replacement for improved water for irrigating household vegetable gardens in Lesotho. Because of the limited availability of resources, tools, and manpower, most of the considerable time and effort invested in this project was spent on constructing the graywater source and collection system and garden itself. Further, the comparison of graywater and improved water for irrigation was, out of necessity, based on physical measurements of the plants of one type of crop. If only the plant measurements that could be made in the field in Lesotho are considered, graywater appeared to be equivalent to the improved water in Peka for irrigating edible garden crops.

However, before graywater can be reused for irrigation of garden crops, additional information must be collected to assess the potential human and environmental health impacts of this practice. In addition, any cultural barriers that may limit the willingness of a society's members to

practice graywater reuse must be overcome. Assessing these potential impacts and barriers to graywater reuse was outside the scope of this project. However, some suggestions for what types of evaluations should be incorporated into future studies of graywater reuse in the irrigation of edible garden crops are described below.

The first step in understanding the potential public and environmental health effects of graywater reuse is to characterize its key constituents, including nutrients, sodium and other dissolved ions, organic compounds, and pathogens. The outcome of this characterization could inform efforts to characterize the effects of graywater irrigation on soil properties and pathogen abundance and survival in soil and on plants, as described below. It is also important to note that the graywater generated and utilized in the current study may not be representative of the graywater of Basotho. Furthermore, graywater in rural areas may be dramatically different than graywater in urban areas of Lesotho. Graywater composition is largely dependent on household uses of cleaning and personal care products. Also analyzing graywater samples of various households in the study area would give information on the typical graywater stream that would be expected in the semi-rural agricultural areas of Lesotho, which would allow for better implementation of graywater recycling in the area.

Most importantly, because previous studies have shown that graywater may contain human pathogens and/or indicators of possible contamination with mammalian fecal matter, samples of irrigated soil and plants should be analyzed for the abundance of these pathogens over time. For example, a previous study showed that domestic graywater contained high levels of bacteria, which suggests that pathogens could be present and possibly cause adverse side effects in humans handling graywater or consuming plants irrigated with graywater (Finley, 2009).

In addition to characterizing pathogen abundance in soil and plants over time, it would be useful to take samples of soils irrigated with improved water and graywater and determine if there are statistical differences in the physical and chemical properties of these soils. Some of the key soil properties that could be impacted by irrigation with graywater and hence affect plant productivity include the concentrations of sodium and other salts, nutrients, as well as soil permeability. The accumulation in soil of pharmaceuticals and personal care products (PPCPs) derived from graywater could potentially impact human health, although little is currently known about the public health impacts of PPCPs in the environment. It would also be useful to compare how irrigation with graywater affects the growth of different plant species compared to irrigation with improved water.

Further research could give much more vital information for graywater reuse. However, costs of implementation of graywater recycling systems are also of concern. A graywater recycling system could be as simple as a single storage bucket located in the home or the practice of designating the wash water discard area to be in the garden where plants could benefit. More sophisticated and expensive graywater recycling systems might contain household drains, holding tanks, pumps, and irrigation systems. The graywater recycling system used in this study is somewhere in between these two options and was possible largely due to low labor costs and availability of recycled building materials.

Even a simple system, as described above, may be unaffordable for most of Basotho households. In Lesotho, approximately 57 percent of the population is below the poverty line (Mundi, 2018). The World Bank poverty line figure is \$1.90 per day, which translates to approximately 700 maloti per month (Project, 2016). Assuming a household has two adults, the monthly income would be less than 1,400 maloti for much of the country. As shown in Tables 5 and 6, the costs for constructing an enclosed garden and graywater collection system were 3,099 maloti. For Basotho who have an existing enclosed garden, a graywater collection system similar to the one used in this study will cost 2,289 maloti, without labor costs. This is a significant cost, with no short-term benefits and is completely unattainable for most of Lesotho.

