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A fesability analysis of a novel constructed wetland design tool for Arusha, Tanzania

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For the degree of Master of Science in Agricultural and Biological Engineering

Is approved by the final examining committee:

John Lumkes

Chad Jafvert

Karoli Njau

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Approved by Major Professor(s): John Lumkes

Approved by: Bernard Engel 7/22/2014
Head of the Department Graduate Program Date

A FESABILITY ANALYSIS OF A NOVEL CONSTRUCTED WETLAND DESIGN TOOL FOR ARUSHA, TANZANIA

A Thesis

Submitted to the Faculty

of

Purdue University

by

Michael R. Sheehan

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Agricultural and Biological Engineering

August 2014

Purdue University

West Lafayette, Indiana

Dedicated to my family; Mom, Dad, Brian, Tim, and Amanda Pearl:

without all of your support, none of this would have been possible.

“We forget that the water cycle and the life cycle are one.”

-Jacques Cousteau

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LIST OF ABBREVIATIONS

ASTER	Advanced Spaceborne Thermal Emission and Reflection
CDC	Center for Disease Control
CFSR	Climate Forecast System Reanalysis
DEM	Digital Elevation Model
E. Coli	*Escherichia coli*
FWS	Free Water Surface
MPIP	Max Planck Institute Process
NCEP	National Centers for Environmental Prediction
NM-AIST	Nelson Mandela African Institute of Science and Technology
RZM	Root Zone Method
SODIS	Solar water disinfection
SSF	Sub Surface Flow
TDS	Total Dissolved Solids
UN	United Nations
USAID	United State Agency for International Development
WHO	World Health Organization

ABSTRACT

Sheehan, Michael R. M.S.A.B.E., Purdue University, August 2014. A Feasibility Analysis of a Novel Constructed Wetland Design Tool for Arusha, Tanzania. Major Professor: John Lumkes.

While water is a resource necessary for all life, in Tanzania alone over 20 million people who live in rural areas have no access to improved water sources. Water stress is a major concern in rural Tanzania, where annual potential evaporation can outpace precipitation by hundreds of mm per year. There is a significant need for improved access to water sources for Tanzanians living in rural regions of Arusha. To improve access to water, both water quantity and quality need to be addressed in a treatment system. Various water collection and treatment systems were compared and contrasted through the lens of appropriate technology. Sub surface flow (SSF) constructed wetlands and ultrafiltration systems were selected for development.

Constructed wetlands have a history of water treatment dating back hundreds of years. SSF constructed wetlands are an appropriate solution for water stress in the Arusha region due to their low cost, low maintenance requirements, and pre-treatment. To help establish a baseline water quality of surface water in Arusha, water was collected from various sources across the region. While they were tested for multiple parameters, turbidity and bacterial contaminants were identified and confirmed as the primary pollutants of concern. To help design constructed wetlands in the region a tool was built in Excel. The tool incorporates rainfall, runoff, and other environmental factors to produce information for sizing and availability to help project planners design a constructed wetland.

The developed tool was applied to the Nelson Mandela African Institute of Science and Technology (NM-AIST) campus and the village of Endallah. A pilot scale wetland was designed for the NM-AIST campus for testing and validating of the tool, and a wetland was designed for the village of Endallah based on incoming runoff and consumption by the villagers. These applications demonstrated how the tool can be used and applied to other places by project planners in the field of water management.

CHAPTER 1. INTRODUCTION

1.1 Background

According to the 2012 UN Millennium Goals Report, “783 million people remain without access to an improved source of drinking water”, 653 million of who live in rural areas. These data overwhelmingly affect the poorest people in sub-Saharan Africa, where “piped in water is non-existent in the poorest 40% of households”. For 75% of sub-Saharan Africa, women and girls travel significant distance to collect water, often from poor or contaminated sources (Nkonya, 2011).

The country of Tanzania especially suffers from a lack of quality water sources. In the country of over 45 million, nearly 80% live in rural areas, 56% of whom have no access to an improved drinking water source during the dry season (UBS, 2013). Water can be rare during the long dry season where rain is scarce and evaporation is greatest. A combination of lack of available water and deteriorating quality of water causes highly contaminated water used for domestic and consumption purposes (Nkonya, 2011). Bacterial contaminants and high turbidity in natural water sources pose a significant health risk: 12.1% of all deaths are water, sanitation and hygiene related (Njau, 2013).

Constructed wetlands as a technology have been in practice for over 100 years around the world for collecting and treating water. Constructed wetlands act like natural wetlands by cleaning and polishing water through natural methods for a comparably low-cost. Constructed wetlands have been primarily used to treat wastewater from domestic or industrial sources before re-introduction to the environment as an alternative or supplement to modern water treatment facilities. Comparatively little research has been done investigating a constructed wetland's ability to collect and treat stormwater runoff for domestic uses as a low cost alternative for drinking and domestic water. Consequently, stormwater wetlands for water consumption are not common in today's art.

1.2 Research Objectives

- *Find the primary pollutant concerns for surface waters in the Arusha region of Tanzania.*
- *To create a tool to help design constructed wetlands for drinking water in the Arusha region.*
- *Apply this tool to the Nelson Mandela African Institute of Science and Technology campus and the village of Endallah.*

1.3 Thesis Overview

This thesis is divided into 8 chapters. Chapter 2-4 are background sections on Tanzania, appropriate technology, and constructed wetland technology, respectively. Chapter 5-7 address the stated research questions. Chapter 5 describes field visits where water quality was tested to establish baseline pollutants, chapter 6 explains and details the wetland design tool, and chapter 7 is an application of the tool at the Nelson Mandela African Institute of Science and Technology and village of Endallah. Chapter 8 is the conclusion that summarizes these findings and suggests future work. References and appendices are at the end of the thesis.

CHAPTER 2. REGIONAL BACKGROUND

2.1 Geographic Background

The Republic of Tanzania, established in 1964 is on the East coast of Africa, South of Kenya and North of Mozambique (see figure 2.1). Tanzania is home to nearly 45 million people, nearly three-quarters of whom live in rural areas (Tanzania, 2014). The country is divided into 30 sub-regions, with the region of Arusha found in the Northeast on the border with Kenya (see figure 2.2). Approximately 1.7 million people live in the Arusha region and 530 thousand of whom live in the city of Arusha, the capital of this region. The Great Rift Valley runs through the Arusha region, but most of the region is between 900 and 1600 meters in elevation. The highest point in the region is Mount Meru, with a peak at 4,655 meters, only exceeded in Tanzania by Mount Kilimanjaro (ASTER 2011).

Figure 2.1 Tanzania on the Eastern coast of Africa (Júnior)

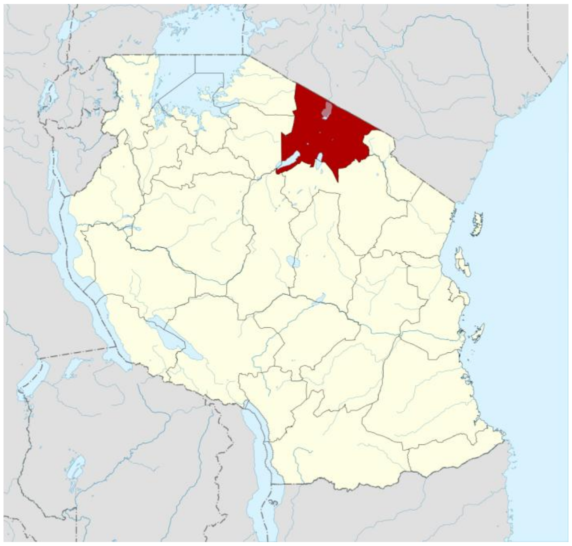

Figure 2.2 Arusha region of Tanzania (Semhur)

The Arusha region is generally characterized as semi-arid highlands with a temperate climate. The land is mostly savannah, with frequent hills and valleys, and some woodland often near water bodies. Soils are generally derivatives of volcanic ash which are very fertile but also fragile and susceptible to erosion. The Savannah domains are populated by perennial herbaceous plants with few trees and little vegetation cover. The Shrub-land is most often found on hills or in rocky terrain with shrubs 0.5 – 3 m tall (Instituto, 2011).

2.2 Climate in Arusha, Tanzania

The temperature in the Arusha region generally ranges from 29 °C in the hottest months, to 8 °C in the coldest, with an average temperature around 18.5 °C. Day to day, the temperature generally remains consistent without major fluctuations.

Arusha experiences a bimodal rainfall pattern, which consists of two wet seasons and two dry seasons: the short dry season in January and February, the long rain, from March through May, the long dry season from June through October, and the short rain, through November and December (Instituto, 2011). With an average rainfall of only 1300 mm per year, 60% and 17% come in the long and short rainy seasons, respectively, for a total of 5 months. Additionally, on average only 8% of precipitation occurs from June – October, which often results in droughts and limited access to water in rural areas.

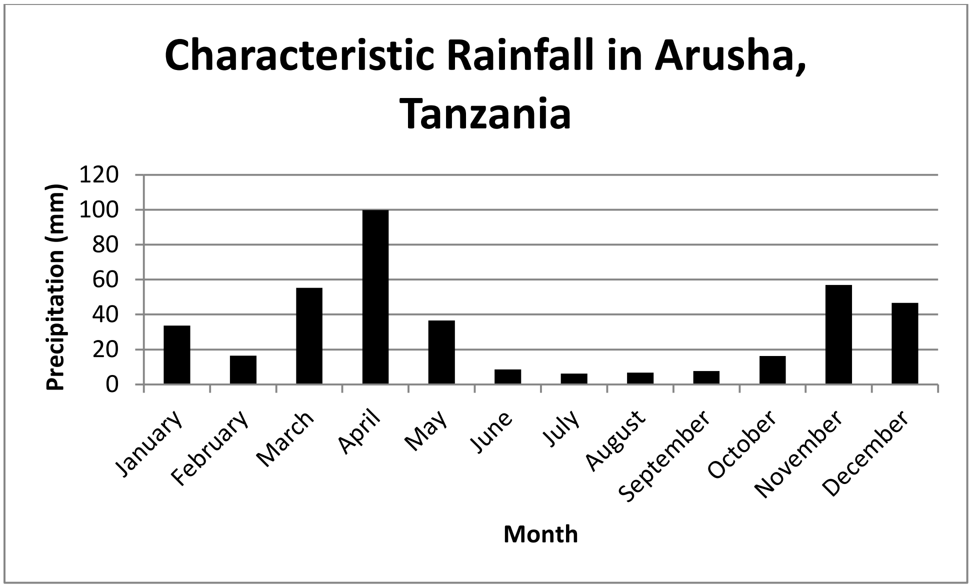

Figure 2.3 Monthly average rainfall in Arusha, Tanzania (NCEP, 2010)

In the more mountainous areas spring water may be available year round, but often in the savannah water is very hard to capture and store. During the rainy seasons, rainfall tends to come in very short duration-high intensity events, often causing the flash flooding of perennial streams and significant loss of soils through erosion. In these events, very little water tends to infiltrate the cracked earth, consequently not replenishing wells. This area tends to have high rates of soil erosion due to the semi-arid and arid climate, and is the leading cause of limited soil fertility (VPO, 1999).

2.3 Availability of Water

Over the years, many estimates for basic water needs have been made. While 2 liters/capita/day has been estimated as the absolute minimum water requirement for survival, many aid organizations estimate a minimum of 20 – 40 l/c/d as a basic water requirement, excluding needs from cooking and cleaning (USAID, 2012;WHO 2011). In his analysis, Gleick estimates that a minimum of 50 l/c/d should be established "independent of climate, technology, and culture", and includes the four domestic basic needs of drinking, sanitation, bathing and cooking. The Tanzanian ministry of water set a goal of a minimum of 25 l/c/d where water is scarce year round (MWLD 2002). Other estimates in literature for basic daily needs varied from 30 – 200 l/c/d. However, these should be seen as a minimum water needs, and not a long term goal.

When people don't have access to clean water, they are forced to use contaminated water which can be dangerous to their health (Dungumaro, 2007). The primary means of water contamination in the rural regions of Tanzania is due to runoff during large storms in the rainy season causing high turbidity and poor water source protection causing bacterial contamination (VPO, 1999).

The World Health Organization (WHO) does not set a water quality standard for turbidity, but turbidity must be lower than 0.1 NTU to ensure that disinfection occurs properly. The WHO standards for nitrate/nitrite are 50 and 3 mg/l, respectively. They also keep a standard for fluoride concentrations of 1.5 mg/l (which is commonly found in ground water within the Great Rift Valley) as wells as maintaining extensive standards for various agricultural pesticides, fertilizers and other chemicals. Because of various microbial concerns, it is recommended that water be sterilized before consumption.

Tanzania itself has also established a number of water quality standards for drinking water sources. These include keeping turbidity less than 5 – 25 mg/l and fluoride less than 1.5 – 4 mg/l. The country also establishes limits on total coliforms and *Eschereichia coli* (E. coli), with four classes based on the total coliform count: Excellent, satisfactory, suspicious, and unsatisfactory. Total coliform counts for these classes are 0, 1-3, 4 – 10, and more than 10 colonies per 100 ml of water, respectively, while one or more E. Coli colony is considered unsatisfactory by drinking water standards (MWLD, 2009).

2.4 Tanzanian Views on Water

In Tanzania, water is seen as a basic right that belongs to every human. The Tanzanian government's national policy enforces this idea and believes that parts of the country which suffer from water shortages require investment priority to alleviate water stress (MWLD, 2002). According to the United Nations Economic & Social Council, a right to water requires three factors to be met: water must be *available* in sufficient quantities for personal and household use, the water must be of good *quality* so that it is not harmful to a person's health, and must be *accessible* to every person without physical, economic, discriminatory or informational barriers.

Despite viewing water as a basic right, rural areas in Tanzania rarely meet these three factors, causing water scarcity across the region. Being a semi-arid region, not much water is available year round. Droughts are an annual occurrence June-October where only 8% of the annual precipitation occurs and the evaporation rates are the highest. In fact, the entire Arusha region experiences anywhere from 1400 – 2200 mm of potential surface water evaporation a year, anywhere from 100 – 900 mm more than the average annual rainfall (Dagg, 1970). This water imbalance means that any water which is not protected or managed correctly could easily be lost during these dry seasons.

While all large cities have some form of piped water and sewage system, these are ineffective, limited and do not cover most residents. In a paper written for the Annual Water Conference in Arusha, Njau and Machunda describe sewage systems only supporting 16.4% of residents on average , with as many as 45% lacking coverage in one area. Despite knowledge of these challenges, the water and wastewater difficulties in Tanzanian cities are only growing. This is due to skyrocketing urban populations and the growth of informal settlements within city boundaries, and urban infrastructure unable to keep up. This has caused a downward trend in safe water access and stagnant household sanitation practices (Njau, 2013).

As poor as the water situation may be in Tanzania’s cities, Tanzanians in rural villages experience much more difficulty collecting potable water and maintaining sanitary practices. With no piped water to the majority of villages, rural Tanzanians are forced to collect water from rivers, ponds, wells (both deep and more common shallow wells), and springs, along with purchasing water from trucks being shipped into villages at very high costs.

Even where water is found, the sources are often flooded with sediment, nutrients and microorganisms after the heavy storms during the rainy seasons, debilitating most water sources. Additionally, ground water in the Arusha region (within the Great Rift Valley) is known to have unacceptable concentrations of fluoride that pose a massive threat to dental and bone health (MWLD, 2002).

Water collection practices often lead to animal contamination, especially in the case of ponds and lakes. Pack animals that are kept next to the water bodies will often defecate where villagers are collecting water. This often causes significant pollution in water used for drinking, bathing, and agriculture. Wells tend to be more protected, but most wells in villages are shallow wells that recharge with rainfall events. This quick infiltration does not allow the water to be as cleaned as water from deeper aquifers, and can still contain bacterial contamination, along with suspended solids and nutrients.

The issue of accessibility for the job of collecting water for households tends to fall on women and girls in rural Tanzania. Because of the scarcity in the climate and poor quality of groundwater women and girls often travel huge distances only to use marginal sources of water, a massive physical barrier. Girls tend to face difficulties in collecting water often cannot attend school and do not receive and adequate education (Nkonya, 2011).

CHAPTER 3. TECHNOLOGY BACKGROUND

3.1 Criteria for Treatment Selection

Many solutions to the problem of high quality water access have been proposed, but not all solutions are equal. The concept of appropriate technology works to discern which technology is likely to have a better, more successful impact than others. While the idea of appropriate technology was first coined by British Economist EF Schumacher, researchers have yet to develop any single definition and often disagree on what qualities a technology should have to be successful in any specific situation. Incorporating societal and cultural aspects into engineering designs often leads to increased rate of project success that benefits all parties involved (Limiac, 2013). Murphy et. al. has developed a list of criteria from a review of literature attempting to define attributes of an appropriate technology, and discusses the benefits these considerations provide.

3.1.1 Appropriate Technology Criteria

An appropriate technology, like any solution to the challenge access to safe water, must first meet the basic needs of the users. If a society does not have its basic needs (such as clean water, food, safety, housing, etc.) met, investing communal resources and energies into other areas is not considered appropriate (Murphy, 2009). Additionally, the technology in question must be able to solve the challenges it claims to. While it may seem obvious, it is important that any introduced technology will actually work as intended, and produce the desired results: any other outcome is unacceptable as a technical solution. Without meeting the basic needs of the users or effectively addressing the issue as planned, a technology is definitely unfit as a solution (Murphy, 2009). Historically, project planners believed that if a technology applies to one part of the world, it can apply everywhere else. Recently, this sentiment has been shown to be false, evident by the countless examples of failed projects in the development sector that were based on “sound technology” that worked somewhere else. This has led to the idea that cultural and social acceptability is nearly as important as having a functioning solution (Limiac, 2013).

