Rainwater Harvesting: A Project for The Walking School Bus

APSC 498H: Humanitarian Engineering

Katrina Berube, Kevin Fan, Kelsea Krawetz, Andrew Sheroubi, Cody Kirbyson

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Part 1: Water Security in Mbale, Uganda

1.0 Introduction

The Republic of Uganda is a landlocked country located in East Africa. After colonial rule ended in 1962, the country was thrown into several conflicts, including a lengthy civil war, that that lasted till 1986. Over the last 20 years Uganda has seen rapid economic growth, and the government has taken major steps to fighting poverty. However, this was coupled with high population growth and rampant corruption (Transparency Intl. 2018), putting further stress on the already struggling infrastructure and limited resources. As of 2013, around a fifth of the Ugandan population lived below the poverty line (The World Bank 2016), with 34% lacking access to clean water (Republic of Uganda 2018).

This case study (Section 1 of the report) examines the Mbale region in Eastern Uganda where the project is located, focusing on water security in the region.

1.1 Brief History of Political Unrest in Uganda

Uganda gained independence from Great Britain in 1962 (Lyons, 2018). A period of terror and war unfolded shortly after, which led to many of the humanitarian issues seen today. Idi Amin Dada took power in 1972 and expelled Uganda's Asian and Jewish communities, this coup allowed for a transition to a long period of political unrest (Hydrant). Conflicts with neighboring Tanzania and Sudan, internal political conflict, and environmental issues led to various epidemics such as AIDS, deforestation, and widespread poverty (Lyons, 2018). In 2007 however, a long term peace agreement was achieved among the Ugandan government which would bring relief to the suffering Ugandan population (Hydrant).

Despite the relief in external conflict, internal government tension has been increasing over the past 10 years. Issues of governance, identity, poor economy, high levels of poverty and unemployment and the youth crisis have led to riots in Kampala and outbreaks of violence (UNICEF, 2012). In addition, as of 2017, Uganda hosts approximately 1 million refugees from Sudan, Democratic Republic of Congo and Burundi (Unicef, 2017). The increase in population, coupled with internal tension has increased strain on poverty levels and various humanitarian issues.

1.2 Economic Poverty in Uganda

Despite high financial poverty numbers, the national poverty line declined from 31.1% in 2006 to 19.7% in 2013. This change can mainly be attributed to thriving agriculture in regions of favorable prices and weather. Urbanization in the Central region has also contributed to strong welfare gains. Northern and Eastern Uganda have been less effective in terms of decreasing the poverty line. Lower levels of human capital, limited access to services, and landslide and flooding issues make these regions more susceptible to poverty than the Central region. These regions struggle with issues in sanitation, access to electricity, education, and child malnutrition (World Bank, 2016).

1.3 Key Humanitarian Issues in the Mbale District

Mbale is subdistrict in Eastern Uganda, which is part of the larger Elgon Sub-Region. Mbale has a population of 488,960 which struggles with widespread poverty, poor infrastructure and limited access to social services. The region is prone to landslides and flooding, which contributes to a series of infrastructure and agriculture related issues. The local government provides assistants to local communities and partners with NGOs, WHO and UNICEF in order to effectively respond to the disasters (UNICEF, 2012).

1.4 Mbale Climate

Mbale’s climate is influenced by its proximity to the equator along with its position at the foot of Wanale ridge. The climate is tropical and typically includes warm and humid days. Mbale’s average temperatures remain relatively constant throughout the year, with limited seasonal variation. The average temperatures range from 19° C in August, to 23° C in March. The region experiences an annual rainfall of 1200mm to 1450mm(Climate Data, 2018). As seen in Figure 1, the average annual rainfall is trending downwards. In addition, Figure 1 shows the extreme contrast in rainfall patterns throughout seasons. The Mbale region experiences an erratic rainfall regime, which is intensifying (WorldWeatherOnline, 2018). Future weather will be influenced by climate change. There will likely be an increase in the "frequency and intensity of extreme weather events, including droughts, floods, landslides and heat waves" (UNDP, 2013).