The simplest graywater recycling system would involve relocating the discharge area for wash water to the garden. Most households have an area where wash water is discarded and it is normally away from the house and where household activities are performed. Changing this discharge area may prove to be more difficult than establishing an automated graywater recycling system. Basotho typically view wash water as dirty and undesirable. Through education programs, wash water could become viewed as a resource, but it may take several years of aggressive implementation to change the cultural views towards 'dirty' water. It is expected that a fully automated graywater recycling system would be more successful in Lesotho because the water is not handled or seen by household members. Alternatively, an affordable graywater treatment system could reduce the suspended solids and potential pathogens in the water. This could be achieved with a plastic storage bucket in series with a shallow plastic basin, which would be covered with clear plastic. Graywater could be collected in the plastic storage bucket to allow for sedimentation or suspended solids. The clarified effluent could pass through a weir and into the basin, where exposure to ultra-violet (UV) light could contribute to a reduction in pathogen levels. These treatment modifications would have to be experimentally evaluated in additional studies to determine how to best construct an affordable system and assess the feasibility of producing aesthetically pleasing water that would be more likely to be reused by Basotho.

Though graywater recycling shows promise, there is still further research that would benefit graywater use. Even with further research though it is expected that establishing graywater in Lesotho would be difficult without a government program to help with educating Basotho about the benefits of graywater reuse and help with capital costs in funding graywater recycling systems. However, even if an education program with financial help is put in place, there is fear that families who do not see an immediate benefit will return to normal water usage when the rains have returned. This has already been observed with rainwater collection systems in the Peka area.

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APPENDIX A – MEASUREMENT DATA

Treatment	Plant ID	Number of Leaves	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Plant Canopy Width (cm)	Robustness	Root Length (cm)	Root System Width (cm)	Number of Root Offshoots	Plant Length (cm)	Weight (grams)	Dry Weight (grams)
Graywater	1A	0	0	0	0	0	Poor	0	0	0	0	0	0
	1B	13	4	3	6	10	Poor	11	4	20-30	18	4	<1
	1C	6	2	1	3	3	Poor	3.5	3	0-10	8	<1	<1
	1D	26	10	6	15.5	26	Good	13	16	20-30	29	38	9
	1E	25	13	8	16	24	Good	12	23	30-40	30	48	14
	1F	26	11	8	15	24	Good	15.5	13	50-60	31	33	9
	1G	19	7	7	12	18	Good	16	12.5	50-60	28	27	7
	1H	19	9	6	10	18	Good	15	16	40-50	28	25	6
Graywater	2A	12	6	3	6.5	10	Good	14.5	3.5	10-20	23	9	2
	2B	10	5	3	6.5	9	Good	15	10	30-40	22	6	<1
	2C	14	8	5	9	17	Good	14	10	20-30	24	17	4
	2D	17	6	6	10.5	20	Good	10	14	20-30	23	20	5
	2E	26	9	5	11	17	Good	16	25	10-20	30	21	5
	2F	18	7	4	10.5	17	Good	13.5	6	20-30	26	17	5
	2G	19	8	5	11	17	Good	15.5	17	20-30	27	22	5
	2H	18	7	4	9.5	13	Good	10	17	20-30	20.5	16	4

Treatment	Plant ID	Number of Leaves	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Plant Canopy Width (cm)	Robustness	Root Length (cm)	Root System Width (cm)	Number of Root Offshoots	Plant Length (cm)	Weight (grams)	Dry Weight (grams)
Graywater	3A	11	8	4	12.5	11	Fair	9.5	4	20-30	22	6	<1
	3B	20	9	7	10.5	22	Good	9	8	10-20	23	25	6
	3C	18	8	5.5	10	13	Fair	6	6	10-20	17	12	3
	3D	17	8	6	13	17	Fair/Good	10	14	0-10	29	17	4
	3E	20	8	6	14	23	Good	9.5	9	20-30	25	15	3
	3F	14	10	7	13	17	Good	15.5	11	20-30	32	19	5
	3G	27	7	9	17	24	Good	12	12.5	20-30	31	26	6
	3H	18	8.5	5.5	11	18	Fair	12	13	20-30	27	13	3
Improved Water	4A	11	4	3	5	9	Fair/Poor	14.5	12	30-40	12	17	4
	4B	16	7	6	7	16	Good	4.5	18	10-20	3	5	<1
	4C	21	9	8	11	24	Good	3	11	20-30	8	4	<1
	4D	23	7	6	9	17	Good	14	6	10-20	21.5	3	<1
	4E	12	4	2	5	7	Fair/Poor	13	13	20-30	24	28	9
	4F	17	3.5	2	6	7	Fair	14	12	10-20	28	30	8
	4G	12	5.5	3	7.5	10	Fair	11	9	20-30	23	18	5
	4H	17	6.5	4	9	17	Fair	5.5	3	10-20	12.5	5	2