Other definitions of appropriate technology include some aspects that are more subjective than binary in their requirements. Sustainability is often considered a requirement for an appropriate technology, as projects need to be environmentally and locally sustainable. Environmental sustainability means that a technology will not damage the environment the community lives in, or deplete resources it uses to function. Social sustainability means that a project should be able to be run and serviced by the local community: the more dependent a technology is on externalities to the community, the less likely that technology will be to succeed (Murphy, 2009). Another common dimension of appropriate technology is affordability. Often this is interpreted as “cheap technology”, but more accurately means that technology needs to be tailored to the community where it is being used (Wicklein, 1998). What may be affordable for one community could be prohibitively expensive in another, or may not preform effectively because of corners cut due to costs. Similar to affordability, a technology using local materials is often included in definitions of appropriate technology. Using local materials in construction and operation often reduces overall and maintenance costs, while foreign materials and technology may be prohibitively difficult to fix or replace, limiting the ability of the community to maintain the equipment and be self-sufficient (Murphy, 2009). However, local materials are not always the best option: For example, cell phones in Africa. While many people in Africa have cell phones, even in rural areas, the phones are often made in Asia. Despite being designed and manufactured across the world, these phones are often the best option for mobile communications in Africa.

Some aspects of appropriate technology have less to do with any kind of engineering design, but about how the technology works in the community. One thing that designers have begun to focus on is gender considerations, specifically focusing on empowering women. Women, especially in rural Africa, are tasked with difficult jobs such as collecting water and firewood (Murphy, 2009). This means that women will tend to be the primary users of technology focused on access to clean water, for example. In addition to a focus on women, appropriate technologies tend to involve at least some aspect of local participation (Limiac, 2013). While there are many levels of local participation that can vary from incorporating local opinions into design to hiring a community member as a project lead, local participation also allows a community to take the technology into their own hands, and increase viability whenever maintenance is needed.

Finally, appropriate technology needs to be flexible and allow for improvements. A flexible technology means that a design that is used for one place can be adapted to another similar place or used under different conditions. This allows a technology not only to remain robust against a variety of climatic or operating conditions, but to grow and expand across more areas with success. Along with being adaptable to different places, technologies that break the traditional "one-way" transfer of information tend to experience less success than technologies that learn from previous experiences. Therefore the "two way" model of gaining feedback and modifying designs based on the use of the communities are invaluable for any appropriate technology (Murphy, 2009).

3.1.2 Evaluation of Technologies

While no single technology can be considered a "perfectly" appropriate technology, these are standards that various technologies can be compared and contrasted in an effort to create the most successful solution to water security in Tanzania (Wicklein, 1998). Therefore, this next section will identify and evaluate a series of technologies with the concept of appropriate technology in mind.

3.2 Water Containment Alternatives

Due to the Arusha region's long dry season, water tends to become very scarce in September and October. Therefore, any solution will need to take into account both water purification and storage so as to address both a lack of water quality and quantity as water stressors. The water storage technologies investigated here are dams, constructed wetlands, and water storage tanks.

3.2.1 Dams

3.2.1.1 Earthen Dams

In contrast to constructed wetlands, dams are a simpler method of holding large quantities of water. Dams have been growing in popularity since after 1950, but have been a common technology around the world for many years earlier. In Africa, the original and simplest way to build an earthen dam is to build an embankment across an already existent stream and create storage space behind it. This allows water to pool behind the embankment and store large volumes of water with relatively little construction (Stephens, 2010).

This method has a number of benefits, the first being that the embankment can be made with local soil, and can be built with comparatively simple farming equipment (Stephens, 2010). However, there are draw backs to earthen dams; the embankment can be damaged by water flowing on or through it (which can be mitigated using a well-designed spillway), and the failure of an earthen dam can cause flooding concerns downstream. Additionally, the open surface water is easily exposed to pollutants and pathogens, creates a breeding ground for mosquitoes, and suffers from high rates of evaporation in the arid Tanzania dry seasons. Finally, stagnant water containing organic matter can produce biogas and unpleasant fumes that could pollute the air around it.

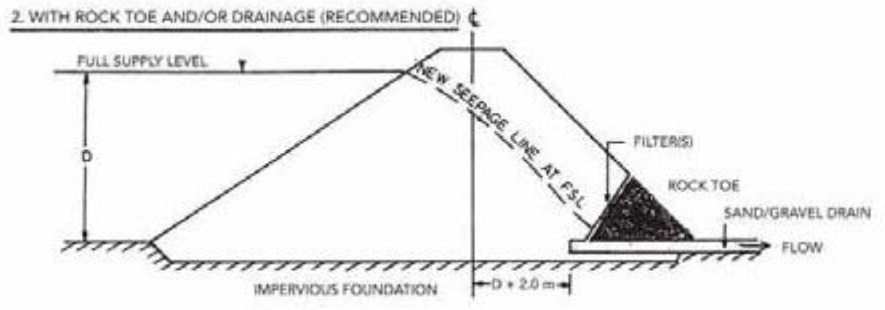

Figure 3.1 Earthen Dam Diagram (Stephens, 2010)

3.2.1.2 Sand Dams

Sand dams are similar to earthen dams, only that they are filled with sand behind the berm, and the water level is kept below the sand level. Sand dams can also be built across river beds so as to reduce construction costs and complexity. In contrast, embankments holding sand dams tend to be made with concrete due to the higher density of the sand. Water is then extracted from the sand aquifer through wells built on top of the structure or from a pipe out of the bottom (Lasage, 2006).

Sand dams, in comparison to earthen dams, help to cut down on evaporation due to the water level being below the level of sand. This also protects the water from pathogens or pollutants entering the water directly, and can provide biological treatment similar to natural aquifers. Similar to earthen dams, they can also be built out of local material and there are numerous examples for designs found across Africa. Also similar to earthen dams, sand dams create flooding concerns if there is ever an embankment failure. In addition, the sand will occupy at least 50% of the area behind the dam, meaning that sand dams require a lot of sand to supply a significant amount of water, and need to be twice as large as a free water dam for the same water volume.

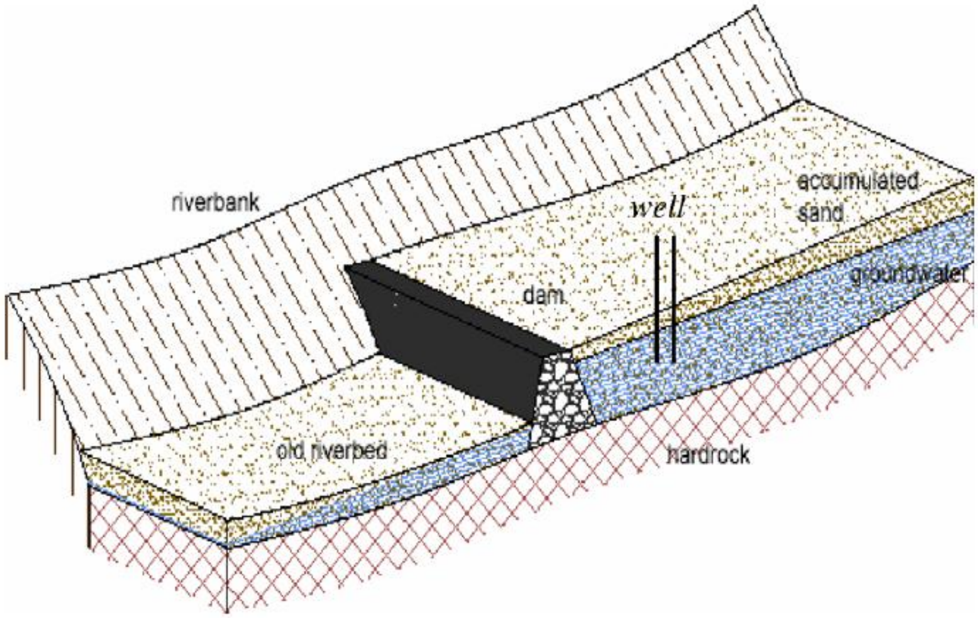

Figure 3.2 Sand Dam Diagram (Lasage, 2006)

3.2.2 Constructed Wetlands

Wetlands area often known as the environment's filters because they tend to be effective at removing various pollutants through natural processes (Kadlec, 2009). To harness these benefits, engineers around the world began to design and build constructed wetlands, artificial interactions between earth and water that are made to mimic the complex processes found in nature. Constructed wetlands have the ability to remove a variety of pollutants, including suspended solids, turbidity, heavy metals, nitrogen and phosphorus, along with storing large amounts of water. Since constructed wetlands first became popular in 1952, various models have emerged that provide different benefits and limitations. Two of the most popular models are free water surface (FWS) and subsurface flow (SSF) wetlands.

3.2.2.1 Free Water Surface Wetlands

In a free water surface wetland, water moves horizontally while getting treated. FWS wetlands look similar to natural wetlands and marshes, and consist of open water inhabited by either floating or submerged plants (Kadlec, 2009). Benefits of FWS wetlands are their relative simplicity to build and maintain, and require few materials therefore reducing cost. They tend to create natural homes for various flora and fauna, and are often appreciated for their natural beauty. However, two major limitations that specifically apply in Africa are high evaporation rates and the creation of mosquito breeding grounds. Since potential evaporation rates in the dry months can be significantly higher than rainfall, evaporation could prove a very debilitating weakness in addition to mosquitoes as the vector for malaria.

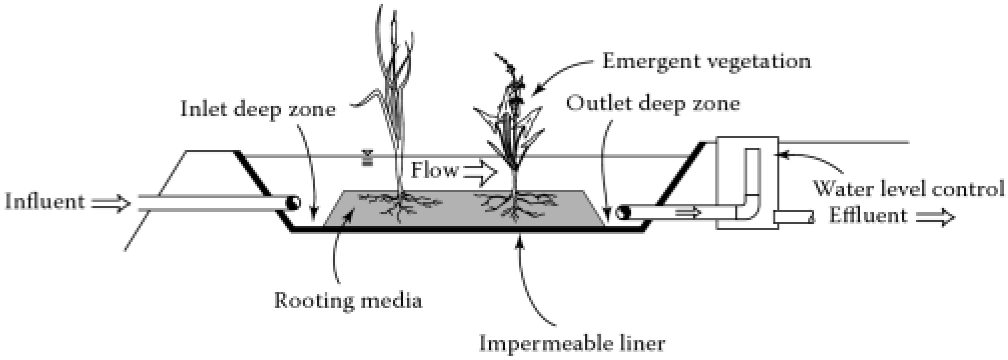

Figure 3.3 FWS Wetland Diagram (Kadlec, 2009)

3.2.2.2 Subsurface Flow Wetlands

Subsurface flow constructed wetlands are similar to FWS wetlands, but are different where the water moves through the wetland below the media surface of soil, sand, or gravel (Kadlec, 2009). These are the type of wetland exclusively designed in Tanzania and heavily favored in warmer climates due to reduced evaporation because of the protected water surface. However SSF wetlands are generally planted with emergent wetland plants (such as bulrushes and common reeds) can experiance significant evapotranspiration. Because these plants are necessary to provide another level of treatment, this evapotranspiration is a major concern in arid regions. SSF wetlands are also considered safer by not having any water body for people to fall into or as a breeding ground for mosquitoes, along with being protected from trash or debris entering the water. Filling the bed with sand or gravel does require additional costs for media and a larger necessary footprint and volume. Sand and gravel media will also clog over time due to biological growth and sedimentation natural to wetlands.

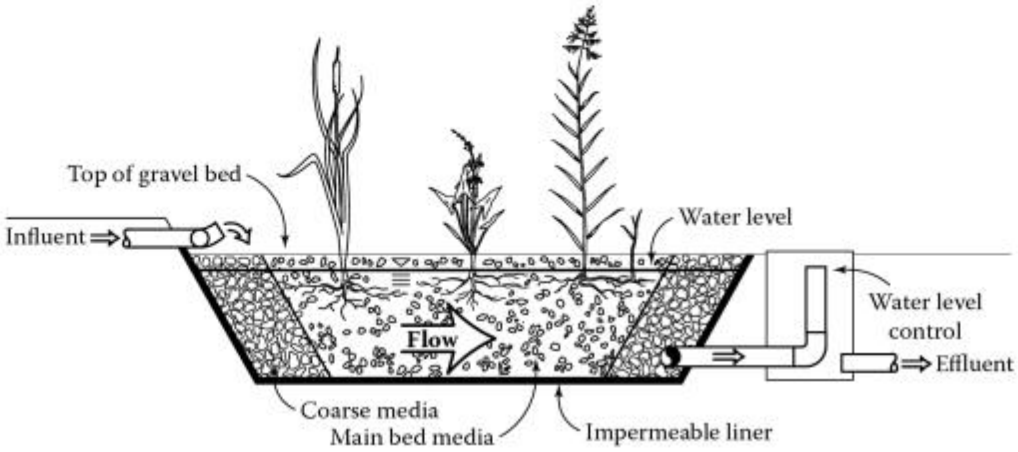

Figure 3.4 SSF Wetland Diagram (Kadlec, 2009)

3.2.3 Water Tanks

3.2.3.1 Large Tanks

In contrast to earthen structures to hold water, large vessels have been applied across the semi-arid landscape in use for centuries. Large containers made out of clay bricks can collect rainwater runoff and store it underground for the rainy season. In more recently, massive plastic water containers are being sold in the Arusha region (as large as 20,000 liters), and concrete structures can be made to hold even more volume.

These tanks are relatively simple to implement, either placing them below ground (common for clay or concrete vessels) and collect watershed runoff, or they can be raised above ground and only collect runoff from rooftops (can be plastic, clay or concrete).

Using large tanks has setbacks however. Purchasing the necessary number of tanks to supply water for an entire village could become very expensive, especially as the price of large tanks increase quickly with increased volume. Additionally, poor maintenance or care could easily lead to contamination in the tank, polluting the water further. This can be controlled through the occasional use of chlorine as a disinfectant. Finally, the type of plastic is important to the water tank, as some plastics (such as PET bottles) will degrade over time and can pollute the water being stored.

3.2.3.2 Household Tanks

In contrast to a village scale project, a smaller tank can be installed at each home, allowing families to control and harvest their own water. A household system simplifies the installation and ownership concerns, as each household can be in charge of their own water. This would also prevent competition or over-use of community resources by individuals. Difficulties however include that many tanks could increase the cost significantly. Also, each family would need to be educated on tank care and maintenance to prevent or treat water contamination. A broader educational program would definitely prove more difficult to implement. Currently, tanks are common in the city of Arusha, with families collecting water off their roofs for future use.

3.3 Secondary Treatment Alternatives

To ensure that water is clean enough to drink, the water quality needs to be addressed as well as the quantity. Most water that would be collected from rainfall would not be clean enough for consumption, and may include various chemicals and pathogens harmful to human health. There are a wide variety of options for secondary treatment of the collected water, some options that work better with other collection systems. The water purification methods that are investigated here are filters, chlorination, the SODIS method, and boiling.

3.3.1 Ultra Filtration Systems

While filters are a very common water treatment method, filters with 0.1 micron pores or finer are small enough so that many particles are filtered out, along with most bacteria and viruses (Pryor, 1998), making water safe to drink.

3.3.1.1 Polymeric Filtration

One of the most technologically advanced options for filters includes plastic 0.1 micron filters. These filters can vary from personal use to capacity for an entire village, and filters are already being used in various places in Arusha, Africa, and the rest of the world. Generally, these filters are easy to use and transport, making them viable for use in rural areas. Additionally, the filter surface can often be cleaned instead of replaced, extending the life time greatly. These filters can also be purchased for personal use or on a village scale, allowing for site specific design. Plastic filters can be expensive however, especially if a specific filter needs the mesh to be replaced. High turbid water, like the water found in Tanzania would quickly clog filters, and they will not remove color that is not due to suspended particles.

3.3.1.2 Ceramic Filtration

Ceramic filters are similar to polymeric filters in that water is purified as water passes through micron sized pores where pollutants and bacteria are stopped. Ceramic filters can also be impregnated or coated with various additives for enhanced protection, such as silver to aid in killing bacteria (Clasen, 2004). Ceramic filters can be made within the region, leading to lower overall costs. The passive use ceramic filters are also relatively simple to use on a household basis. Limitations on ceramic filters include the inability to build a system the size for a community, that ceramic filters can clog quickly but can be cleaned and reused, and that they may not remove all impurities. If water with high turbidity is passed through a ceramic filter, it will likely clog within only a few days.

3.3.1.3 Slow Sand Filtration

Sand filters are the oldest filtering technology, consisting of layers of sand and gravel in a bucket or other vessel. Water is added to the top, and is allowed to gravimetrically pass through the pores in the sand which filters out particulates, while bacteria consume pollutants or pollutants attach to the sand particles themselves (Urbonas, 1999). Sand filters are relatively simple to build and design, can be scaled to any size or volume, with materials commonly available in Tanzania. While some sand filters may last for 10-20 years, they will clog over time and will require the media to either be cleaned or replaced entirely. Sand filters also require training to design, build, and maintain, creating barriers to flexibility. These filters are not technically ultra-filtration systems (since the pores between sand tend to be larger than 0.1 microns), but sand filters offer the additional treatment from non-harmful bacteria out performing and consuming harmful bacteria living in the water.