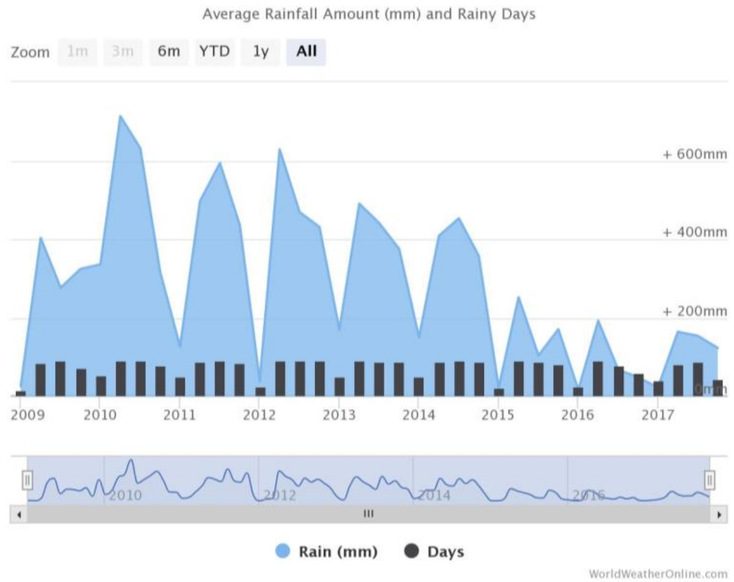


Fig 1: Average Rainfall Amount in Mbale, Africa (WorldWeatherOnline, 2018)

1.5 Mbale Topography and Geology

Mbale district is composed of hills, valleys and steep mountainous slopes covering a geographical area of 25 km2. The most striking topographical feature is Mt Elgon; a stratovolcano with craters, deep valleys, and ridges. The Mt Elgon area hosts fertile volcanic soils (UBOS, 2012). Additionally, Mbale soils are majorly clayey in the highlands, clay loams in mid-altitude areas and sandy in the lowlands and valleys (UNDP, 2013).The Mbale region is underlain by two major formations: The Pre-Cambrian and The Cainozoic. The Pre-Cambrian rock system is primarily classified into granites and gneisses. The Cainozoic formation consists of Pleistocene to recent sediment, alluvium, black soils and moraines (UNDP, 2013).

1.6 Mbale Materials

The Mbale region is heavily cultivated, with little natural vegetation remaining at lower elevations (UNDP, 2013). The vegetation above the cultivated areas is mainly savannah ranging from tropical, grassland, plains with forests and alpine vegetation towards mountain summits. The different vegetation zones include grass, bas mboo, and swampy vegetation. Farmers cultivate their land to grow crops including bananas, Irish potatoes, maize, millet, cassava, sweet potatoes, fruits, coffee and cotton (UBOS, 2012). In addition, the primary materials used in local construction include grass, iron sheets, mud, and burnt bricks. (ACTogther-Uganda, 2015).

2.0 Water Security in Mbale

The Mbale region of Uganda has long been subject to high rates of water insecurity. According to the Ministry of Water & Environment, Republic of Uganda in 2018, on average, the access rate to safe water in Mbale was 66%. These access rates are extremely variable depending on the region of interest (Figure 2) and can "vary from 27 % in Nakaloke Sub-County to 95 % in Wanale Sub-County" (Republic of Uganda 2018). Unfortunately, these rates are on the decline in recent years, a trend that must be curbed immediately. One of the major issues of water security in Mbale is the accessibility. "Water is not scarce in Mbale, however it is often a significant distance from where people live and/or is contaminated, leading to health problems and death." (Pont, 2018).

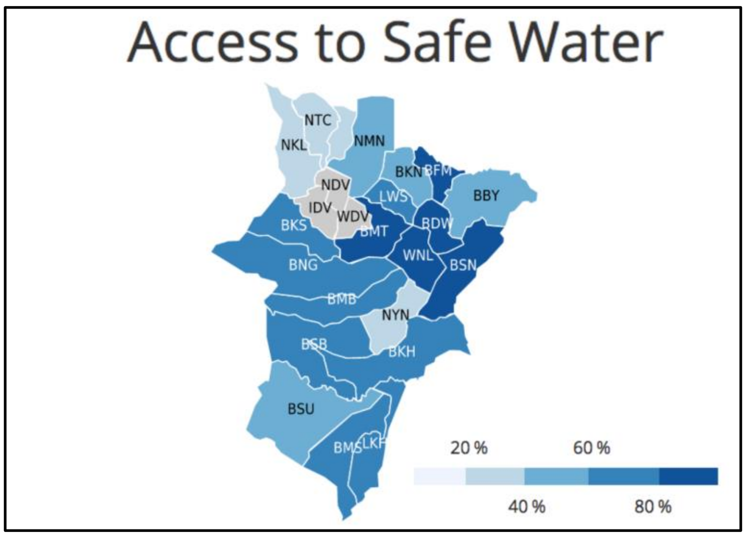


Figure 2: Rates of access to safe water (Republic of Uganda, 2018)

In the region, there are two pressing issues which are leading to decreased water security. The first factor causing increased stress on the water system is that "all urban centers in Uganda that have undergone rapid growth" (Air Water Earth Ltd., 2017) in the recent years. As a result, this has "placed immense pressure on the capacity of [National Water and Sewerage Corporation] to effectively deliver water and sewerage services" (Air Water Earth Ltd., 2017). The water and sewage systems have been unable to keep up with the rapid development of the rest of Uganda's infrastructure, therefore adding to the already tough water situation.