Treatment	Plant ID	Number of Leaves	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Plant Canopy Width (cm)	Robustness	Root Length (cm)	Root System Width (cm)	Number of Root Offshoots	Plant Length (cm)	Weight (grams)	Dry Weight (grams)
Graywater	5A	34	7.5	5	9.5	20	Good	15	11	10-20	26	22	6
	5B	12	7	4	8	14	Poor/Fair	11	7	10-20	21	7	2
	5C	22	10	8	13	17.5	Fair/Good	16	5	20-30	30	20	5
	5D	18	7	5	9	13	Fair	16	15	10-20	29.5	8	2
	5E	15	5.5	5	10.5	17	Fair	11	4	10-20	21	8	<1
	5F	13	9	4.5	12	17	Fair/Good	17	6	10-20	29	11	3
	5G	19	8	6	9	17	Good	10	9	20-30	22	19	4
	5H	14	8	4.5	12	11	Fair	16	9	10-20	29	11	2
Improved Water	6A	12	5.5	4	9	9	Good	9	3	10-20	25	6	2
	6B	19	7	4	10	16	Fair/Good	10	15	30-40	25.5	17	4
	6C	16	7	4	7.5	14	Fair/Good	12.5	7.5	20-30	22.5	12	3
	6D	18	6	5	7.5	12	Fair/Good	16	6	20-30	25	15	4
	6E	13	5	3.5	5	14.5	Poor/Fair	12	4	10-20	23	5	<1
	6F	13	7	4.5	8.5	14	Fair/Good	12	5	10-20	21	8	2
	6G	10	5	3	3	20	Poor/Fair	6	10	10-20	19	6	3
	6H	23	7	5	9	15	Fair	12.5	10.5	20-30	23	15	4

Treatment	Plant ID	Number of Leaves	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Plant Canopy Width (cm)	Robustness	Root Length (cm)	Root System Width (cm)	Number of Root Offshoots	Plant Length (cm)	Weight (grams)	Dry Weight (grams)
Graywater	7A	11	3	1.5	2.5	8	Poor	5.5	4	10-20	11	2	<1
	7B	17	4	2.5	5.5	7	Poor/Fair	4	3	20-30	11	3	<1
	7C	27	10	7	14	24	Good	18	12	10-20	36	41	12
	7D	21	9	5.5	16	25	Good	13	6.5	20-30	30	33	8
	7E	20	9	5.5	16	16	Good	18	10	20-30	36	28	7
	7F	23	10	6	13	17	Good	10	19.5	30-40	25	23	5
	7G	14	8	7	11	17	Fair/Good	6	11.5	20-30	20	16	5
	7H	17	7	6	12	22	Fair/Good	5	12	20-30	18	19	5
Improved Water	8A	22	9	4	10	19	Fair/Good	15	15	10-20	28	23	8
	8B	16	7	5	8	13	Fair/Good	13	10	10-20	22	11	5
	8C	28	10	8	12	29	Good	22	17	20-30	38	60	18
	8D	21	9	6	10	23	Good	15	8	20-30	28.5	28	10
	8E	23	8	6	11	20	Good	14	9	10-20	27	36	11
	8F	27	10	7	14	22	Good	21	7	10-20	37	33	8
	8G	20	9	7	12	24	Good	15	11	30-40	31	35	8
	8H	20	7	6	13	14	Good	19	6	10-20	32	21	5