3.3.2 Chlorine Treatment

Chlorine treatment is a chemical treatment that is used around the world by developed and developing countries alike. Since the early 1900s, chlorine in the form of tablets, powders, gases, and liquids has been used to disinfect and prevent diseases (Lantagne, 2010). Chlorination is a simple, cheap and common method of disinfection, where even household bleach can be used to effectively kill bacteria at safe concentrations to drink. While chlorine can be found around the world at reasonable prices, rural communities would need a continuous supply for long term solution. Water treated with chlorine needs to have low turbidity to make sure it works effectively, and if not properly applied, drinking water can be over-chlorinated and could be harmful to human health.

3.3.3 UV Treatment – SODIS

One method that is increasing in use in rural and underserved areas is solar water disinfection, or SODIS. SOIDS is a method where water is put into clear bottles and left in the sun for a minimum of 6 hours in order to let UV light from the sun's rays disinfect the water. This is becoming more popular in developing countries due to its simplicity and ease of use in areas with a lot of sunlight (CDC, 2008). The benefits of the SODIS method are how cheap it is to implement, no need of additional resources, and that it can be done by any individual. Limitations of the method include needing water to have a low turbidity, ineffectiveness on cloudy days, and the fact that the SODIS method will not remove any organics or minerals suspended in the water. Additionally, water bottles that are exposed to light over a long period of time will tend to degrade due to the UV radiation, and leak harmful chemicals into water, so bottles will need to be discarded and new ones used fairly often.

3.3.4 Boiling

Finally, the current method of treating water in the region is to boil contaminated water, often with wood fired stoves or charcoal briquettes. This method is very effective in disinfecting water and can be done anywhere in the world. However, communities that primarily depend on wood burning all too often cause deforestation and various environmental problems. Additionally, fire wood collection is commonly the job of women and girls in rural areas, a commitment that often prevents them from being able to attend school. Finally, if boiling is done indoors, the smoke from fires can cause various adverse health effects over time.

3.4 Summary

History of development shows that not all technologies are appropriate, and that some technologies will perform better than others. Appropriate technology is generally compared and evaluated on criteria such as if it meets a basic need, works like it's supposed to, is socially acceptable, environmentally and socially sustainable, affordable, uses local materials as appropriate, considers social equality, involves local population, is flexible and incorporates feedback.

A water improvement system will need to address both water quantity and quality to improve access to water supplies. Therefore, a combination system of both water containment and secondary treatment will be needed and applied in series. Constructed wetlands, earthen and sand dams, and various sizes of water tanks were considered as water storage systems. Constructed wetlands meet many qualities of appropriate technology as reviewed above, and offer primary water treatment along with the ability to store water. SSF wetlands are ideal for regions such as Tanzania in contrast to free water systems, and will be used in the tool for improving water collection and storage.

It is the opinion of this author that constructed wetlands can be used primarily as an effective method of storing water in rural Tanzania. Historically, constructed wetlands have been used as a system for treatment, but in this design, the primary purpose is to store large amounts of water for later use (especially during the dry season). The next technology is primarily concerned with purification for drinking water.

Ultra filtration systems, chlorination, SODIS system, and boiling were all investigated and compared for treatment effectivity. Ultra filtration systems are considered an appropriate technology for water purification to follow constructed wetlands in treatment. Filters that can remove bacteria along with the ability to be cleaned and reused are recommended for secondary treatment. Filters can be used for the household scale or village, depending on what local populations would prefer. These technologies were compared using a series of selected appropriate technology qualities and a -1, 0, +1 system. The results of this table can be found in table 3.1.

Table 3.1 Analysis of Apropriate Technology

Water Collection	Earthen Dam	Sand Dam	FWS	SSF	Large Tank	Small Tank
Affordable	1	0	1	1	0	1
Evaporation	-1	1	-1	1	1	1
Local Material	1	1	1	1	0	0
Saftey	0	1	0	1	1	1
Easily Maintained	1	0	1	0	0	0
SUM	**2**	**3**	**2**	**4***	**2**	**3**

Water Purification	Polymeric Filter	Ceramic Filter	Slow Sand Filter	Chlorine Treatment	SOIDS Method	Boiling
Affordable	1	1	1	1	1	1
Evaporation	1	1	1	1	1	0
Local Material	0	1	1	0	0	1
Saftey	1	0	0	1	-1	-1
Easily Maintained	1	0	0	0	0	1
SUM	**4***	**3**	**3**	**3**	**1**	**2**

* Indicates selected technology

CHAPTER 4. CONSTRUCTED WETLAND BACKGROUND

4.1 What is a Wetland

Wetlands are defined by the United States Environmental Protection Agency (EPA) as transitional land areas that are characterized by saturation with water. Specifically, land must have one or more of three attributes to be classified as a wetland: 1) supports wetland plants for at least part of the year, 2) substrate is predominantly saturated, hydric soil, and 3) the land is either saturated or covered by shallow water for at least part of the growing season every year (FGDC, 2013). While definitions may vary from country to country, or organization to organization, emphasis is on the saturation of media with water and growth of "wetland plants" that require hydric conditions.

4.1.1 Natural and Constructed Wetlands

Natural wetlands provide numerous benefits to the environment and the societies they are found. Wetlands have the unique ability to act as buffers to extreme rainfall events, absorbing potential flood waters and protecting water during times of drought. Because of water's importance to life, wetlands become a hotbed of biological activity with the ability to transform common pollutants into inert chemicals and provide habitats for many unique flora and fauna (FGDC, 2013).

Constructed wetlands are wetlands that are intentionally designed by humans either for wastewater or stormwater treatment, or to produce or replace natural wetland habitat (Brix, 1994). Constructed wetlands also provide many environmental benefits including water storage, water treatment, and plant and wildlife habitats. Treatment constructed wetlands are specifically designed for the treatment or removal of particular pollutants or undesirable water characteristics, to clean water for re-use (for agriculture or domestic use) or safe reintroduction to the environment.

4.1.2 How Wetlands Clean Water

Wetlands naturally purify water through a variety of methods. The primary method of purification is through microbially mediated processes, commonly known as the biofilm layer. Bacteria in wetlands will thrive on the immersed surfaces of sand, soil, gravel, or plant matter (while less commonly found free-floating in water), and live off the chemicals and materials in influent water. These bacteria can consume or out-compete other bacteria that can be more harmful to humans, consume various chemical pollutants, and trap solids that would otherwise wash away. The media or plant material can also absorb chemical pollutants onto its surface, common removal processes for phosphorous, ammonia nitrogen and various organic chemicals. Other processes in wetlands can cause chemicals to escape the system via volatilization, including ammonia and methane. Suspended solids such as sand or clay are removed through sedimentation which can also remove additional chemicals that have adhered to them, however sedimentation leads to clogging in wetland systems and/or raising the wetland bed. Photodegradation occurs from ultraviolet sun rays in free water surface wetlands and contributes to killing various bacteria, viruses and microorganisms, and plants can uptake nutrients from the water such as nitrogen and phosphorous (Kadlec, 2009).

4.1.3 Parts of a Constructed Wetland

For diagrams of FWS and SSF wetlands, see figures 3.3 or 3.4. Constructed wetlands are comprised inlet/outlet structures, water control structures, berms and liners, aquatic vegetation, and either rooting media (for FWS) or bed media (for SSF). Inlet and outlet structures apply and remove water from the wetland at the beginning and exit, respectively. Common inlet structures include weirs or perforated pipes with the goal of spreading the influent mixture evenly across the width of the wetland. Outlet structures often consist of perforated pipe imbedded at the bottom of the end of the wetland that allows the treated water to flow out, often into a water control structure. The control structure is used to ensure that the wetland does not empty completely during normal use, but is optional. The sides and bottom of the wetland can be made from concrete, but compacted earth generally provides a much more affordable option. To prevent a loss of water from infiltration, designers can install a plastic liner on the bed of the wetland, unless the soil has high clay content and a low hydraulic conductivity.

Wetland vegetation is characteristic for wetlands, offering additional treatment to water and introducing oxygen below the water level (although the amount of oxygen transfer due to vegetation is disputed). Vegetation can be classified as free-floating on the water surface (such as water hyacinth or duck weed) or submerged (as waterweed and watercress) in FWS wetlands, or emergent vegetation (such as bulrushes or cattails) that can be found in either FWS or SSF (EPA, 1988). FWS wetlands must have some soil or gravel media at the bottom of the wetland to allow for vegetation to take root, while SSF wetlands have soil or gravel media throughout the entire bed. SSF wetlands can have coarse media like gravel at the inlet and exit zones, and a finer media in the middle of the bed for more efficient treatment. Constructed wetlands often have as settling tank that water moves through before entering the wetland to remove large particles and sand or a grease trap if grease or soap are expected in the influent water.

4.2 History of Constructed Wetland

4.2.1 Origins of Constructed Wetlands

Since the beginning of civilization, societies have been discarding wastewater in nearby low lying areas. While there may not have been wetlands there, lands that receive a constant discharge of water will over time turn into a wetland. Civilizations have used natural wetlands to receive wastewater for centuries, the oldest documented record of a constructed wetland occurs from a handwritten note in 1904 in Australia (Brix, 1994).

The first research on constructed wetlands was performed by Dr. Käthe Seidel in West Germany who developed the Max Planck Institute Process (MPIP), which consists of a series of vertical flow then SSF wetlands to treat wastewaters. Dr. Seidel then began collaborating with Dr. Reinhold Kickuth from Göttingen University who then went on to develop the Root Zone Method (RZM) in the 1960s which designed SSF wetlands similar to how they look today. The root zone method assumed that the roots of wetland plants in soil media will overall increase the hydraulic conductivity and treatment efficiency of the wetland. Competition between Drs. Seidel and Kickuth often resulted in conflicting information and confusion by wastewater engineers and regulatory agencies.

Large scale treatment systems, known as the Lelystad Process, developed in 1967 in Holland, designed to treat wastewater for thousands of people per day. In the 1970s, researchers in North American began to recognize the ability of constructed wetlands to be optimized for improved wastewater treatment while still protecting natural wetlands. Since 1985, the popularity of constructed wetlands has been accelerated because of their ability to provide a high level of treatment with minimal maintenance (Brix, 1994; Kadlec, 2009).

4.2.2 Constructed Wetlands in the Present Day

In the United States the most common type of wetland used for wastewater treatment is the FWS wetland, comprising of two thirds of total wetlands made. One half of the FWS wetlands are natural wetlands used to treat various types of wastewater. In Europe however, most wetlands in use are considered SSF wetlands, and many are products of either the MPIP or RZM. In Africa, wetlands were first built in South Africa in the 1980s to treat a variety of wastewaters including raw sewage, septic tank effluents, stormwaters and agricultural waters (Kadlec, 2009). While Africa has a shorter history of constructed wetlands, they are quickly growing in popularity: The Arusha region of Tanzania alone has nearly 30 constructed wetlands built, all SSF wetlands designed and built since 1998 (Njau, 2013).

4.3 Types of Constructed Wetlands

4.3.1 Free Water Surface Wetlands

Free Water Surface (FWS) constructed wetlands most closely mimic natural wetlands, and are characterized by areas of open water and floating or emergent vegetation. Water enters at the inlet and is treated as it moves through the open pond through various free floating, emergent or submerged plants. FSW wetlands, whether intentionally or not, naturally become habitats for wildlife and tend to support a robust healthy ecosystem. These wetlands are often the choice for agricultural, urban or industrial runoff due to their ability to receive pulse flows by changing water levels. However these wetlands are rarely used for wastewater treatment due to potential of human exposure to pollutants. FWS wetlands can also be used in all climates, but suffer from high evaporation in hot climates and occasional freezing in cold ones, both of which decrease treatment efficiency (Kadlec, 2009).

4.3.2 Sub Surface Flow Wetlands

SSF wetlands act in the same way as FWS wetlands, with the exception that the bed is filled with media, generally soil, sand, or gravel. The water level is kept below the media surface through a water level control structure, and vegetation grows out of the media implanting roots into the water. These systems are common for wastewater treatment because the media protects humans from coming in contact with pathogens, and does not create a breeding ground for mosquitoes. SSF wetlands tend to be more expensive than FWS wetlands due to the additional cost of the media, but are still considered cost effective compared to other treatment options. SSF wetlands also prevent more evaporation than FWS wetlands and are more resistant to freezing in cooler climates (Kadlec, 2009).

4.4 Current Applications of Constructed Wetlands

One common use for constructed wetlands is for collection and treatment of stormwater, similar to the impacts of natural wetlands. Primary pollutants of interest with rural runoff are various fertilizers, such as nitrogen and phosphorous, pesticides, animal waste and soil erosion. Constructed wetlands have been known to be able to absorb nutrients and destroy pesticides, while killing any potential pathogens in animal waste. Constructed wetlands also trap and remove erosion from incoming water but, especially with SSF wetlands, wetlands will clog over time and perform less effectively. Urban runoff, in contrast, will generally contain more heavy metals and pollutants from cars and roadways. Constructed wetlands have been known to settle out heavy metals absorbed by suspended solids, but these deposited metals are not destroyed and need to be removed when the wetland is cleaned.

Wastewater is generally produced from either domestic or industrial sources. Most wetlands used to treat domestic wastewater only treat greywater: water from showers, sinks or other sources that do not include fecal waste. However, there are examples of constructed wetlands acting as septic systems, which require extra care to ensure that no there is no human interaction with potentially deadly pathogens. This water is generally treated before being released to the environment; although there are many cases of wastewater being treated for agricultural uses in water stressed parts of the world. Domestic water can also contain unnatural products such as soaps or other surfactants that should be removed before entering a wetland system. Industrial uses for constructed wetlands in the United States are often used to improve the water quality before re-introduction into rivers or lakes. The natural processes in constructed wetlands can balance pH, average temperatures, and remove any potential contaminants that may remain in water after processing.

4.5 Constructed Wetland Design Methods

4.5.1 Water Balances

The first model important to designing constructed wetlands is the water balance model:

$$I - O = \Delta S$$

Where I is wetland inflows, O is wetland outflows, and ΔS is the change of volume stored in the wetland. Inflows commonly consist of water entering the inlet and rainfalls falling on the wetland, outflows include water exiting the end of the wetland, any infiltration and evaporation. Any change of storage in a wetland would mean a raising or lowering of the wetland's water level. The volume of water in the wetland at any given time can be calculated by using a running water balance based on the inflows and outflows over time.

4.5.2 Loading Charts

One method of sizing a constructed wetland is with a loading chart. Loading charts are graphs plotting the concentration of a pollutant in outflow water vs. loading rate of the influent. This iterative process consists of choosing a desired loading rate (in g/m^2*yr), then selecting the corresponding outflow concentration (in mg/l), and repeating until an appropriate wetland size and outflow concentration are selected. Loading charts provide an easy and simple method of sizing wetlands, but are criticized for the large spread of the data available. While only accounting for a central tendency of a wetland, the data does not account for seasonal or stochastic variations in the wetland.

4.5.3 Empirical Equations

Another method of sizing wetlands that is more complicated is using reaction rate equations. Many wetland processes can be modeled by the P-k-C* model, that is based on k, a pollutant weathering rate, P, the number of wetland cells in series, and C*, the input concentration. This model can take many aspects into account for seasonal, temperature, and water losses. However, constants that have been developed cannot necessarily be extrapolated from the locations and operating conditions that they have been derived from. Since nearly all of the data has been collected from North American or European sources, it is not necessarily appropriate for use in Africa.

CHAPTER 5. ARUSHA WATER QUALITY

5.1 Background Information on Testing

5.1.1 Gaps in Data

It is well known that surface waters in Tanzanian, despite 7% of land area covered by lakes and rivers, are of a generally poor quality (Office, 1999). However there is a significant lack of water resources data that is easily and widely available to the public (MWLD, 2002).

5.1.2 Testing Goals

In April and May of 2014, a team from Nelson Mandela African Institute of Science and Technology collected and tested a series of water samples from various sources across the Arusha region. The goal of this research was to help establish a baseline water quality for natural waters in the Arusha region and to make this data available for future work. The team traveled twice to the field to collect water samples. On the first trip on April 16th, it had only rained the day before and had not rained that day. The team traveled again on May 6th, where it had rained earlier that day before collections were done.

5.1.3 Research Team

This team consisted of Professor Karoli Njau, of NM-AIST, two graduate students at NM-AIST, Gilbert Chintokoma and Anna Msiqwa, and one graduate student from Purdue University, Michael Sheehan.

5.2 Water Collection Methods

5.2.1 Where Samples Were Collected

Water was collected from various sources, primarily on highways A-104 and B-144 between the cities of Arusha and Karatu, while water was also collected in the village of Endallah located near Karatu overlooking Lake Manyara above the Great Rift Valley.