The second factor leading to intense destabilization of water security in Mbale are the severe droughts that have plagued the region over the past decade. Dry spells of up to three months are not uncommon in certain regions of Mbale, these dry spells put extreme pressure on the rivers, lakes, and groundwater aquifers present in the region which are expected to supply as a lasting water source for residents.

In certain cases “water consumers in some areas haven't had water supply for over a week” (Among, 2018), greatly affecting their health and wellbeing. The effects of climate change, which will be further elaborated upon in the next section, are only expected to increase the frequency and severity of such droughts in the region, further complicating the water security of the region.

Quantity is not the sole issue that Mbale faces in regard to water security, contaminants are also an immense issue which further limits the amount of safe drinking water available. A gravity flow system in Mbale was “condemned by the Ministry of Health [in 2009] and shut down after [five] cholera deaths” (Elunya, 2018). Upon investigation into the deaths, it was found that there was a “high concentration of human feces mixed in the water” (Elunya, 2018). This contamination stems from the lack of infrastructure surrounding waste disposal and sanitation services. The sad reality of this situation is that residents have been forced to continue drinking from this contaminated source, as there is no alternative option present.

2.1 Current Water Systems

In Mbale, there are five main sources of public water, in the order of the most popular, they are: protected springs, deep boreholes, public taps, shallow wells, and rainwater collection tanks (Figure 3). While there are a few piped systems in place throughout Mbale and Uganda, these are only present in major towns. This means that people who reside in rural villages and smaller towns must “walk miles to collect water and it is mainly women and children who do this” (Pont, 2018). In recent years, rainwater collection has been on the rise in Mbale. Currently this system accounts for the lowest percentage of end users, however, its potential is high and its popularity is on the rise. In the fight against water insecurity, this may be one of options with the most unexplored potential.

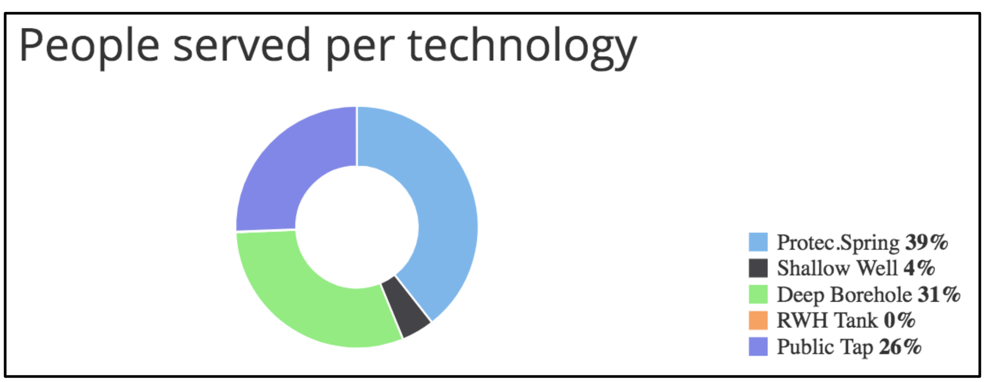


Figure 3: Percent of usage for water systems (Republic of Uganda 2018)

2.2 Future Outlook: Potential Impacts of Climate Change on Ugandan Water Security and Interactions with Social Effects

At a summit of the African Union in 2007, Ugandan President Yoweri Museveni called climate change 'an act of aggression' by the developed world against the developing world, demanding compensation for the damage that global warming would cause African nations (Clark, 2007; as cited in Brown, Hammill, and Mcleman, 2007). Indeed, a group of eleven high-ranking, retired American admirals and generals released a report in the same year arguing that climate change will act as a 'threat multiplier' that will exacerbate existing concerns including water security and food insecurity (NPR, 2007) and make them more complex and intractable, with estimates that human-induced climate change is likely to increase average temperatures in Uganda by up to 1.5C in the next 20 years and by up to 4.3C by the 2080s (Hepworth and Goulden, 2008).