Treatment	Plant ID	Number of Leaves	Leaf Length (cm)	Leaf Width (cm)	Plant Height (cm)	Plant Canopy Width (cm)	Robustness	Root Length (cm)	Root System Width (cm)	Number of Root Offshoots	Plant Length (cm)	Weight (grams)	Dry Weight (grams)
Improved Water	9A	18	7.5	6	9	25	Fair/Good	7	16	20-30	19	16	4
	9B	18	3	3	4	8	Poor	12	5	10-20	17.5	3	<1
	9C	20	6	3	7	18	Poor/Fair	13.5	11	10-20	25	12	2
	9D	23	12	8	12	30	Good	11	11	20-30	29	47	14
	9E	27	10	6.5	11	24	Good	11	28	20-30	27	41	9
	9F	14	7	4	6	23	Poor/Fair	15	17	20-30	28	11	3
	9G	15	8	5	17	30	Fair/Good	10.5	21	10-20	28	26	7
	9H	18	9	6	14	26	Good	14	15	20-30	32	33	10
Improved Water	10A	17	8	7	12	23	Good	19	10	20-30	34	25	7
	10B	8	5	3	5	13	Poor/Fair	10	7	10-20	18	5	2
	10C	13	5	4	6	15	Poor/Fair	9	9	20-30	20	8	2
	10D	14	5	4	4	21	Poor/Fair	8	30	20-30	18	12	4
	10E	17	7	5	4	17	Poor	13	16	20-30	23	12	3
	10F	12	5	4	5	18	Poor/Fair	11	10	20-30	22	11	3
	10G	19	7	7	14.5	30	Fair	10	16	20-30	30	37	9
	10H	11	4	2	3	15	Poor	9	6	10-20	13	2	<1

APPENDIX B – MEASUREMENT AVERAGES

Average Leaf Width Per Treatment

Average Plant Height Per Treatment

Average Plant Canopy Width Per Treatment

Average Plant Root Length Per Treatment

Average Plant Root System Width Per Treatment

Average Plant Length Per Treatment

Average Plant Weight Per Treatment

Average Plant Dry Weight Per Treatment

APPENDIX C – EXAMPLE CALCULATIONS OF $\sum(y_{gi} - \bar{y}_g)^2$ AND $\sum(y_{wi} - \bar{y}_w)^2$ FOR NUMBER OF LEAVES

Graywater					
Plant ID	Leaves	$\bar{y}_g$	$y_{gi} - \bar{y}_g$	$(y_{gi} - \bar{y}_g)^2$	$\sum(y_{gi} - \bar{y}_g)^2$
1A	0	17.75	-17.75	315.0625	1551.5
1B	13		-4.75	22.5625	
1C	6		-11.75	138.0625	
1D	26		8.25	68.0625	
1E	25		7.25	52.5625	
1F	26		8.25	68.0625	
1G	19		1.25	1.5625	
1H	19		1.25	1.5625	
2A	12		-5.75	33.0625	
2B	10		-7.75	60.0625	
2C	14		-3.75	14.0625	
2D	17		-0.75	0.5625	
2E	26		8.25	68.0625	
2F	18		0.25	0.0625	
2G	19		1.25	1.5625	
2H	18		0.25	0.0625	
3A	11		-6.75	45.5625	
3B	20		2.25	5.0625	
3C	18		0.25	0.0625	
3D	17		-0.75	0.5625	
3E	20		2.25	5.0625	
3F	14		-3.75	14.0625	
3G	27		9.25	85.5625	
3H	18		0.25	0.0625	
5A	34		16.25	264.0625	
5B	12		-5.75	33.0625	
5C	22		4.25	18.0625	
5D	18		0.25	0.0625	
5E	15		-2.75	7.5625	
5F	13		-4.75	22.5625	
5G	19		1.25	1.5625	
5H	14		-3.75	14.0625	
7A	11		-6.75	45.5625	
7B	17		-0.75	0.5625	
7C	27		9.25	85.5625	
7D	21		3.25	10.5625	
7E	20		2.25	5.0625	
7F	23		5.25	27.5625	
7G	14		-3.75	14.0625	
7H	17		-0.75	0.5625	