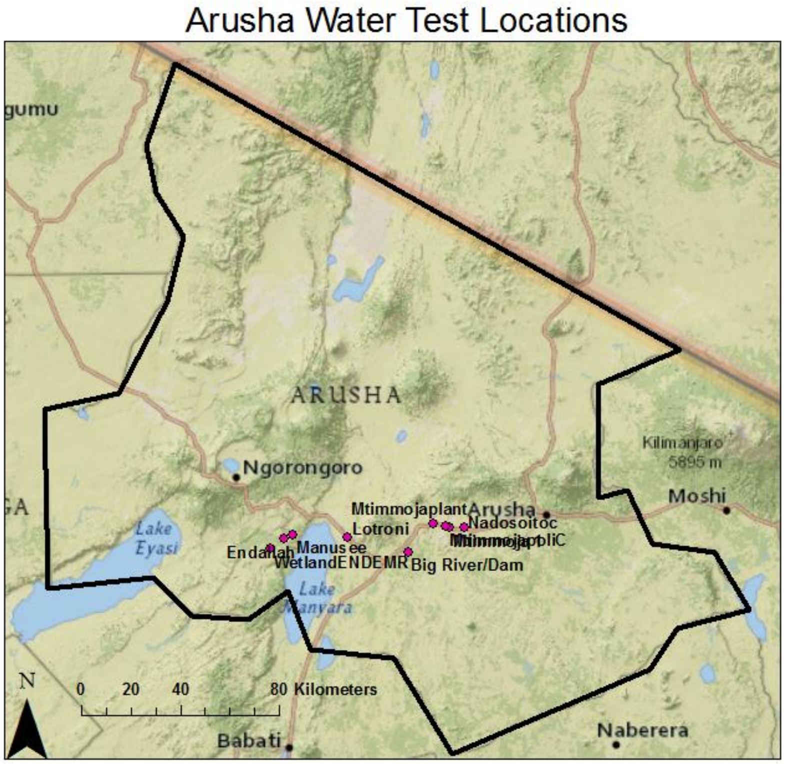

Figure 5.1 Arusha Water Test Locations

5.2.2 How Samples Were Collected

Water was collected in 1.5 liter Kilimanjaro water bottles. The team attempted to collect water in a way that was most similar to the method that people would collect it for daily use. In lakes, water was collected by wading into the lake and holding the bottle under water (while trying not to stir up sediment from the lake bed). Where appropriate, water was also poured out of a well spigot or scooped with a small bucket or cup provided by local villagers. In one case, local villagers filled buckets for us as they would their own, and the team used that water to fill our test bottles. Water bottles were then put in coolers filled with ice to keep the samples cold and maintain the viability of any bacterial contaminants.

5.2.3 Information on Sites

If locals were present during the collection samples, the team would ask a few questions, such as how far do you travel for this water, do livestock drink from this source, or does this source run dry during the year. If no one was present, we inferred information from observation, such as if the water was protected, and if animal tracks were visible indicating that livestock consume water directly from the source. This information was recorded on each site. Photos of the collected water can be found in the appendix A. Table 5.1 shows the site name and descriptions of both the site location and water.

Table 5.1 Samples Site Location

Site Label	Site Name	Site Description	Water Description
A	Mhmmoja	Surface pond fed by rainwater. Water is used for cooking and drinking. Users say that animals are not allowed to drink from the pond, but some tracks were seen.	Cloudy green color. Some sediments
B	Mhmmoja Police Stop	Surface pond fed by rainwater. People draw water for cooking. Animal tracks present.	Very cloudy brown/green color. Some sediment.
C	Industrial Plant	Pond near production plant. Used for drinking and watering animals.	Cloudy water with a yellow tint. Little sediment.
D	Big River/Dam	Large lake with water all year around. No animals allowed. Man-made, built in 2005-2007, and took 3 years for water level to stabilize.	Cloudy with orange color. Some sediment
E	Lotroni	Semi-protected open pool near road. People were collecting drinking and cooking water, while rinsing their bodies and watering animals in the same place.	Cloudy water, orange green tint, some sediment.
F	Basodawish	Huge rain fed open surface dam. Animals present.	Significant burnt orange tint, very cloudy and little sediment.
G	Endallah Bondeni	Trickle of water coming from under road in river bed. Kids scoop water into buckets with cups for drinking and cooking. Playing with water nearby.	Very clear water. No sediment or tint.
H	Pump Endallah	Well/pump system. Appears to be a shallow well	Very clear water, no tint or sediment.
I	Manusee Endallah	Orange Lake. Plants growing in 50% of it. Water is used for washing and livestock when necessary. Tap water nearby at the price of $0.50 (USD) per bucket	Very bright orange tint, cloudy, with little sediment.
J	Manusee Spring	Spring trickled from underground. A lot of kids scooping water into buckets with cups. Water is used for everything. Dog nearby the spring.	Very clear water, maybe slight tint, little sediment.
K	Nado Soitoc	Large lake fed by rainwater. Water used for everything. Allegedly the water clears if boiled.	Very dark brown water, not clear at all. Little sediment.
X*	Lambo La Endemrarie	Natural Wetland used for drinking and cooking water.	Orange color that is somewhat cloudy. Little sediment.

* Indicates site was only visited second time.

5.3 Tested Parameters

The samples collected on the first field visit were tested for the following constituents:

5.3.1 pH

The pH was measured on site with a Hanna portable pH meter by placing the meter in the water, and after a few seconds the meter displayed a stabilized pH value. The pH itself is not a major health concern, but can impact other pollutants, and can be a valuable datum to record (WHO, 2007).

5.3.2 TDS

Total dissolved solids (TDS) were measured like pH with a Hanna portable TDS meter also by placing the meter into the water on site and reading the display after the reading stabilized. While high levels of TDS as a whole in drinking water have not been linked to any specific health effects, it does affect taste (WHO, 2003).

5.3.3 Temperature

Temperature was also measured on site with a mercury thermometer being placed into the water body until the thermometer stabilized. While reasonable temperatures are not a threat to human health, temperature impacts other pollutants and the growth of aquatic organisms and biological activity.

5.3.4 Phosphorus, Ammonia, Nitrate and Nitrite

Phosphorus, ammonia, nitrate and nitrite were measured using Hach brand test strips. These were used as an easy and inexpensive way to test aqueous nutrients in the water, and allowed the team to get readings for these values without expensive equipment such as a digester. The provided instructions were followed for each test strip, which involved placing the strip in water and waiting until comparing the color change to a standard color chart. Phosphorous and nitrogen primarily pose a threat of eutrophication, which leads to a significant decrease in water quality.

5.3.5 Fluoride

Fluoride was tested April 23rd in the lab using a Mettler Toledo meter. The standard method was followed for each test and was calibrated using a standard curve. High concentrations of fluoride in water can cause dental and skeletal fluorosis which is the browning of teeth and deformation of bones, respectively (Whelton).

5.3.6 Turbidity

Turbidity was measured on April 23rd. The samples were sent to nearby lab which had access to a turbidity meter. Two samples (F and K) needed to be diluted to obtain an accurate reading, and each were tested three times with the values averaged to find the final turbidity results. Turbidity indicated high levels of fine sediment, creates an environment to protect pathogens, can carry chemical pollutants such as nutrients, heavy metals and pesticides. Additionally, turbidity severely limits the effectiveness of any purifying or sterilizing treatments (Borok, 2010).

5.3.7 Fecal Coliform

Fecal coliform was tested using HIMEDIA brand M-FC Agar Base and the vacuum filter method. Meru Spring brand drinking water was used a control with the same method after all of the samples were plated. While the HIMEDIA instructions indicate to stop incubation after 24 hours, due to unforeseen holidays, plates were left in the incubator for 5 days. This caused plates to over grow and the ability to get an accurate colony count was compromised. Therefore, all fecal coliform tests can only be described as positive or negative for fecal coliform. While fecal coliforms don't pose a threat to human health themselves, their presence infers that pathogens may be present and are tested to indicate polluted waters (Ashbolt).

5.3.8 Second Field Visit

The second field visit consisted of re-visiting the same sites and testing some of the same constituents. pH, temperature and TDS were all measured in the same way as the first field visit. Test strips were not used on the second visit because the team had doubts of their accuracy in cloudy water. Nitrate, phosphate, and phosphorous were all tested using Hanna HI 830099 COD and multiparameter photometer according to directions, but only for samples G, H and J, due to all of the other samples having too much color. Fecal coliform and E. Coli were also tested by plating, but the results were deemed inconclusive due to contamination. Additionally, a sample was collected for a natural wetland that was not tested on the first trip (represented as sample X).

5.4 Water Test Results

Testing results can be found in Appendix B, while only selected results are included in the following section. The test strip results found in table 5.2.

Table 5.2 Test Strip Results

Site Label	Phosphate (mg/l)	Ammonia (mg/l)	Nitrate (mg/l)	Nitrite (mg/l)
A	5	0.250	0.0	0.000
B	15	0.125	1.0	0.000
C	5	0.125	0.5	0.075
D	5	0.250	1.0	0.000
E	5	0.250	0.5	0.075
F	10	0.250	2.0	0.075
G	20	0.250	0.0	0.000
H	35	0.000	1.0	0.000
I	30	0.300	0.0	0.000
J	3	0.000	1.0	0.000
K	50	0.250	0.5	0.000

The test strips displayed results with high phosphate and low nitrogen values. This would imply that nitrogen is a limiting nutrient in these water bodies. However, the test strip results were very subjective, and there is likely human error in reading the results and color change. There was also a difficulty with a lot of the water sources because of high levels of turbidity and color.

Turbidity is of special interest as research and observation show that surface waters in Tanzania tend to have high turbidity. In addition to high values, this turbidity is largely comprised of either very fine particles, or color dissolved into the water because of the incredibly slow rate that turbidity settles out of the water column. In fact, water from source F (Basodawish) was kept undisturbed in a lab for over three months, and still had significant turbidity and color present in the water column. While the turbidity in the different sources of water are comprised of a medley of pollutants and some sources settle out more material faster, all sources had significant turbidity over long periods of time. These observations where confirmed for all surface waters that were tested, and all subsurface waters were mostly clear. Two samples, F and K, had to be diluted significantly before accurate readings could be taken.

Total dissolved solids were all considered “excellent” except for site J, which is still considered “good” (Borok, 2010). Fluoride was low in all water sources. This is expected for two reasons: all surface waters should have low fluoride because fluoride dissolves into water underground, and that water had not infiltrated into the soil yet. The second is that all subsurface sources that we tested were from above the rift valley, where there is less fluoride in the soil. If these samples were taken within the rift valley, such as in or near Arusha, we would expect much higher values. The results of turbidity for both trips, TDS, and fluoride tests, as available, are displayed in table 5.3.

Table 5.3 Water Test Results

Site Label	Turbidity (NTU) (First Visit)	Turbidity (NTU) (Second Visit)	TDS (ppm)	Fluoride (mg/l)
A	555	754	61	2.02
B	1380	N/A	30	1.74
C	229	214	130	5.02
D	415	460	230	7.15
E	187	N/A	160	1.22
F	2031	1438	110	2.41
G	2	4	250	1.61
H	17	18	250	1.68
I	395	170	60	1.45
J	20	12	370	2.30
K	8173	N/A	90	2.55
X	N/A	42	70	N/A

N/A indicates data is not available.

Due to the challenges previously stated, we were not able to count colonies and make an estimate on the concentration of fecal coliform. However, we were able to identify whether or not the bacteria were present in the sample. All of the water sources except for the first site (A) and the control tested positive for fecal coliform. It should be noted that the users of the first site make an effort to ensure that no animals drink from that water, which should help prevent harmful bacteria and fecal coliform from entering the water. The test from the second field visits did not produce any viable results due to contamination.

5.4.1 Wetland Observations

While no useful test results were collected from the wetland found on the second field visit, it is valuable to note that the water quality appeared to be higher than other surface waters in the area. The local villagers reported that they tend to use that water for all domestic purposes, likely because it is the best surface water source available.

5.5 Testing Conclusions

5.5.1 Results

The important results from these water quality tests are that we can confirm the reports that turbidity and bacterial contaminants are significant pollutants of concern in rural waters. Turbidity found in the surface waters manage to stay in the water column for a very long time and resist settling out, significantly limiting the number of appropriate technologies that can remove and treat such fine or dissolved sources of turbidity.

While we were not able to collect specific counts on fecal coliform or receive any results concerning E.Coli, we can say with confidence that bacterial contaminants are common in our surface water sources, while also being present in all our subsurface sources. Pictures of plates can be found in appendix C. Table 5.4 shows the results of the fecal coliform test, where blue indicates negative and red indicates positive for fecal coliform.

Table 5.4 Fecal Coliform test Results

Fecal Coliform Test Results			
Site	Result	Site	Result
A	🟦	G	🟥
B	🟥	H	🟥
C	🟥	I	🟥
D	🟥	J	🟥
E	🟥	K	🟥
F	🟥	Control	🟦

5.5.2 Limitations and Further Work

Many of the results were inconclusive or incomplete. Most of the bacterial tests failed: the first E. Coli test did not produce any results, the second E. Coli test suffered from contamination and no results could be drawn, and the second fecal coliform test also did not produce any results. While bacterial contaminations are noted as a major concern for water quality in Tanzania, more research is needed to confirm this.

The test strips did produce results, but they are highly suspect due to the high turbidity in most of the water sources. It is believed that the color of the water distorted the color on the test strips leading to inaccurate results. When nitrate, phosphate and phosphorous was tested using a multiparameter photometer, only samples G, H and J were tested because there was too much color in the other samples. It would be beneficial to test for these nutrients using methods appropriate for high turbidity and color.

Finally, more research needs to be done by testing iron in water samples. The color in many surface water samples may indicate iron in the runoff water, and this should be confirmed in future work.

CHAPTER 6. TOOL DESIGN

6.1 Background Information

The goal of this constructed wetland design tool is to make data available and simplify the design process for constructed wetlands in the Arusha region of Tanzania. Primary pollutants that this system are designed to treat are turbidity and bacterial contaminants. Wetlands are designed with large media and a minimum length to width ratio so as to effectively remove turbidity and with high hydraulic retention times so as to remove bacterial contaminants.

This tool was designed and operated primarily in Excel. This allows the tool to be more widely available, and does not require expensive software packages to use. Additionally, ArcMap can be used to investigate drainage areas and find curve numbers, but maps are also provided to help if ArcMap is not available.

6.2 Included Data

6.2.1 Rainfall

Rainfall is based on the Climate Forecast System Reanalysis (CFSR) rainfall estimates by the National Centers for Environmental Prediction. The CFSR estimated daily rainfall data based off of satellite observations for the 31 years between 1979 and 2010. Daily data is accessed through online portals and is delivered through “stations” gridded evenly over a selected area. For this project, only stations within the boundaries of the Arusha region were used for a total of 34 stations. Rainfall estimates were then summed for each month in each year for each station, providing 31 months of total rainfall in each month for each station. The natural log of each monthly rainfall was taken so as to ensure a more standard curve, and the mean and 90% confidence intervals were found using internal Excel functions, finding the 5th and 95th percentiles for the rainfall for each month at each station. Using this method, we were able to find an upper bound (95th percentile), mean (50th percentile) and lower bound (5th percentile) for rainfall for each month at each station. Figure 6.1 shows the locations of the “weather stations” in Arusha.

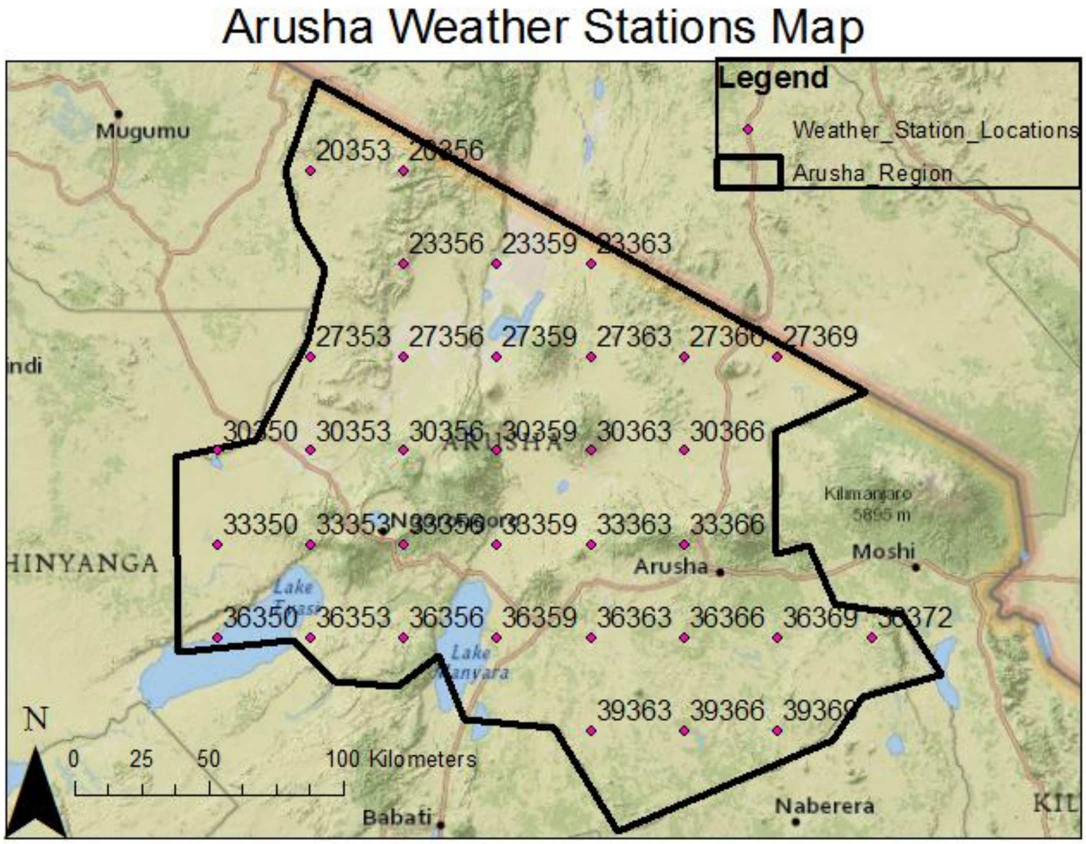

Figure 6.1 Arusha Weather Stations (NCEP, 2010)

Rainfall for any location in the Arusha region is found using the arithmetic mean method based on an inverse squared distance method. The weight of any station, *n*, is calculated by finding the inverse squared of the distance, *d* between the location of interest and the station (Haan, 1994). The weight, *w*, for any station can be calculated by using the following equation:

$$w_n = \frac{1}{{d_n}^2} \Big/ \sum \frac{1}{d^2}$$

The average rainfall is then the sum of the monthly station rainfall multiplied by their associated weight, for each the upper bound, median, and lower bound. The data is then reported as total annual expected rainfall for the location with an upper bound, median, and lower bound. This means that users can find what the average rainfall will be in this location, a high expected rainfall (precipitation that will be exceeded approximately every 20 years), and a low expected rainfall (precipitation that will not be exceeded once every 20 years).