Furthermore, there has been increasing concern about climate change and its impacts in the Mbale region specifically. The region is highly vulnerable given its high population, high poverty levels, and mountainous landscape, while there have been numerous cholera outbreaks, particularly in the rainy season, and rural areas in mid-high elevation areas have experienced landslides and reduced agricultural yields (UNDP, 2013). Specific projected effects of climate change upon water resources include higher precipitation, especially in high-elevation areas of the Mbale region and the rest of Mt. Elgon, as soon as the 2020s. While ostensibly this may appear to reduce water stress, much of the landscape where natural vegetation has been lost will be liable to increased runoff, resulting in topsoil erosion, nutrient reduction, and reduced agricultural yields (UNDP, 2013). Moreover, reduced rainfall is projected during the December, January, and February months, translating into increased water stress for crops during these months. Further exacerbating the situation is the fact that groundwater is currently the major source of rural domestic water supply in Uganda, as evidenced by the fact that it is main source of water for small towns and rural growth centres (~800 for the latter) up to 2015. However, some of the aquifers are limited in yield, extent, and hydraulic characteristics, while recharge is low in certain parts of the country, rendering the availability and quality of groundwater for rural supply projects, irrigation, and municipal supplies a significant future challenge. Unfortunately, little is known about Uganda's groundwater resources – much less how climate change will impact them (Nsubuga, 2013).

The first of many projected effects of climate change upon water security in Mbale is an anticipated reduction in water resources and supplies relying upon snowmelt due to the occurrence of a warmer dry season and fewer cold days and nights (estimated to be virtually certain). The social consequences of this could range from reduced energy demand for heating and increased demand for cooling, and adverse effects upon winter tourism.

Another anticipated effect is increased water demand and water quality problems (eg. algal blooms) due to increased frequency of warm spells and heat waves over most land areas (estimated to be very likely). This would result in a reduction in quality of life for people living in warm areas without appropriate housing, disproportionately impacting marginalized groups including the elderly, very young, and very poor. Climate change will also impact the quality of surface and groundwater and contamination of water supply (despite prospect of some relief of water scarcity) due to increased frequency of heavy precipitation events particularly over high elevation areas (estimated to be very likely). Social implications could include the disruption of settlements, commerce, and transport due to flooding, in addition to pressures on both urban and rural infrastructures and loss of property. Finally, there could be more widespread water stress due to higher incidence of drought in low elevation areas of Mbale, resulting in water shortage for housing and industry, reduced hydropower generation, and the potential to spur large-scale migration (UNDP, 2013).

On a broader scale in addition to water security, temperature increases from climate change are likely to have significant implications for a wide swath of socio-economic issues, including increased food insecurity, shifts in the spread of diseases like malaria and public health, soil erosion, and land degradation (Hepworth and Goulden, 2008). For instance, a climate-induced shift in the viability of coffee growing areas could potentially wipe out US $ 265.8 million (40%) of Uganda's total export revenue. In spite of these challenges, Hisali (2011) identified 2 potential measures to increase resilience to climate change in Uganda in general, which can also be applied to the specific case of water resource resilience: a) increasing the availability of credit, in order to smooth short term household consumption fluctuations from climate-related shocks and enable households to access the resources required to implement adaptation practices, and b) increasing labour supply and productivity, particularly in the agricultural sector (Hisali, 2011). While a number of initiatives targeting the latter have been pursued by government, they have thus far not been able to materially affect the agricultural sector's productivity.

3.0 Conclusion

Despite being water stressed, the issues with water security in the region of Mbale aren't restricted to quantity. Water insecurity also exists due to the variability of water access throughout the region and the lack of adequate treatment in several cases. The region relies heavily on groundwater sources, however they are limited. Rainfall collection methods are gaining popularity and have great potential in helping alleviate the water stress of the region. Different methods for tackling water insecurity are heavily need, particularly considering the devastating effects of climate change.

Part 2: Technical Report

1.0 Background

The Walking School Bus (TWSB) is an organization that promotes access, curriculum and nutrition. Their involvement in Indian and African communities encourages educational attainment through a holistic approach. TWSB is composed of a diverse team of experts from a range of fields that is "committed to academia and research that scientifically tests procedures prior to implementation" (TWSB, 2018). Ideas are implemented over time in collaboration with the community at hand. This all-inclusive approach ensures processes are meaningful and successful. Initially, TWSB was formed to provide safe transportation for students to get to school who would otherwise be walking long distances. This issue was addressed through the addition of transportation in the form of busses. Once at school, teacher absenteeism was hindering student literacy. Therefore, a curriculum was developed though the SiMBi Reading Application; an app powered using the organization's solar-powered classrooms constructed from shipping containers. While tackling the access and curriculum issues, it was noted that once students arrived at school they were not adequately nourished to learn effectively. From this realization, the nutrition program was launched, focusing on three main areas: water catchments, chicken coops, and community gardens. The water catchment system utilizes rainwater that falls onto the roof of the shipping container classroom. The rain runs down the slanted roof and flows into a gutter where it is then stored in a holding tank. TWSB rainwater collection system eliminates community concern surrounding water used in the nutrition program and has proven to be a successful method of rainwater harvesting.