Improved Water					
Plant ID	Leaves	$\bar{y}_w$	$y_{wi} - \bar{y}_w$	$(y_{wi} - \bar{y}_w)^2$	$\sum (y_{wi} - \bar{y}_w)^2$
4A	11	17.35	-6.35	40.3225	931.1
4B	16		-1.35	1.8225	
4C	21		3.65	13.3225	
4D	23		5.65	31.9225	
4E	12		-5.35	28.6225	
4F	17		-0.35	0.1225	
4G	12		-5.35	28.6225	
4H	17		-0.35	0.1225	
6A	12		-5.35	28.6225	
6B	19		1.65	2.7225	
6C	16		-1.35	1.8225	
6D	18		0.65	0.4225	
6E	13		-4.35	18.9225	
6F	13		-4.35	18.9225	
6G	10		-7.35	54.0225	
6H	23		5.65	31.9225	
8A	22		4.65	21.6225	
8B	16		-1.35	1.8225	
8C	28		10.65	113.4225	
8D	21		3.65	13.3225	
8E	23		5.65	31.9225	
8F	27		9.65	93.1225	
8G	20		2.65	7.0225	
8H	20		2.65	7.0225	
9A	18		0.65	0.4225	
9B	18		0.65	0.4225	
9C	20		2.65	7.0225	
9D	23		5.65	31.9225	
9E	27		9.65	93.1225	
9F	14		-3.35	11.2225	
9G	15		-2.35	5.5225	
9H	18		0.65	0.4225	
10A	17		-0.35	0.1225	
10B	8		-9.35	87.4225	
10C	13		-4.35	18.9225	
10D	14		-3.35	11.2225	
10E	17		-0.35	0.1225	
10F	12		-5.35	28.6225	
10G	19		1.65	2.7225	
10H	11		-6.35	40.3225	

APPENDIX D – SOUTH AFRICAN AGRICULTURAL WATER REUSE STANDARDS

	Concentration (mg/R)	
Aluminum	5 - 20	
Arsenic	0.1 - 2.0	
Beryllium	0.10 - 0.5	
Boron	0.5 - 15.0	
Cadmium	0.01 - 0.05	
Chloride	140 - 700	
Chromium (VI)	0.10 - 1.0	
Cobalt	0.05 - 5.0	
Coliforms (Fecal)	E. Coli	1 - 1,000 / 100 mR
Copper	0.2 - 5.0	
Fluoride	2.0 - 15.0	
Iron	5.0 - 20.0	
Lead	0.2 - 2.0	
Lithium	0.075 - 5	
Manganese	0.02 - 10.0	
Molybdenum	0.01 - 0.05	
Nickel	0.20 - 2.0	
Nitrogen (Inorganic)	5 - 30	
pH	pH Range	6.5 - 8.4
Scaling/Corrosion	Langelier Index	-0.2 to +0.2
Selenium	0.02 - 0.05	
Sodium Absorption Ratio	SAR Range	2.0 - 15.0
Sodium	70 - 460	
Suspended Solids	50 - 100	
Total Dissolved Solids	40 - 540	
Uranium	0.01 - 0.10	
Vanadium	0.10 - 1.0	
Zinc	1.0 - 5.0	

(Africa, 1996)

APPENDIX E – WORLD HEALTH ORGANIZATION HEALTH STANDARDS FOR USE OF WASTEWATER IN AGRICULTURE

Category	Reuse Conditions	Intestinal nematodes (arithmetic mean no. of eggs per liter)	Fecal coliforms (geometric mean no. per 100 ml)	Wastewater treatment expected to achieve the required microbiological quality
A	Irrigation of crops likely to be eaten uncooked, sports fields, public parks	≤ 1	≤ 1000	A series of stabilization ponds designed to achieve the microbiological quality
B	Irrigation of cereal crops, industrial drops, fodder crops, pasture and trees	≤ 1	No standard recommended	Retention in stabilization ponds for 8-10 days or equivalent helminth and fecal coliform removal
C	Localized irrigation of crops in category B if exposure of workers and the public does not occur	N/A	N/A	Pretreatment as required by the irrigation technology, but not less