6.2.2 Runoff

Once rainfall is found for each location, runoff can be found using the Soil Conservation Service (SCS) Curve Number method. The SCS Curve Number method was developed to find runoff values based on rainfall, infiltration and initial abstraction estimates (Haan, 1994). Curve numbers are calculated based on the land use and infiltration rate of the drainage area. Soil data was found using the Soil and Terrain Information for the Southern African Region (SOTERSAF) database, which provides soil information for eight African countries, including Tanzania, and is considered the best soil estimate based on currently available data (van Englen, 2001). Figure 6.2 is a map of the Arusha region divided among its various SOTERSAF soil classes (this map is available as an ArcMap map document for increased accuracy). Project users can choose the location of their drainage area on the map, find the soil type, and use table 6.1 to find the curve number based on the land use characterization: herbaceous, desert shrub, or woods. For example, if the drainage area was in the southern part of the Arusha region, in soil region 17, and the local vegetation was desert shrub, the associated curve number would be 71.65.

Table 6.1 Curve Number Table

ID	**Herbaceous**	**Desert Shrub**	**Woods**	**ID**	**Herbaceous**	**Desert Shrub**	**Woods**
17	72.5	71.65	59.55	132	71	57.15	46.8
44	83.9	82.4	74.35	133	71	55	36
48	72.5	73.35	61.95	135	71	72	60
63	71	72	60	136	71	45	36
117	78	77.75	68	137	71	72	60
118	72.5	73.35	61.95	138	71	72	60
119	72.5	70.8	58.35	141	81	81	73
120	71	72	60	142	76.5	76.95	67.15
121	74	74.7	63.9	143	81	81	73
122	72.5	73.35	61.95	155	84.2	83	75.4
123	73	73.8	62.6	156	72.5	73.35	61.95
125	71	61.2	50.4	157	72.5	73.35	61.95
126	71	72	60	158	79.5	79.65	71.05
127	71	72	60	165	71	45	36
128	71	62.55	51.6	167	71	45	36
129	71	72	60	168	71	45	36
131	71	72	60	169	71	45	36

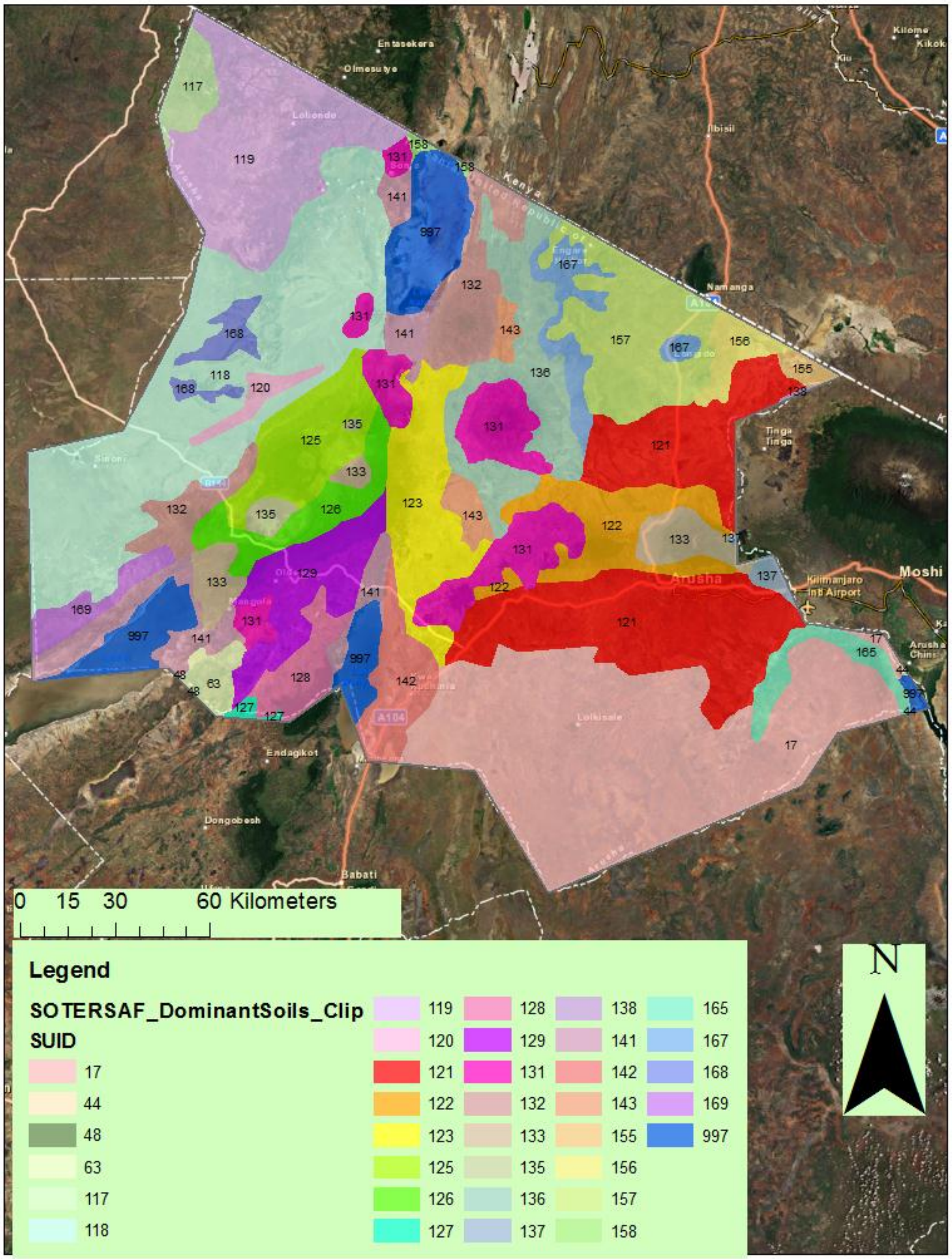

Figure 6.2 SOTERSAF Soil Gorups

6.2.3 Evaporation

Evaporation can be a major source of water loss from a constructed wetland. Evaporation data for Tanzania is lacking at best, and even less information is available for evapotranspiration rates from constructed wetlands. An evaporation rate of 4 mm/day is assumed based on other research and similar conditions, but more work needs to be done to find more accurate evaporation estimates (Papaevangelou, 2012).

6.2.4 Infiltration

Infiltration can be one of the major water losses from the wetland. Infiltration is based on both the surface area of the wetland and the bed material. The simplest bed lining is compacting soil to reduce permeability and retain water. However, the soil must have high clay content or too much water will escape from the wetland. A maximum permeability should be 0.865 mm/day. Tests may need to be performed to find the infiltration rate and judge its appropriateness. If local soil does not have high clay content, clay can be imported and laid at 30 cm minimum layer after compaction. If importing clay is prohibitively expensive, plastic liners can be laid on the bed and used to assume a 0 mm/day infiltration rate. Plastic liners are becoming more common around Tanzania and are recommended if available (Kadlec, 2009).

6.2.5 Consumption

Consumption is the volume of water that each person will consume from the wetland each day. As described previously, 20 l/c/d is considered the minimum appropriate water consumption, but 50 l/c/d is considered an appropriate minimum volume of water regardless of cultural influences or location. This consumption is removed from the water balance each month and the consumption rate is chosen by the user.

6.2.6 Topography

While the tool cannot analyze the local topography for a wetland or recognize the drainage area feeding to it, there are other ways to find information. The digital elevation model (DEM) used for this project is the Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) DEM produced by The Ministry of Economy, Trade and Industry (METI) of Japan and the United States National Aeronautics and Space Administration (NASA). This ASTER DEM is the most accurate global DEM available for this region, and the Arusha region is included for project planners to use with access to ArcMap and is displayed in figure 6.3.. Through ArcMap, various tools are recommended such as ‘Watershed’ or ‘Flow Direction’, but this information on drainage area will likely need to come from measurements or estimates on site.

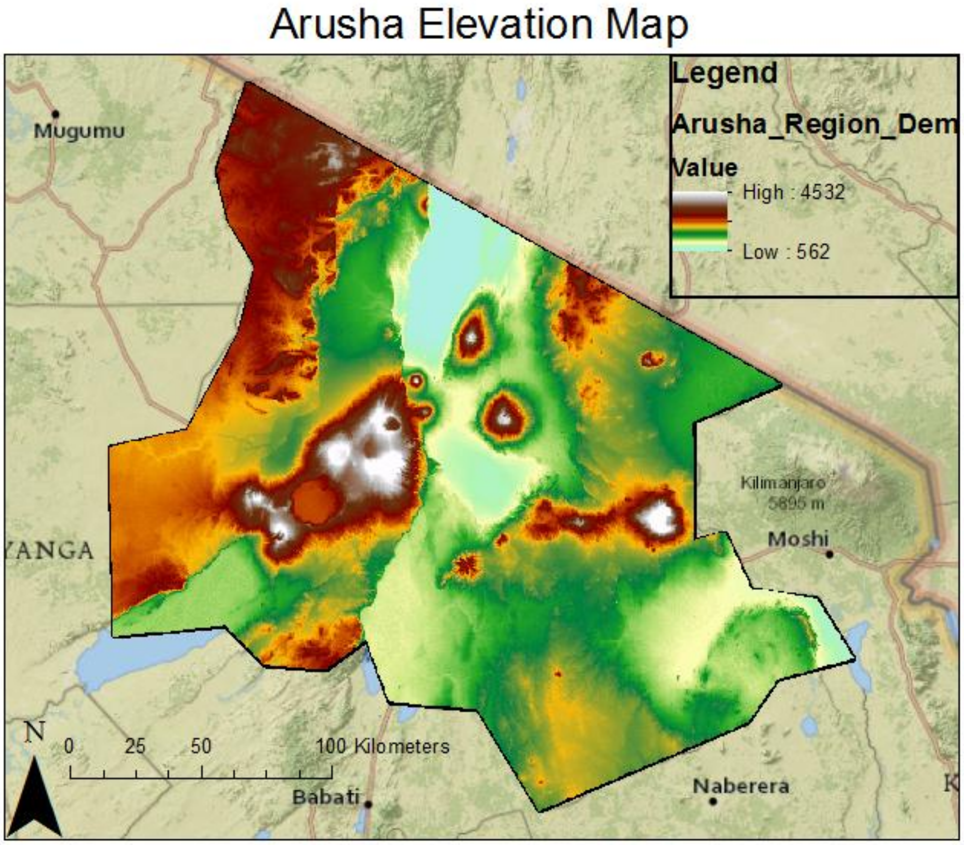

Figure 6.3 Arusha ASTER DEM

6.2.7 Sizing Calculations

The wetland is sized based off a series of decisions by project planners. It would be unwise and reckless for this tool to attempt to make sizing decisions autonomously for any specific wetland, but the tool documentation describes a series of equations to be used to find minimum sizes and size estimates, along with reporting constraints and suggestions while choosing design specifics. However the specific sizing is to be done by project planners with the help of this tool.

6.2.8 Other Design Notes

The following are other notes not inherent to the tool but are notes to be included in design.

6.2.8.1 Plants

A wide variety of plants that have a positive effect on wetland treatment. In general, wetland plants facilitate treatment of influent water in many ways, including additional surface for biofilm growth, limited additional oxygen infusion into the wetland, and chemical absorption. Although research has not yet found which plants are most successful for treatment in Tanzania, a number of plants have been found to help in the treatment of inflow in subsurface wetlands in Tanzania. This list includes *Phragmites mauritianus* (common reed grass) and *Typha latifolia, domingensis,* and *capensis* (bulrush/cattails) as providing beneficiary treatment, while *Cyperus grandis* and *Cyperus dubius* can be used as ornamental plants (Vymazal, 2011).

6.2.8.2 Media

Due to high turbidity in Tanzanian runoff, it is recommended that gravel is used as a bed media. Gravel is the optimal media because it will take more time to clog than soil or sand media with smaller pore spaces. Specifically, gravel should be considered coarse, but should be largely chosen on what gravel is available near the wetland location.

6.2.8.3 Settling Basin

Due to high turbidity and the presence of bacterial contaminants in Tanzanian runoff, it is recommended that gravel is used as a bed media. Gravel is the optimal media because it will take more time to clog than soil or sand media with smaller pore spaces.

6.2.8.4 Turbidity Removal

Turbidity removal is one of the primary benefits of the constructed wetland. Generally, turbidity is removed very rapidly and effectively in SSF wetlands (Kadlec, 2009). In fact, the loading chart for turbidity is nearly horizontal, suggesting that a similar background turbidity that is significantly low will result regardless of the input turbidity. The major concern that this causes clogging. Using large gravel will reduce the rate of clogging and extend the life of the wetland media. However, over time the wetland will clog and require the media to be removed, cleaned, or replaced.

6.3 How to Use the Tool

The constructed wetland Excel tool is simple to use: project planners simply follow the steps 1 – 21, entering information on the left side under input in purple and calculations are made on the right side under output in orange. Users can also see, with their current inputs, a monthly water balance on page two of the spreadsheet, Water Balances. This will show in what months could they expect their wetland to run dry, and how often: a negative value in any of the Remainder rows indicates that the wetland will run dry that month, and the cells are shaded red. Users can also refer to the accompanying documentation, which describes each entry by number and provides a series of equations relating the various inputs. This flexibility allows users to make all of their own decisions on what the wetland should look like without prescribing inappropriate parameters.

Table 6.2 Constructed Wetland Design Tool

1	Site X Coordinate	1		**6**	95% Available Water	5861	cu. Meters	(Will receive this or more runoff every 1/20 years)
2	Site Y Corrdinate	1		**7**	Average Available Water	2475	cu. Meters	(Will receive an average of this much runoff)
3	Selected Curve Number	70		**8**	5% Available Water	881	cu. Meters	(Will receive this or less runoff every 1/20 years)
4	Watershed Area	100	sq. km					
5	Lining Infiltration	0	mm/d	**9**	Max Monthly Water Volume	1633	cu. Meters	(Most runoff in any month)
Wetland Sizing								
10	Volume of Wetland	5714	cu. meter					
11	Max Water Volume	2000	cu. Meter					
12	Surface Area of Wetland	71.5	sq. meter	**17**	Length:Width Ratio	10.57	:1	(Minimum 3:1)
13	Depth of Wetland	0.60	meter					
14	Length of Wetland	317	meter					
15	Width of Wetland	30	meter					
16	Media Porosity	0.35						
Performance Information								
18	Daily Water Consumption	20	l/c/d	**20**	Minimum Water Velocity	13.33	m/h	
19	Number of People	500	People	**21**	Estimated Retention Time	23.775	h	(Minimum 8 hours)

6.3.1 Instructions

The corresponding numbers on the wetland spreadsheet is denoted with **[#]**. The first section is Location Information.

1. First, choose a location of the drainage area with X **[1]** and Y **[2]** coordinates off of the attached map.
2. Next, choose a curve number **[3]** by finding the associated soil ID number for you drainage area and observing the type of vegetation using table 6.1. Curve numbers can be averaged based on area if appropriate.
3. Then input the drainage area **[4]** using the ArcMap DEM or measuring the surface area through other methods, in square kilometers.
4. Finally, select a lining infiltration rate **[5]**, either based on compacted soil or a plastic liner and table 6.3.

From this, users will receive the upper bound **[6]**, mean **[7]**, and lower bound **[8]** of available water based off precipitation estimates and curve number. Users will also see the maximum runoff available **[9]** in any given month, to help with design.

The next section is the Wetland Sizing section. Users will chose all wetland sizes but can use the equations included in the documentation to help guide them if needed.

5. Either choose the total volume of the wetland **[10]** (if space is a limiting factor) or the maximum volume of water that can be contained by the wetland **[11]** (if water volume is the limiting factor).
6. After choosing the total volume of the wetland or maximum water volume, surface area **[12]**, depth **[13]**, length **[14]**, and width **[15]** can be chosen using the accompanying equations.

7. Additionally, media porosity **[16]** should be included and can be used for water volume to wetland size conversions.

The important information reported in the Wetland Sizing section is a length to width ratio **[17]**. This is important to ensure appropriate treatment and to limit short-circuiting, and should be a minimum of 3:1.

The final section is Performance Information.

8. Next pick the amount of water which will be consumed **[18]**, estimate the amount of water consumed per capita per day **[19]**, and the number of people expected to be withdrawing from the wetland.

Choosing these numbers will give users the minimum water velocity **[20]** in the wetland and more importantly the estimated hydraulic retention time (HRT) **[21]**. The HRT is important to ensure appropriate bacterial treatment and should be at least 8 hours. Additionally, after filling in the data for this section, users can turn to the Water Balances table to observe a monthly water balance, and see if the wetland is expected to go dry during the year. This table also runs off the assumption that the wetland is dry at the beginning of each November, so as to allow for a worst case scenario or cleaning/media replacement.

Additionally, notes on the types of media, plants, and some design tips are included in the documentation.

Table 6.3 Wetland Bed Material Table

Wetland Bed Material	**Infiltration Rate (mm/day)**
Compacted Clay	0.865
Plastic Liner	0

6.4 Example Scenarios

This constructed wetland tool can be used for many purposes, with three examples here.