1.1 Purpose and Scope

The rainwater collection system in TWSB's target school in Mbale currently contains two purification processes. As seen in Figure 1, first, the water is filtered using a wire mesh as a sieve. This method removes matter larger than 5mm. Following this, the water enters a 1000L holding tank where water is chlorinated using chlorine balls. This report aims to develop a method to increase the water quality collected from the rainwater harvesting system for drinking and nutrition programs. It will identify potential sources of contaminants, analyze first flush systems, and explore different filtration methods. Several methods will be analyzed based on the considerations presented below.

Figure 4: Current Water Collection System (TWSB, 2018)

2.0 DESIGN REQUIREMENTS AND CONSIDERATIONS

Throughout the design the following five factors were continuously evaluated:

1. Budget
2. Resource Availability
3. Technical Complexity
4. Sustainability
5. Flow Rate

The system should require minimal expenses and maintenance, as well as be constructed of locally available material. The system should also be sustainable; the proposed method aims to have a long life span with a high durability. Additionally, the design should be technically simple to promote replication in other communities and to promote construction and maintenance by the local community. Furthermore, the rainfall patterns and the corresponding flow rate through the gutter need to align with filter method flow rates.

3.0 CONCEPT STAGE

Based on the requirements and context of the problem, the system considered included a first flush system and a filter. Those are examined bellow.

3.1 First Flush System

Through research and client consultation, the main source of contamination in the rainwater harvesting system was determined to be from the accumulation of dust, leaves, bird feces and other debris and particulate on the catchment surface. The rainwater itself is a very clean source of water, containing only trace impurities “picked up by the rain from the atmosphere” (WHO, 2018). Therefore, reducing the contamination resulting from the catchment process will greatly improve final water quality. In practice, the most effective method of reducing contamination input from the catchment surface is through the implementation of a first flush system.

A first flush system is a concept that utilizes the first portion of the rainfall to clean the catchment surface of any debris, diverting this contaminated water away from the main holding tank, into a secondary catchment tank. This contaminated water can then be used for any purpose not requiring potable water, such as in community gardens. Our design process, analyzed three different first flush concepts to determine the most effective approach: a) manual diverter, b) gutter-pulley system, and c) diversion tube.

3.1.1 Manual Diverter

The first method considered was a manual diversion system. In this concept, the pipe entering the main holding tank contains a swiveling elbow that can be turned away from the tank at the start of the rainfall. Thus, diverting the contaminated water into a separate holding tank. This basic design is simple to use and is effective when utilized properly; however, the downside is that someone must always be present to manually move the spout. If this is not done every time at the start of the rainfall, the main holding tank will be contaminated by the first flush. This could prove to be problematic if the rainfall were to occur in the middle of the night or when nobody is around. This design can be seen in figure 5 below.

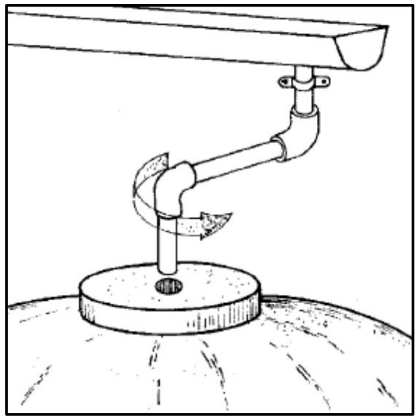


Figure 5: Diversion Tube (Thomas and Martinson 2007)

3.1.2 Gutter-Pulley System

The Gutter-Pulley system is an automatic system which utilizes a moving gutter and pulley to divert the first flush. As seen in figure 3 below, prior to the rain, the gutter is positioned to divert the water into a bucket which is connected to the end of the gutter via a cable and pulley. As the first flush begins to fill the bucket, it increases in weight. This begins to pull down on the end of the gutter, lifting it up, diverting the clean water into the main holding tank. The hanging bucket slowly drips empty into the waste tank below and eventually resets itself to the starting position. The advantage of this system is that the process is entirely automated, eliminating the main issue of the manual diversion technique. The downside of this technique is the number of moving parts required. Working in Mbale and similar areas where the required parts may not be readily available.