(WHO, 1989)

APPENDIX F - GRAYWATER REUSE, GUIDE TO CONDUCTING IN-FIELD STUDIES IN DEVELOPING COUNTRIES

1) Planning ahead

When departing for your Peace Corps post, you will not know much about the availability of resources that can be used to conduct graywater reuse research at the site to which you will be assigned. In fact, sites are often assigned during your in-country training. Internet access, electricity, and cell service are all things that can be drastically different within your country of service and between different country assignments. For example, bringing an electric scale for weighing plants to your Peace Corps field experience, might prove useless if your assigned site does not have electrical service. Researching your assigned country may help answer some of your questions prior to departure. How many volunteers typically have electricity? Is Internet access available within a day-trip of most volunteer sites? It is also worth noting that smaller items can be shipped to you while in service or potentially purchased in-country. Some items to think about bringing with you to your Peace Corps service include:

- Electronic (or physical) copies of technical manuals
- 25-foot tape measure, level, and other small tools
- pH strips or other test kits for characterizing graywater
- Test kits for analyzing soils or plants
- Battery-powered electronics

Table 1 shows an estimated project timeline to give an idea of time allocation. The initial three months of service will be devoted to in-country training and site placement.

Table 1 – Example project schedule

Project Stage	Month of Peace Corps Service																										
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
Planning																											
Community needs				X	X	X																					
Available resources				X	X	X																					
Design																											
Graywater collection system						X	X	X																			
Garden for experimentation						X	X	X																			
Construction																											
Material transportation									X	X	X	X	X	X	X	X											
Funding logistics									X	X	X	X	X	X	X	X											
Labor logistics (if needed)										X	X	X	X	X	X	X	X										
Building										X	X	X	X	X	X	X	X										
Experiment																											
Planting																		X									
Maintaining garden																		X	X	X							
Data collection																			X	X							
Post-experiment																											
Restart experiment (if needed)																					X	X	X	X	X	X	
Recording data					X	X																				X	X
Laboratory analysis					X	X																				X	X

It is worth noting that this is a generic schedule to be adapted for use at a given site. The maintenance period for the experimental garden is dependent on the growing time for the chosen crop. Laboratory analyses may not be possible or practical in your country.

2) Materials and resources needed on-site

Graywater source, collection, and storage

A source of graywater is needed and this will depend on your site. Personal graywater may not be enough for a study and you may have to arrange with your host family or a neighbor to use their graywater. Collection and storage of graywater needs to be consistent to avoid experimental bias.

Garden/seeds

Experimenting with a personal garden prior to the start of your experimental trials may prove to be beneficial in the long run. A personal garden can usually be established quickly, gives access to a larger variety of vegetables, and acts as a trial garden that can be used to identify potential problems (e.g., with irrigation, crop damage by animals, etc.) and troubleshoot solutions to these problems. In general, maintaining a personal garden will give you a better chance of developing a successful experimental garden in your country during your study.

Control or reference improved water source or rainwater

You will need a control water to use as a point of reference in comparison to graywater. Using the typical irrigation source in your village will help design a study that can potentially help your community. So, when you arrive at your site, you will want to explore how the locals irrigate their gardens.

Measurement tools/techniques

Physical plant attributes can be measured relatively easily in Peace Corps. A tape measure, ruler, and scale can be used to obtain most physical measurements and can be brought with you to Peace Corps, purchased in country, or mailed to you during your service. If you are planning to use laboratory testing tools or planning to construct a complex graywater collection system, then the tools needed may be larger and more complicated. This can be evaluated in the available resources portion of your study design. It is important to know what options are available locally and what will be more difficult to acquire. This will have a large impact on your experiment design.