6.4.1 To Check Location Feasibility

One of the most important decisions for planners to make is choosing the appropriate location. Simple site surveys may show planners where a wetland would fit well, but the size of the watershed and expected available water may be more difficult to anticipate. Using this tool, planners can input the location of interest into the work sheet, and find the expected runoff available. This can allow them to decide whether or not a location will supply the volume they need, or if they need to find a new location. Additionally, access to ArcMap would allow planners to use ArcMap tools to easily delineate watershed and grade topography.

6.4.2 For Initial Design Steps

Another use of this tool would allow planners to make a quick estimate of wetland characteristics. The Wetland Sizing section allows planners to make estimates on the depth, length and width of a wetland to be built. While this won’t be enough of a comprehensive plan to build a wetland directly, it would allow planners to quickly iterate rough drafts and quickly change parameters so as to ease the next stages of design.

6.4.3 To Plan for the Future

A third way this tool can be useful to planners is to allow them to re-evaluate current systems in the light of changing parameters such as population growth. While there are only a handful of constructed wetlands in the Arusha region currently, as populations grown more water will be necessary and current systems will likely dry up more and more often. This tool will allow for analyzing a change in wetland size or consumption and the impact that may have, or to quickly investigate new systems to supplement.

6.5 Secondary Treatment

As mentioned previously, secondary treatment is necessary for any water that is going to be consumed by humans. Based on the review of appropriate technology, it is recommended that water be run through a 0.1 micron filter before drinking. 0.1 micron filters can filter out potential harmful bacteria and viruses which many not be removed by the wetland, and offer a cheap and reusable method of cleaning the water.

Alternatively, if the water is coming out of the wetland is very clear, chlorine can be used to effectively eradicate potentially harmful bacteria and viruses. The method of secondary treatment will be to the discretion of project planners and based on each individual location’s conditions.

CHAPTER 7. APPLICATION OF WETLAND DESIGN TOOL

7.1 Nelson Mandela Campus

The tool was first applied to the NM-AIST campus as a pilot scale model. The intent is for this wetland to be designed and tested as validation for the tool in the future. The campus is located directly east of Arusha and is surrounded by crops and herbaceous plants. Figure 7.1 shows where the Nelson Mandela campus is found in Arusha.

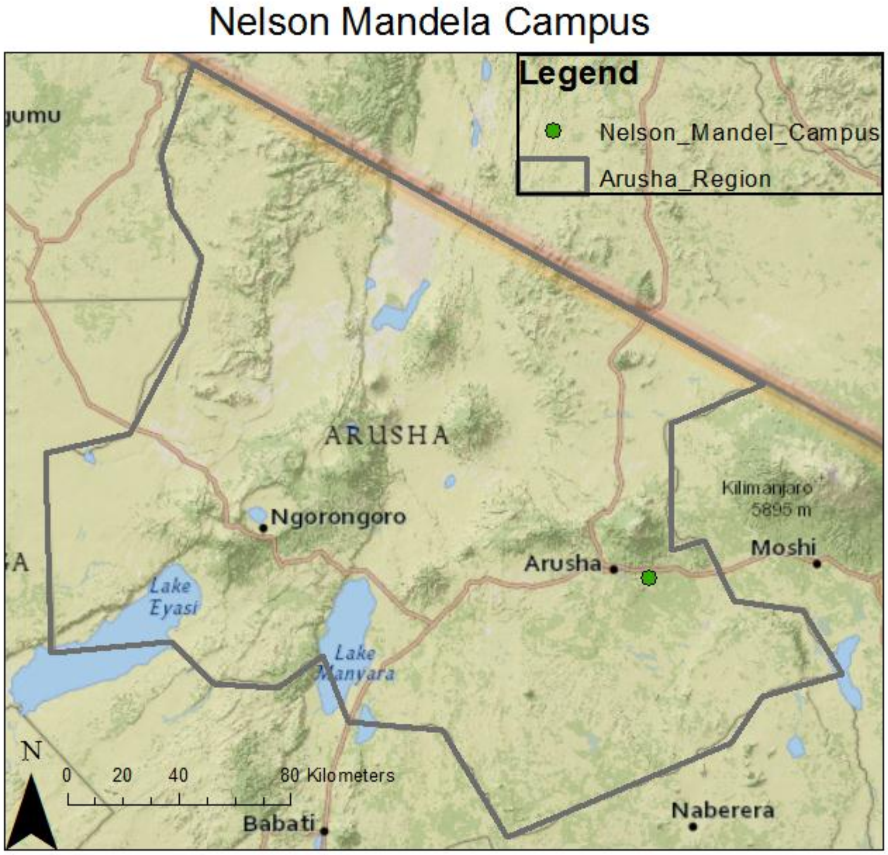

Figure 7.1 Location of the Nelson Mandela Campus

7.1.1 Wetland Inputs

The coordinates were found by finding the Nelson Mandela campus on Google Maps, then estimated using the attached map. The curve number of 74 was estimated by finding the soil ID 121 and a herbaceous local vegetation. Because we could not find a DEM fine enough, the drainage area was assumed to be the Nelson Mandela campus with an area of 0.861 km^2 shown in figure 7.2. While this is far too small to support a community of any size, this is only a pilot scale model. The lining is assumed to be a plastic liner with no infiltration.

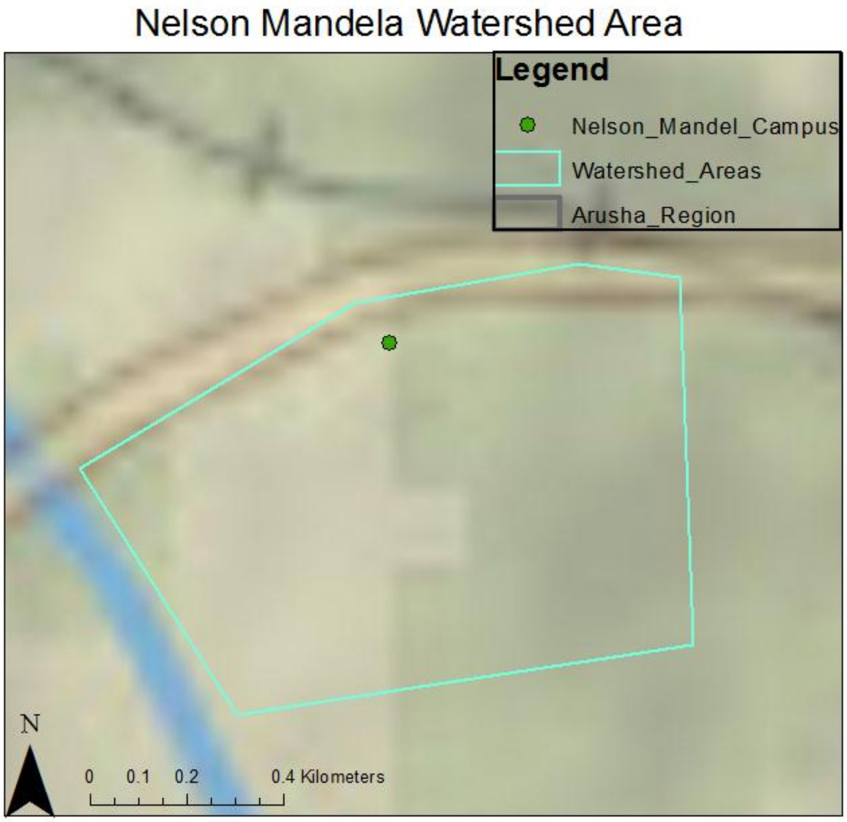

Figure 7.2 Watershed for Nelson Mandela Constructed Wetland

The associated annual runoff values of 84, 48 and 26 m^3 were calculated for the high bound, median, and low bound, respectively, while the maximum monthly runoff is 36 m^3. From this the design volume of water was selected to be 40 m^3, and the total wetland volume was found to be 114 m^3 by dividing by the estimated media porosity, 0.35.

Next, the wetland was sized. The first design had a depth of 0.6 m, which lead to a wetland surface area of 190 m^2. However, when the water balance was checked, the wetland was estimated to go dry 11 months annually with average rainfall. Since consumption and infiltration are both estimated to be zero, the wetland surface area is the only design factor that can decrease the water loss due to evaporation. To decrease the surface area, the depth was increased to 1 m and the surface area decreased to 114 m^2. This allowed the wetland to still go dry 11 months annually in a year on average rainfall, still not acceptable. When the depth was increased to 2 m and surface area decreased to 57 m^2, the wetland would stop producing water 7 months annually on average. Finally, at 2.5 m depth, the surface area required is 46 m^2 and will allow the wetland to go dry 6 months out of the year on average, it will produce water all year with higher bound rainfall. Therefore, the length and width were found to be 13 m and 3.5 m respectively with a depth of 2.5 m to allow for a length to width ratio of 3.7:1, greater than the minimum 3:1.

While running dry on an average of 6 months annually a year may work for a pilot scale test model, the tool can be used to run dry less often. With a depth of 3 m, a surface area of 38 m^2 and a length to width ratio of 3:1, the tool expects the wetland to only run dry 3 months out of the year. If the depth is increased to 4.5 m, a surface area of 25.4 m^2 with a length to width ratio of 4:1, the wetland will not run dry any month of the year with average rainfall.

7.1.2 Analysis of Tool Outputs

The Nelson Mandela campus is a very small watershed for this test. The small watershed does not lend itself to much runoff or high volume of captured water. In fact, the model predicted that 4 months would have no runoff at all, and 2 months would only have insignificant runoff if there is a high precipitation. This makes the campus a poor location for an actual wetland to collect water, but can be appropriate for water quality tests.

The final concept of 2 meters is much deeper than most subsurface wetlands that have been built, but is necessary in this situation as described by the tool. The effectivity of wetlands with 2 m of depth needs to be verified, but is outside the scope of this tool. The depth can be increased up to 4 m so as to ensure the wetland will not run dry any month with average rainfall, but as mentioned earlier, wetlands with this depth need to be researched and proven effective.

Additionally, this design could not estimate a number of people it could help water because of the little runoff the wetland would be receiving. But because this is designed as a pilot scale test wetland, this should be of little consequence.

Despite these limitations, the tool did demonstrate an iterative process that can be used to estimate viability of a location and expected volume from a watershed.

7.2 Village of Endallah

The tool was also applied to the village of Endallah near the city of Karatu in the Arusha region, as shown in figure 7.3. Many of the water sources available to this village were tested with by the team, and villagers reported that water stressors during the long dry seasons can force villagers to use poorly protected sources. Improving their access to water during these dry seasons for this village of over 6,000 could improve their quality of life and decrease the rate of waterborne illnesses.

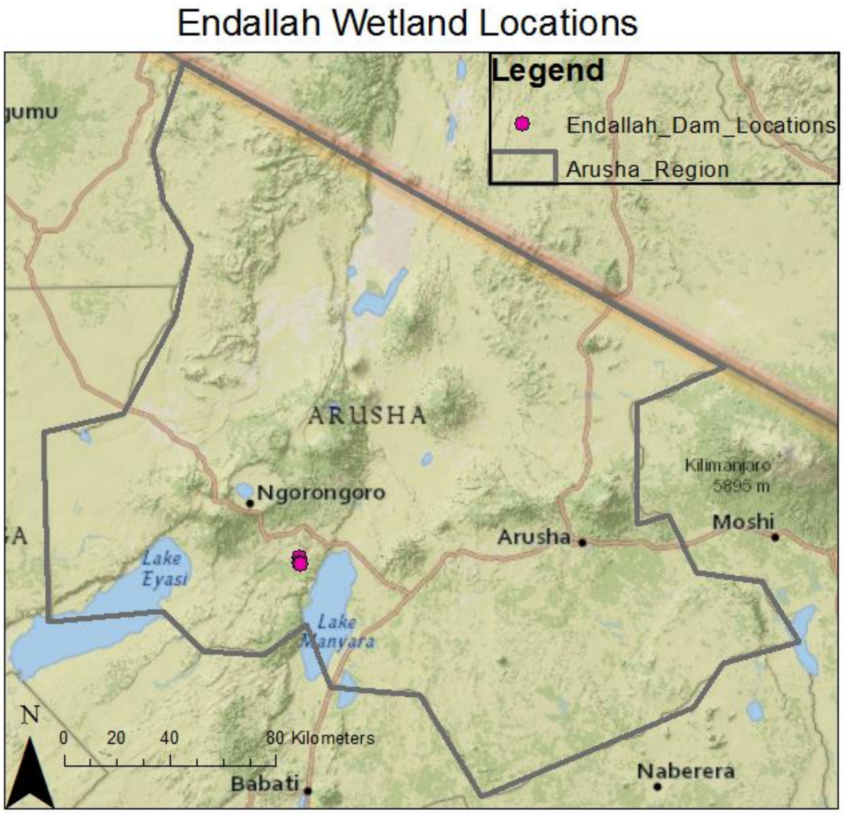

Figure 7.3 Location of Endallah Proposed Wetland Sites

7.2.1 Wetland Inputs

During previous visits to Endallah, villagers indicated three locations they believed would be good for stormwater collection. These three watersheds were delineated, and the result is in figure 7.4. It should be noted that all three locations are of the same watershed, with each watershed area larger than the last one. The areas were 4.68 km^2, 3.36 km^2, and 0.92 km^2. For this exercise, only the largest watershed is investigated.

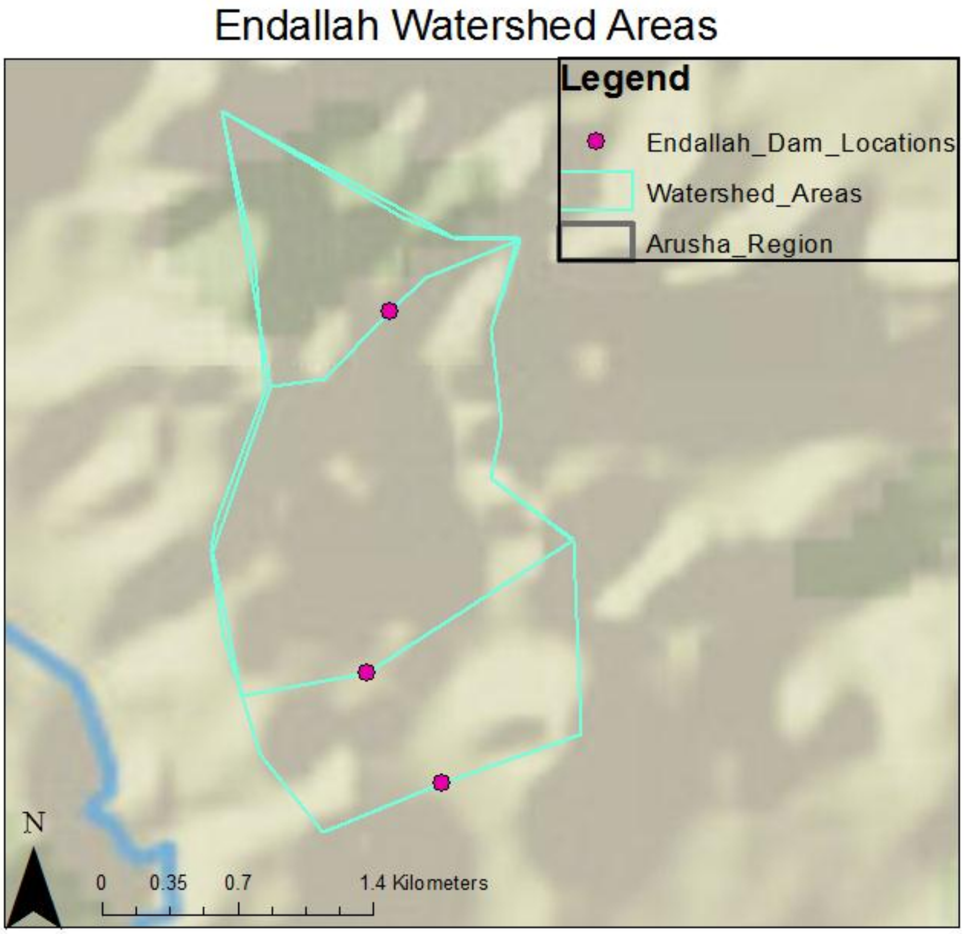

Figure 7.4 Watershed Areas for Endallah Wetlands

The coordinates for the watershed was found to be (3.75,3.25) on the associated map, and the curve number was found to be 67.275. The curve number was calculated by averaging the desert shrub for soil IDs 128 and 129, since the watershed appears to cover both evenly. A plastic liner was also assumed so that infiltration would be 0. These inputs produced runoff of 847 m^3, 502 m^3, and 288 m^3 for upper bound, median, and lower bound rainfall, and 265 m^3 for the maximum monthly runoff.

After these runoff values were found, a series of wetland sizes and shapes were analyzed. Table 7.1 shows the various wetland volume, water volume (which was found based on a media porosity of 0.35), and surface area pairs that were tested. A depth of 3 meters was selected due to hesitation to design a wetland deeper than that, and the length to width ratio was maintained over 3:1.

Table 7.1 Wetland Sizes Investigated

Total Watershed Volume (m^3)	Maximum Water Volume (m^3)	Surface Area (m^2)
3000	1050	1000
1500	525	500
750	26.5	250
450	157.5	150
300	105	100
225	78.75	45
60	21	30

A wetland with 450 m^3 of total volume and a surface area of 150 m^2 was recommended based on these trials, with 30 m and 5 m length and width having a 6:1 length to width ratio. However, any 150 m^2 surface area with a length to width ratio over 3:1 would be appropriate.