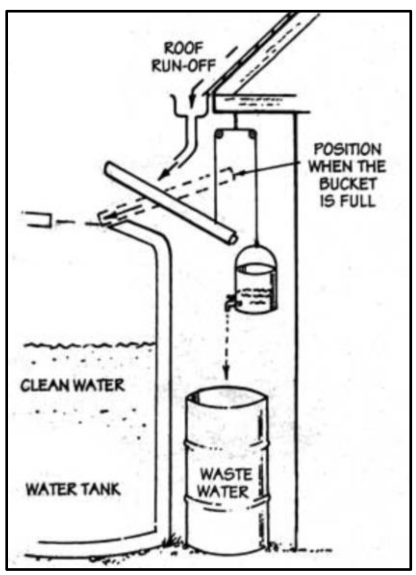


Figure 6: Gutter Pulley-System (Thomas and Martinson 2007)

3.1.3 Diversion Tube

The diversion tube uses a separate downspout to capture the first flush. As seen in figure 7, the initially empty downspout is filled with the first flush water, as the level increases and reaches the top of the downspout, the water is now able to flow past and into the main holding tank. In some modified methods of this version, a ball is put into the diversion tube. As the water level rises, the ball floats on the water until it reaches the top of the diversion pipe and seals off the flow, allowing it to pass into the main holding tank. This rendition can be seen in figure 8 below. The end cap on the diversion tube can be fitted to slowly trickle out into the waste tank, making it fully automated just like the pulley system. The upside of this design is the minimal number of moving parts and the overall simplicity.

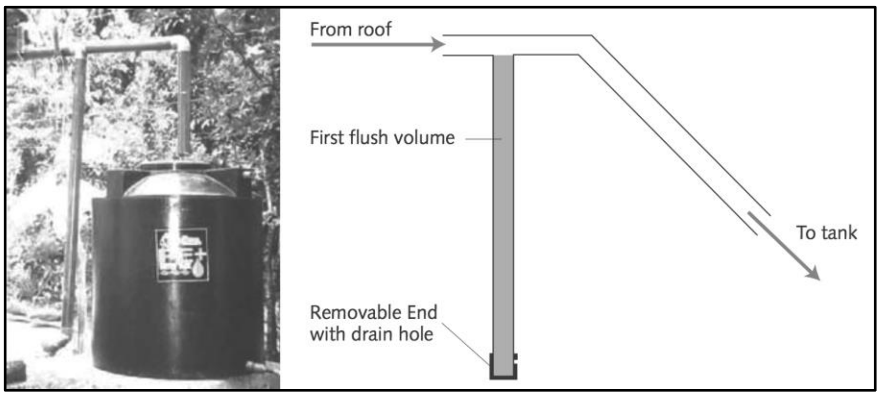


Figure 7: First Flush System (Thomas and Martinson 2007)

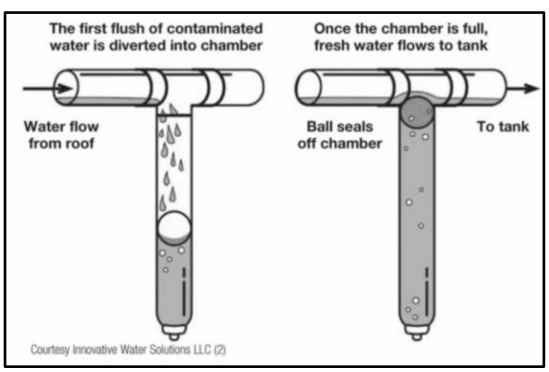


Figure 8: Ball First Flush Diverter (ATKC Warehouse, 2018)

3.1.4 Decision Making

To determine which first flush system would be the most effective of the three, a decision matrix was created to quantitatively assess the three options. The five categories we assigned for assessment were: the degree of automation, the effectiveness of the system, cost, reproducibility and maintenance. Weights were then assigned to the categories based on their relative importance. The degree of automation was assigned 25% due to the importance of ensuring every flush is diverted away from the main holding tank. With the manual diverter, if one single flush is not diverted properly, the entire holding tank will be contaminated, hence its high importance. The effectiveness of the system was rated to be the most important at 35%, as the system must remove the debris from the water. The reproducibility was rated to be worth 20% as we want other communities to be able to adapt this into their current water catchment system without the need for an experienced technician. Maintenance and cost were both rated at 10%.

Through analysis, the most effective first flush system was found to be the diversion tube, this is due to its high degree of automation, high effectiveness and its ease of reproducibility. This method is considered to be the most effective and overall best method of implementation of the first flush system. The results of the decision matrix can be viewed in Table 1 below.