3) Methods

Key considerations:

- Time scheduling
Planning for time can be much different than in the United States. Even if you have prepared for things to move more slowly in your country of service, it can be drastically different when immersed in your country. Therefore, careful planning is critical. If your project includes a lot of construction, materials may be needed from areas far removed from your site. Your neighbors or coworkers can be of great help with organizing transportation, but acquiring materials may take several months.
- Labor / Help
If you plan to enlist the help of locals in construction or other aspects of your project, anticipate that the work may be performed differently than you had envisioned. For example, building styles may be different in your country than in design manuals. You may have to work with locals more than you planned to achieve the desired outcomes.

Graywater design example

An example graywater collection system design is shown in Figure F1. This graywater collection system was built in Lesotho and involved connecting to an existing water source to pipe water

into the house to a hot water heater. Water was then used for showering and collected in a graywater collection tank outside the house. This system created a graywater stream, collected that stream, and stored it in a protected area to keep animals and rain out.

Figure F1 – Example graywater collection system

Garden design example

An example garden layout is shown in Figure F2. This garden layout was built in Lesotho with bermed rows. Two treatments (graywater and improved water) were used and tested randomly on 10 separated rows. Each row was separated by a berm and walking lane to allow access to plants and keep plants separated.

Figure F2 – Example garden design

Key considerations:

- **Randomize treatments**
Randomized treatments minimize bias. Samples can be randomized using playing cards or a rolling die. For playing cards, randomizing can be achieved by assigning a treatment to a card suit or card color, shuffling, and dealing cards to each row. If you are using a rolling die, randomizing can be achieved by assigning a treatment to either an odd or even number and rolling for each row.
- **Design for animals**
Livestock and/or wild animals can ruin a garden project and are a key garden design consideration. Large animals will need barriers, whether that entails buying fencing or building barriers with materials found locally. Smaller animals like chickens may mean chicken wire or other means of preventing chicks from entering your garden are needed.

- **Local gardening techniques**

It is important to consider using local gardening techniques. These can be learned by talking to neighbors, and often there are good reasons for using these local “best practices” including weather patterns that you are unaware of, or specific soil properties. It is recommended that you practice gardening with these local methods to become aware of some of the issues with gardening in your country. Pests can be a problem and often locals will have a method for pest control that works or you will have time to research methods for solving a pest problem.

4) Cost analysis

When calculating costs, especially if your project includes construction, anticipate paying for unexpected services. Communication challenges can make it difficult to plan for all costs. For example, you make arrangements with local acquaintances regarding transportation or help and find that prices that were agreed upon change after the service is performed or perhaps individuals who you thought were donating their time and effort end up expecting compensation. To minimize these miscommunications, it is important to start planning early and potentially go on smaller trips or hire out someone for a small project to see how everything works. Once you have a relationship with an individual or transportation service you can better predict how larger parts of the project will go.

5) Potential research ideas

Possible research ideas that would continue graywater research could include:

Comparing different plant types – This could determine if graywater irrigation may work better for some species than others.

Comparing soil samples – This could determine if graywater irrigation affects nutrient, salt, chemical, and/or pathogen levels in soils.

Comparing plant samples – This could determine if graywater irrigation increases pathogen levels on plants. If so, are they in the root system, stalk, or edible portions of the plant? Further measurements could be taken to determine how persistent potential pathogens are.

Comparing graywater samples – Graywater and the control irrigation water could be measured for nutrients, salts, chemicals, and pathogens. This type of measurement will need laboratory analysis or an on-site testing kit. Characterization of graywater could be further explored by characterizing the average graywater produced by your village.

Comparing graywater filtration methods – This could compare different graywater treatment methods testing for total suspended solids, nutrients, salts, chemicals, and pathogens. This can further be explored to determine which methods would produce a graywater that locals would deem acceptable for irrigation use. Methods could also be compared using physical plant measurements. This type of study could benefit from laboratory analysis or on-site testing kits.