7.2.2 Analysis of Tool Outputs

Finally, the population consuming the water was changed between 10, 20, 30, 40, 50, 75, and 100 people, and the consumption was changed between 20 and 10 l/c/d. It was found that a wetland this size would only dry 4 months out of the year with average rainfall watering 50 people with 20 l/c/d, or would not run dry watering 10 people. Alternatively, if the village used this wetland as a supplement to alternative sources and only consumed 10 l/c/d, the wetland could water 100 people with only running dry 4 months annually.

This location, with a larger watershed, is more appropriate for use as a water source by a village. Specifically, it was looked at for providing 20 l/c/d for 50 people, or as a part of a larger water plan and offering 10 l/c/d for 100 people. This demonstrates that this tool can be used to plan SSF constructed wetlands for rural areas in Arusha, Tanzania. While more work needs to be done to ensure an appropriate wetland would actually be built at this location, this provided a user an iterative testing method comparing volumes, surface areas, and consumption.

Similar to the Nelson Mandela wetland, this wetland is designed with a depth of 3 m. This is deeper than the more typical .6 m depth commonly found in SSF wetlands, but is not expected to limit treatment effectiveness.

7.3 Summary

The constructed wetland design tool was applied to the Nelson Mandela campus and village of Endallah. Constructed wetlands were designed for both using an iterative process. The constructed wetland for Nelson Mandela proved too small to provide water for consumption, but is appropriate for testing and validation. This is primarily due to the small watershed which needs to be confirmed locally before a final design is made. The constructed wetland for Endallah was successfully designed, but is not able to provide enough water for all villagers. The tool showed ways in where a constructed wetland could be built on this location as a part of a larger water regime, but can allow villagers better access to protected water during the long dry season.

CHAPTER 8. CONCLUSION

8.1 Key Findings

While there are many types of water treatment technology available, sub surface flow constructed wetlands offer a low cost technology that is low maintenance and viable for water collection and treatment in the Arusha region of Tanzania. It is of note that constructed wetlands have a history of water treatment and storage around the world, but not much research has been done about how they function in Tanzania.

Before a system could be designed, it was important to analyze the water to be treated. Background research indicated that high turbidity and bacterial contaminants are of large concern in Tanzania, and site visits supported this claim. Surface water was often very cloudy, too cloudy to allow for common water treatment methods. Bacterial contaminants were also found in nearly all water sources, posing significant health risks. Other pollutants were more difficult to confirm or rule out because of failed tests, lack of access to necessary equipment, or the fact that turbidity obscures many water testing parameters.

Next a tool to help design a SSF constructed wetland was developed based on the best available data for the region of Arusha. Incorporating 31 years of rainfall data, the SCS curve number method, and monthly water balances, the tool allows project planners to input information on the specific site and receive expected runoff information that can be used to size a constructed wetland. The water balance can also account for consumption of the water, and can report how often planners can expect het wetland to run dry. The tool is expected to help project planners design and develop constructed wetlands for Tanzania and help relieve the water stress often experienced in dry months.

Finally, this tool was applied to both the Nelson Mandela African Institute of Science and Technology to design a pilot test model and to the village of Endallah to see if it can relieve water stress in the field. The wetland for the Nelson Mandela campus was found to have a far too small watershed to support any consumption, but may be viable for research purposes. An average annual runoff volume was found to be 64 m^3, and a 143 m^3wetland was designed with 2 m depth and a 3.56:1 length to width ratio to ensure proper treatment while reducing evaporation from drying out the wetland too often. A wetland was also design for the village of Endallah, in a watershed that receives an average annual runoff of 502 m^3. This wetland has a volume of 450 m^3 with a depth of 3 m and a length to width ratio of 6. This proved the tool can help design a wetland that can be part of a comprehensive water system for the village.

8.2 Research Objectives

The research objectives stated earlier were addressed in this thesis:

- *Find the primary pollutant concerns for surface waters in the Arusha region of Tanzania.*

It was found from a review of the literature, observation and testing that the primary concerns in surface waters in Tanzania are high turbidity and bacterial contaminants. Bacterial contaminants are likely the results of water sources that are not protected from livestock and human waste, while the cause of high turbidity in runoff water is unknown.

- *To create a tool to help design constructed wetlands for drinking water in the Arusha region.*

A tool was created to help project planners design constructed wetlands in the Arusha region of Tanzania. This tool streamlines rainfall and runoff data while making recommendations based on current design practices. While the tool requires decisions and calculations to be made by the users, it is flexible enough to be used in a variety of locations for various scenarios.

- *To apply this tool to the Nelson Mandela African Institute of Science and Technology campus and the village of Endallah.*

The while the tool was successfully used to design a constructed wetland on the Nelson Mandela campus, it showed that it is only appropriate for small scale testing. A constructed wetland was successfully designed for the village of Endallah as a supplement to other water sources. However, more work is necessary to closely calculate the actual watershed area because of insufficient available data.

8.3 Future Work

8.3.1 Tool Validation

It is important that this tool is validated. Specifically, this must be done in two ways: wetlands must be built using the information from this tool, and the treatment effectivity must be confirmed through testing. While the tool is used in chapter 7 of the thesis, these wetlands will look very different than these plans once they are actually built. It is important to build these wetlands, document the disparities, and improve the tool. Additionally, while these wetlands theoretically provide significant treatment to influent water, this needs to be confirmed through actual use. Because of the lack of wetland information in Tanzania, treatment efficiencies were extrapolated and need to be confirmed.

8.3.2 SSF Wetland Performance in Tanzania

The lack of data on constructed wetlands in Tanzania also leads to assumptions on the design parameters of constructed wetlands. Most SSF wetlands designed today have a depth between 0.3 and 0.6 m, but increasing this depth can allow for more storage and less evaporation and infiltration. While no adverse effect on bacterial or turbidity treatment is expected, more research needs to be done on SSF wetlands with larger depths in Tanzania. Second, evaporation data from SSF wetlands in situ in Tanzania is potentially nonexistent. Variation of evaporation due to the variation of months is vital to accurate modeling of water balances within wetlands, and needs to be investigated further.

8.3.3 Confirm Baseline Water Quality

Beyond constructed wetland concerns exists the issue of a gap in water quality data in Tanzania. The turbidity in surface water needs to be investigated more thoroughly to find its exact make up and sources. This can allow for more appropriate technology or even alternative technology that may perform better. While it was not able to be tested at this time, the team believes that iron could be a significant source of color in the water, and needs to be researched further. Additionally, while only fecal coliform was confirmed in the surface water sources, E. Coli, salmonella and various other contaminants may be commonly found. Different contaminants may require different treatment regimes.

8.3.4 Expand Tool Region

Similar to investigating water quality, soil information should be investigated in the Arusha region. Particularly, the infiltration rate of the many different soil types should be tested and reported. Also, a survey of the different soil profiles beyond the top layer in the region would be valuable. Both of these sets of data could allow for more accurate curve number and runoff estimation.

8.3.5 Expand Tool Region

Finally, the tool should be expanded to cover more land in Tanzania. In its current form, it is only appropriate for the region of Arusha and can only report accurate data for it. Constructed wetland technology can be valuable across the country and improved access to this technology can only benefit project planners.

But most importantly, efforts must be turned towards improved access to quality water sources, in Tanzania and across the globe.

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REFERENCES

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APPENDICES

Appendix A Water Source Photos

Figure A 1 Water sample A

Figure A 2 Water sample B

Figure A 3 Water sample C

Figure A 4 Water sample D

Figure A 5 Water sample E

Figure A 6 Water sample F

Figure A 7 Water sample G

Figure A 8 Water sample H

Figure A 9 Water sample I

Figure A 10 Water sample F

Figure A 11 Water sample K

Appendix B Water Quality Results

Sample	Location	pH	Temperature (°C)	TDS (ppm)
A	Mhmmoja	8.1	22	61
B	Mhmmoja Police Stop	7.9	21	30
C	Mtimmoja Plant	8.6	21	130
D	Big River/Dam	8.8	24	230
E	Lotroni	8.8	27	160
F	Basodawish	8.6	28	110
G	Endallah Bondeni	7.1	25	250
H	Pump Endallah	7.1	26	250
I	Manusee Endallah	8.9	34	60
J	Manusee Spring	7.1	25	370
K	Nado Soitoc	8.2	23	90

Table B 1 Location, pH, Temperature, TDS

Sample	Phosphate	Ammonia	Nitrate	Nitrite
A	5	0.25	0	0
B	15	0.125	1	0
C	5	0.125	0.5	0.075
D	5	0.25	1	0
E	5	0.25	0.5	0.075
F	10	0.25	2	0.075
G	20	0.25	0	0
H	35	0	1	0
I	30	0.3	0	0
J	3	0	1	0
K	50	0.25	0.5	0