Table 1: First Flush Decision Matrix

First Flush System						
Weighting	25	35	10	20	10	100
Weighting (%)	25%	35%	10%	20%	10%	**100%**
Option	**Automated**	**Effectivness**	**Cost**	**Reproducibility**	**Maintenance**	**Score**
Manual Diverter	0	3	8	8	9	**5**
Gutter- Pulley System	9	8	5	3	4	**7**
Diversion Tube	9	7	6	8	7	**8**

3.2 Filtration System

Several filtration methods were considered in a comparative analysis for this design, taking into consideration the requirements and constraints. The full description of each filtration method can be found in the literature review seen in Appendix A.

A preliminary analysis was performed to eliminate out rightly non-viable options as described in table 2.

Table 2. Filtration Systems Summary

Method	Proceed (Y/N)	Rationale (main argument)
Activated Carbon	N	Difficult to procure/produce
Ceramic	**Y**	**Cheap and excellent treatment**
Glass	**Y**	**Widely available, effective and cheap**
Membrane	N	Expensive, difficult to maintain
Paper Cloth	N	Not scalable
Reverse Osmosis	N	Energy intensive and difficult to operate
Sand	**Y**	**Widely available, effective and cheap**
Tree/Wood	N	Not scalable

From this analysis we proceeded to examine ceramic, sand, and glass and potential options for our system.

3.2.1 Ceramic

Ceramic filters are highly porous materials which are able to filter out a majority of contaminants in the water. The main advantages of ceramic water filters are their low costs, ease of fabrication and use, and effective bacterial removal. They are relatively easy to produce and are widely used around the developing world as point of use water filters (Sobsey et al. 2008).

Some of the disadvantages of ceramic water filters are the inability to remove viruses, and their fragility. The formation of any cracks on the filter will significantly decrease its effectiveness. However the main drawback is the filtration rate, which is between 1-3 L/hr with an optimal rate at 2 L/hr (Nyongesa et. al, 2013). Based on the flow calculations this method is not suitable for this design. Ceramic filtration could be implemented as a point of use filter rather than in a collection system.

3.2.2 Glass

Crushed glass shows promising potential for effective water treatment. Different particle sizes display varying characteristics. Fine glass, with a particle size of 0.2–1 mm, is the most effective at removing suspended solids from the water stream, however it also requires more frequent treatment. On the other end coarse media (particle size 1.5-2.5 mm), is able to treat more water but at a lower quality. It is found that a medium grade (particle size 0.5–1.45 mm) works best, although the effluent quality was close to the coarse particles (Horan and Lowe, 2007).

This method has been shown to be comparable or superior to sand filtration in terms of water quality. Additionally, backwashing is much more effective at rejuvenating the filter due to the sheer surfaces of the glass. Finally, this method can filter up to 610 L/min per square meter of media. This method requires proper sieving to control the particle size, and there is a risk of fine glass shards ending up in the water source if it is not performed properly.

3.2.3 Sand

Sand filtration is one of the most common and widely understood water purification methods around the world. It utilizes sterilized, sieved sand to filter out contaminants from the water. The primary types of sand filtration methods are slow and rapid sand filtration. Slow sand filtration integrates physical and biological/chemical treatment of the water source. This combination makes slow sand filtration very effective; however as the name implies, has a low flow rate of 1.5–3.5 L/min per square meter. Rapid sand filtration on the other hand is only a physical treatment process, but can treat 65–200 L/min per square meter. It is important to note that for more turbid water a pretreatment step (coagulation and flocculation) might be needed prior to rapid sand filtration.

This is further analyzed in section 5.2.3.

3.2.4 Final Evaluation

Sand filtration was selected over ceramic and glass filtration on the basis that ceramic systems have too low of a flow rate for rainwater harvesting systems. Glass filtration was not selected as it requires a sieve set to achieve an effective grain size distribution. Moreover, without proper preparation methods, crushed glass poses a risk due to the difficulty of removing small glass shards from the medium. Furthermore the water quality does not require extensive treatment, thereby eliminating the need for a complex system.

4.0 RAINFALL ANALYSIS

In order to estimate the expected flowrate through the system, a rainfall analysis was performed to provide both the average and the peak rain volumes. This was used in conjunction with the surface area of the collection roof to estimate flowrate.