Table B 2 Sample test strip results

Appendix C Fecal Coliform Plating Results

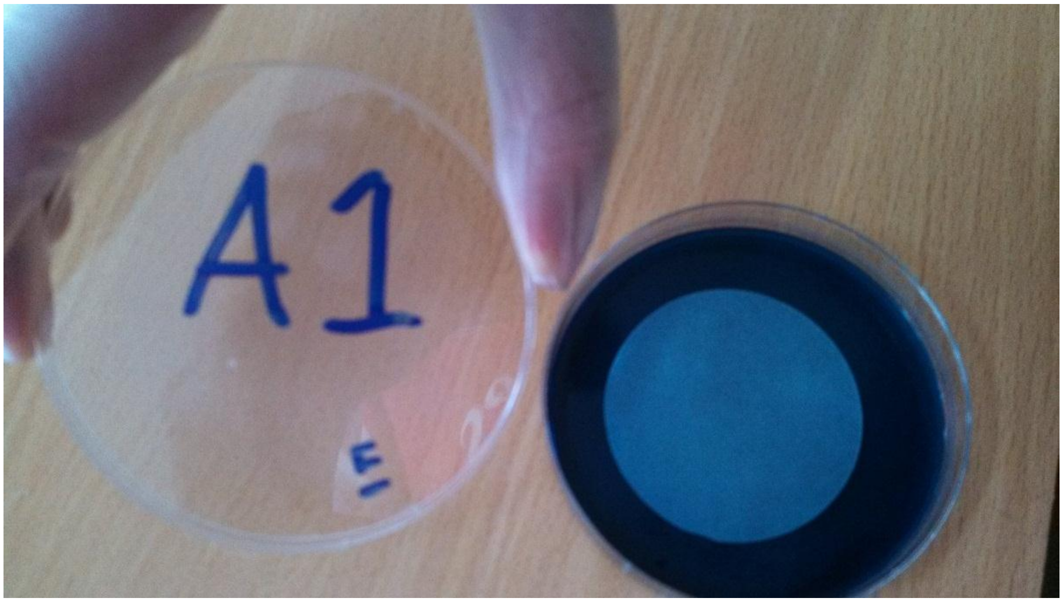

Figure C 1 Plate sample A

Figure C 2 Plate sample B

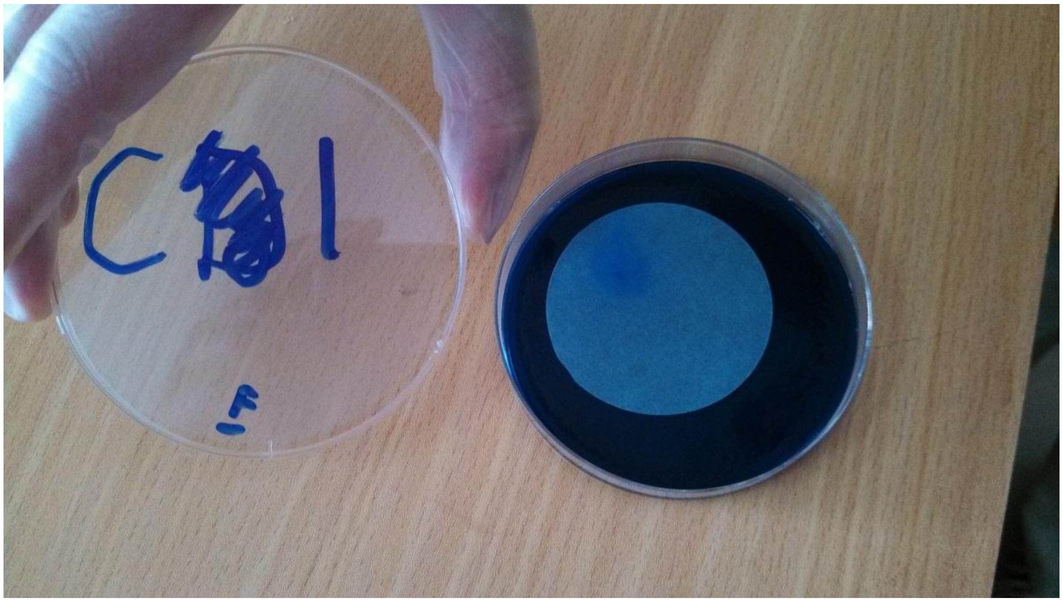

Figure C 3 Plate sample C

Figure C 4 Plate sample D

Figure C 5 Plate sample E

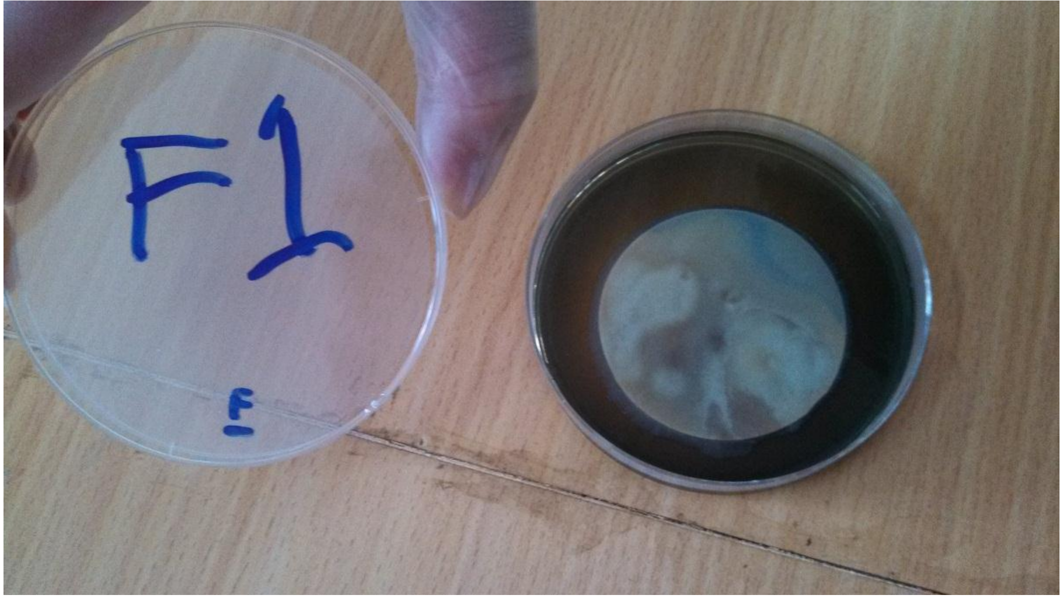

Figure C 6 Plate sample F

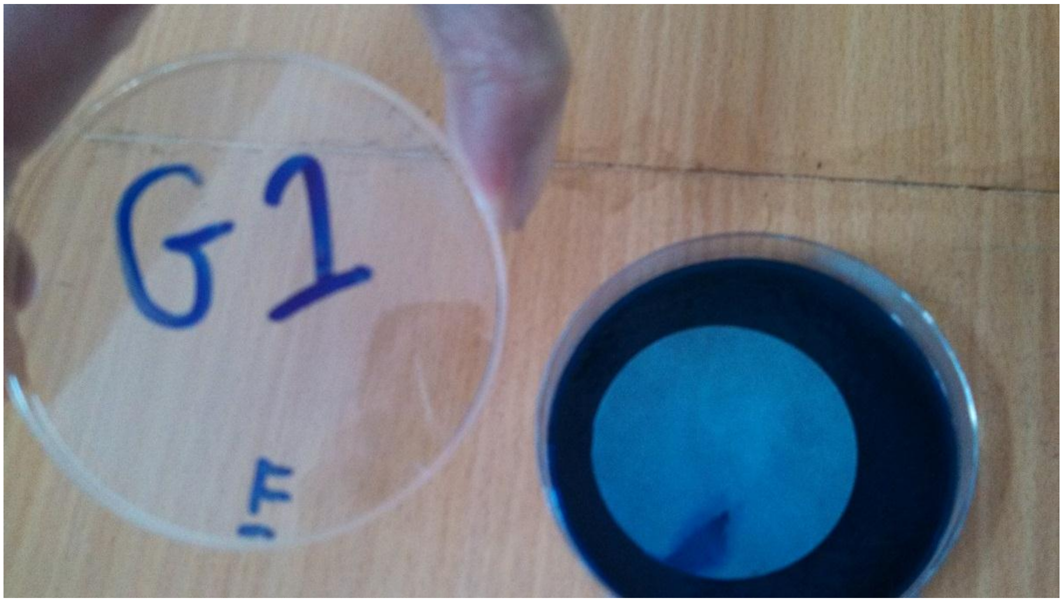

Figure C 7 Plate sample G

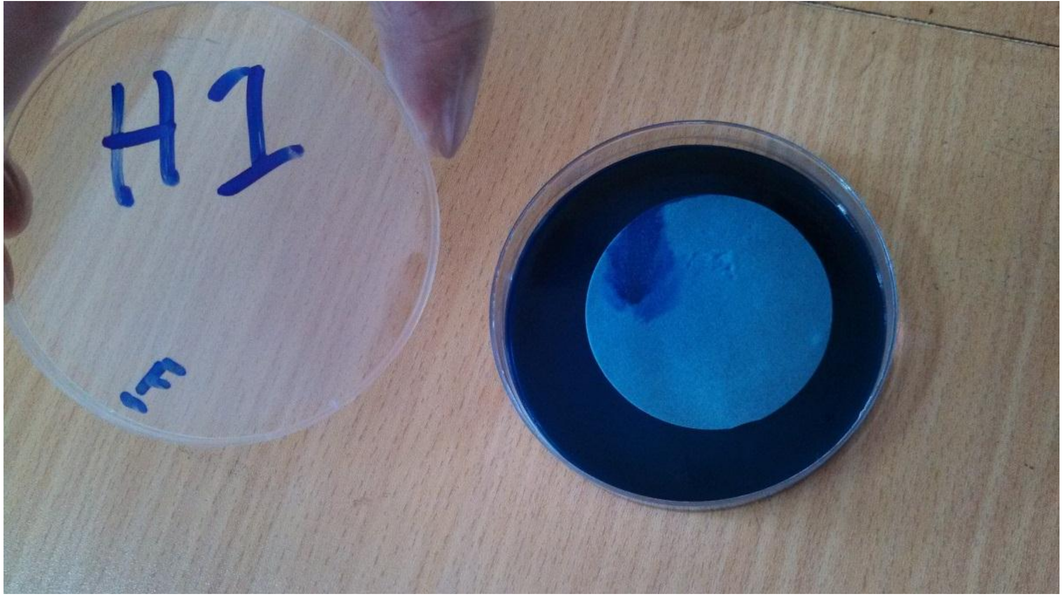

Figure C 8 Plate sample H

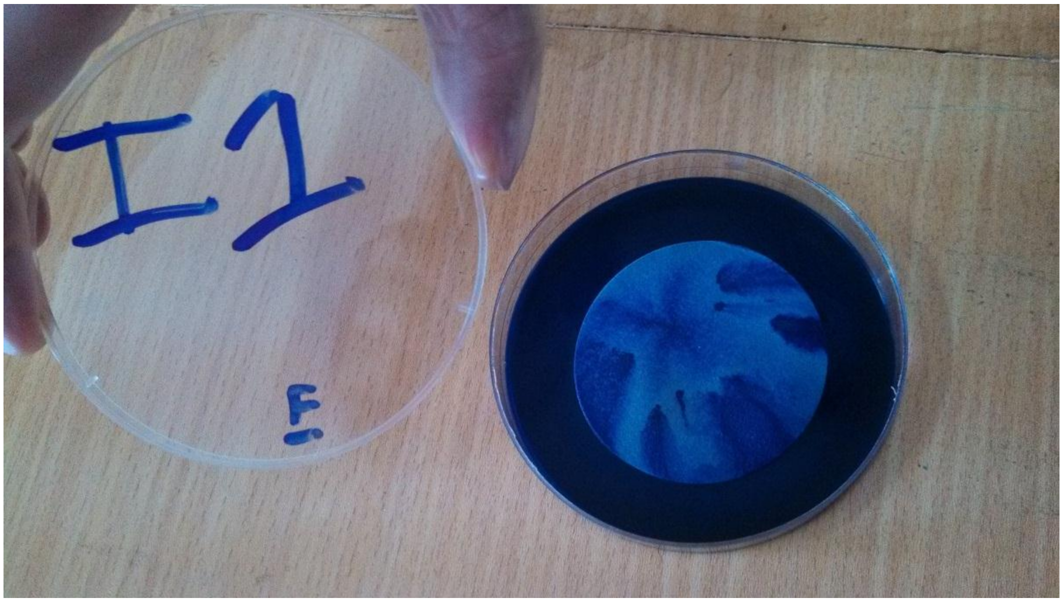

Figure C 9 Plate sample I

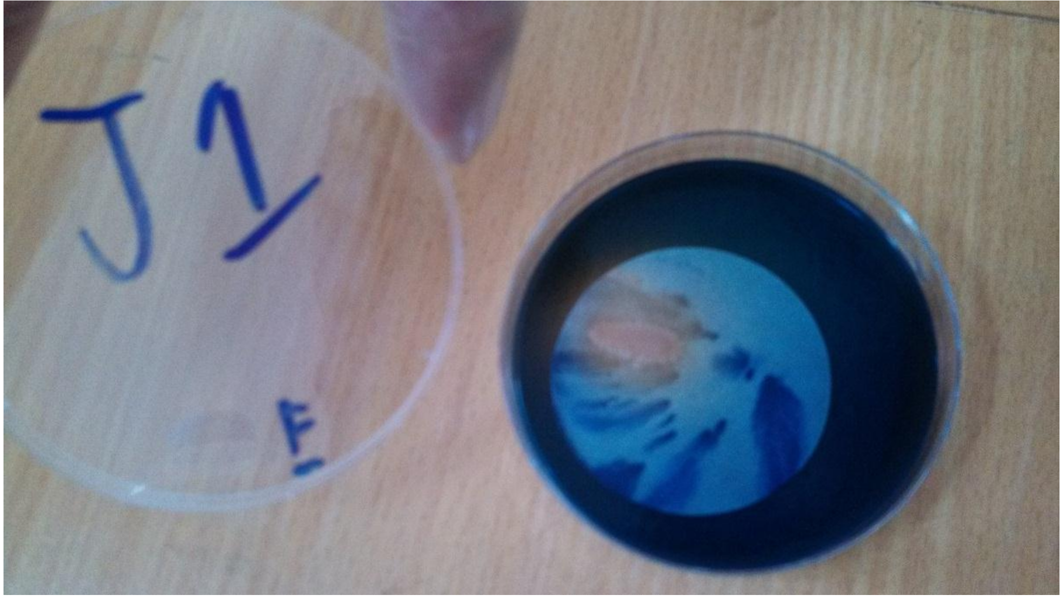

Figure C 10 Plate sample J

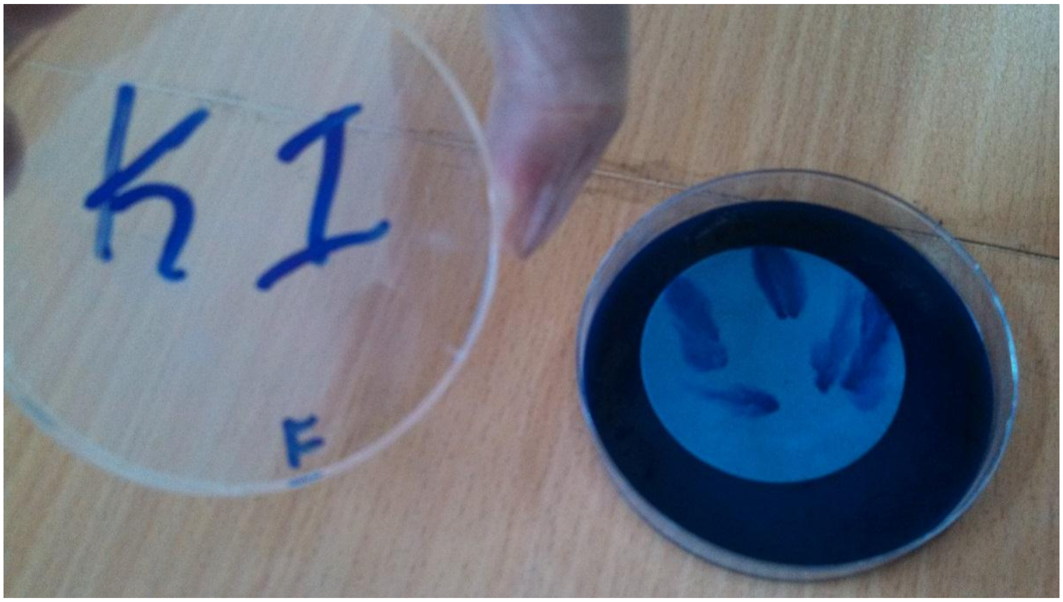

Figure C 11 Plate sample K

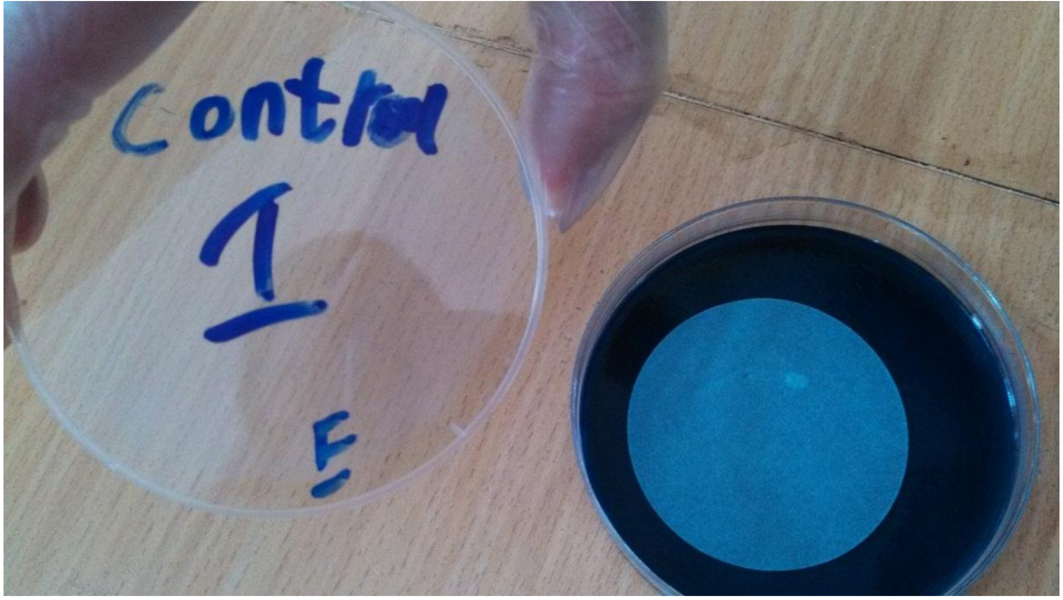

Figure C 12 Plate control

Appendix D Maps

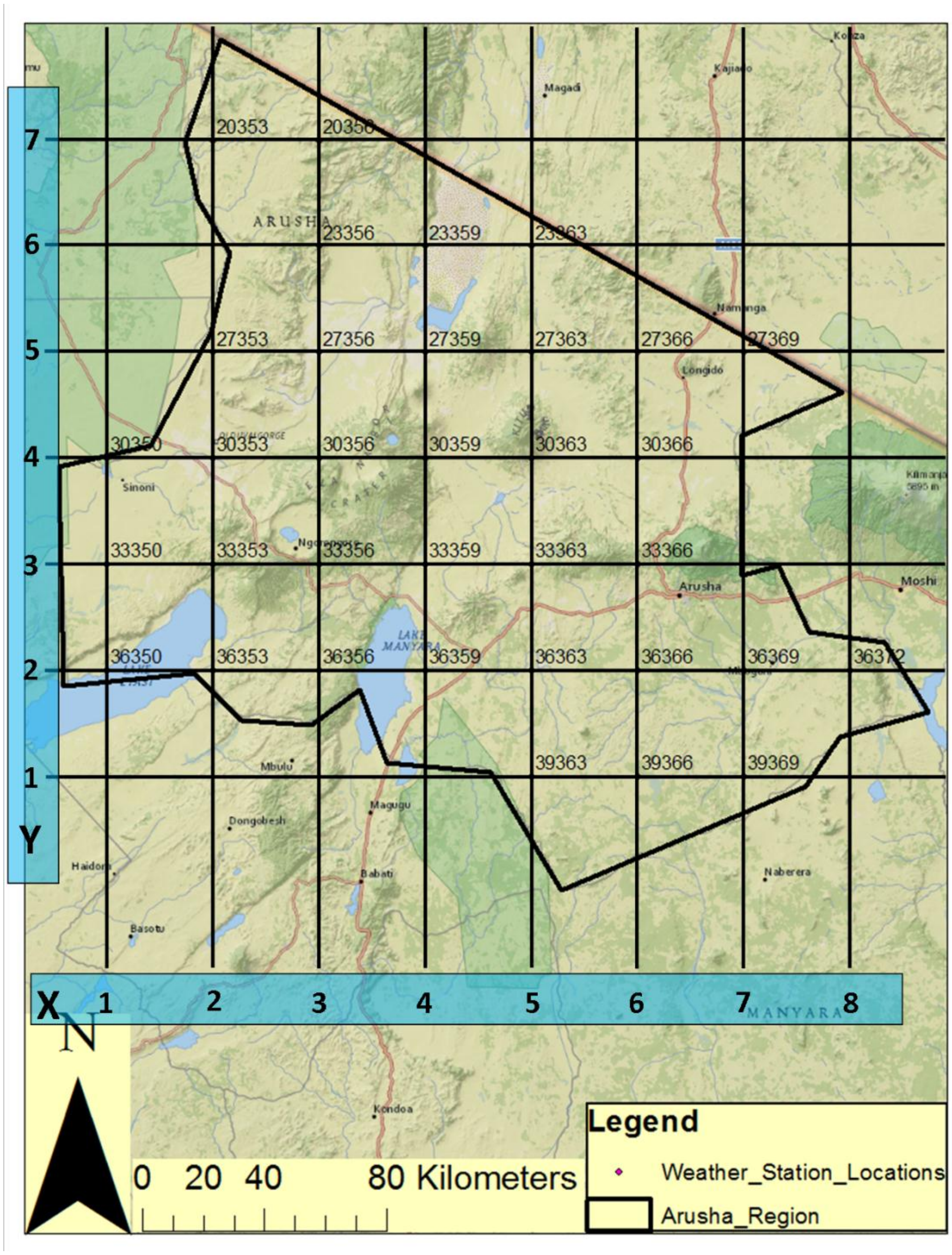

Figure D 1 Grid for wetland location

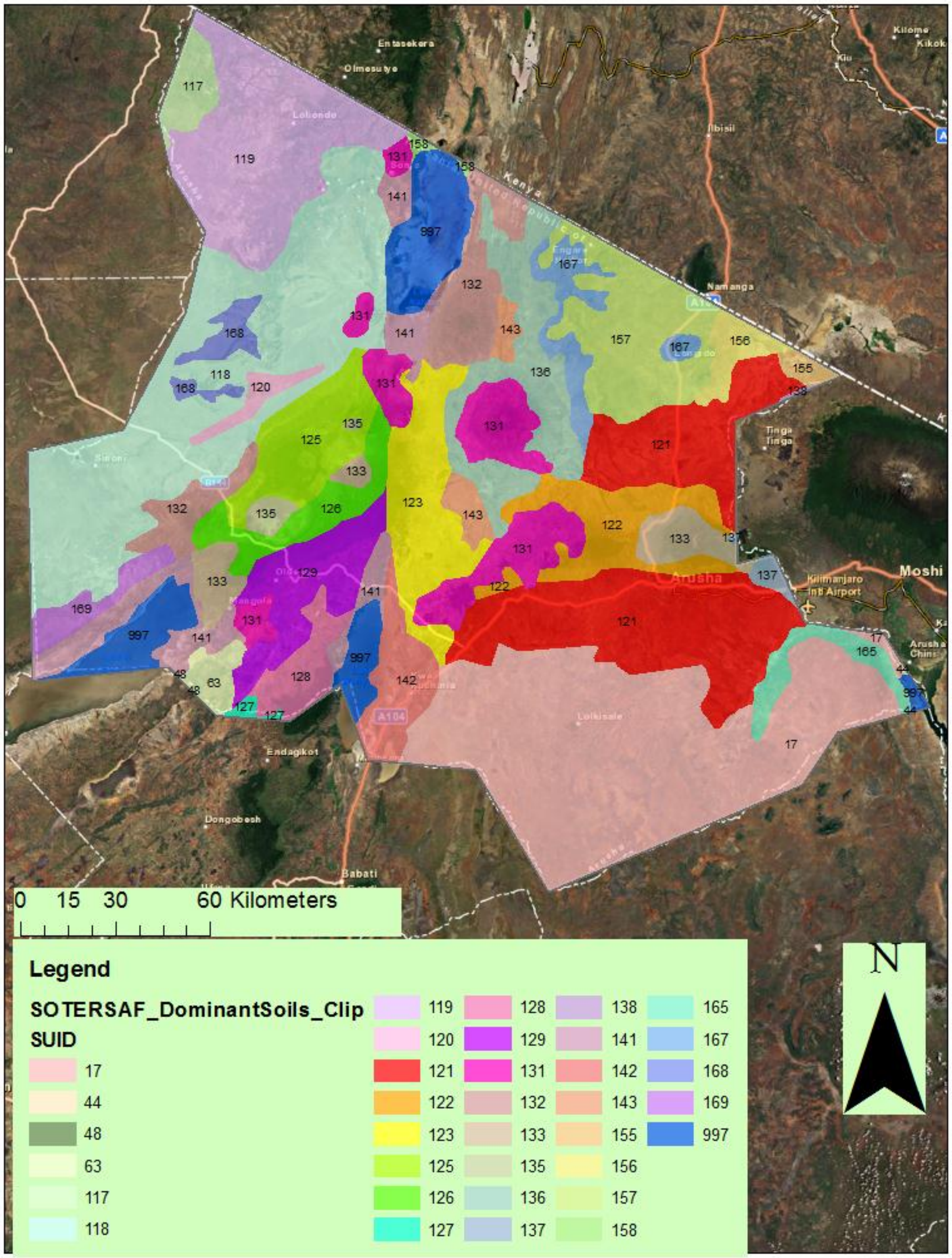

Figure D 2 Soil ID Map