4.1 Historic Rainfall

Data used for this section was obtained from a 2013 report on climate profiles throughout the region. The average monthly rainfall data from 2002 to 2011 is presented below in figure 9:

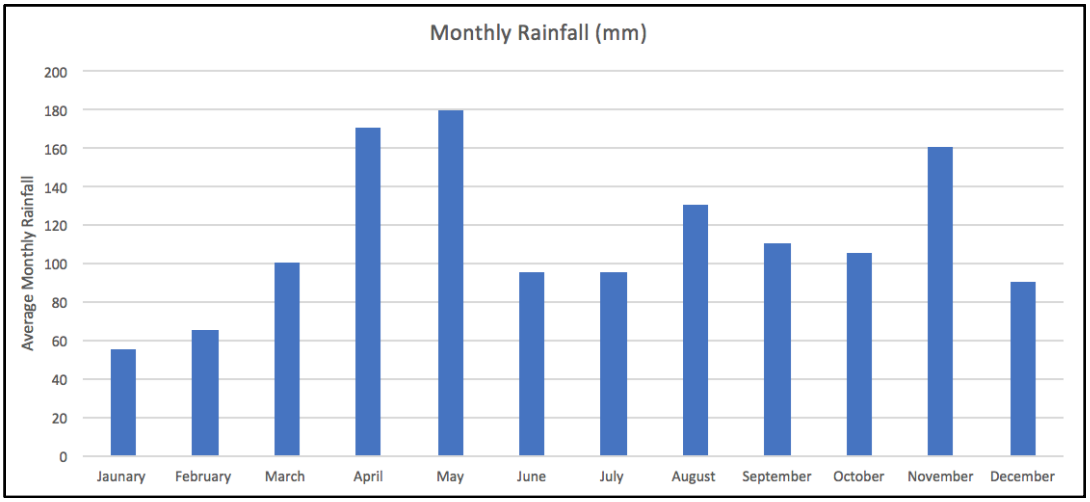


Figure 9: Average Monthly Rainfall, Mbale Region 2002-2011

As displayed in this plot, Mbale experiences two rainy seasons, one lasting from mid-April to May and the second occurring in November. The other factor considered in the analysis was the expected impact climate change will have in the coming years.

To determine the required capacity of our system, the daily rainfall was a more important statistic. Due to a lack of available data, these values had to be estimated by dividing the monthly rainfall by the number of rainy days per month, giving an average rainfall per rainy day. The average rain per rainy day was found to be consistent over every month at approximately 20 mm/ day. The data is plotted below in figure 10.

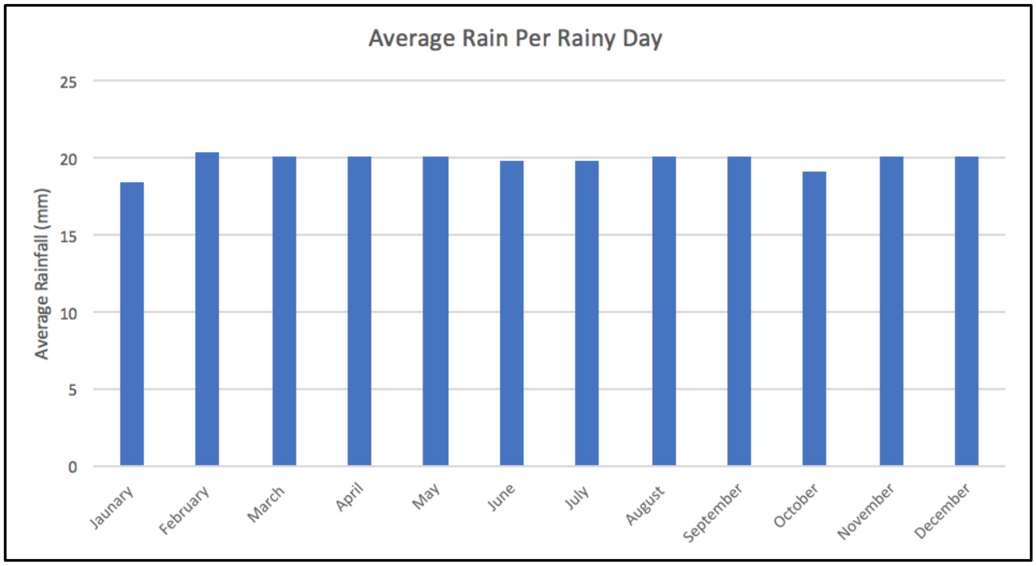


Figure 10: Average Rain Per Rainy Day

4.2 Climate Change Analysis

According to a 2013 report on the vulnerability of the Mbale region, the impact of climate change on the monthly rainfall is expected to range from -8.0% to + 11.6% by 2050 (Mbogga, 2012). These limits were used in the assessment as a best and worst case for the rainfall in the region. To calculate the estimated rainfall in 2050, the average rainfall per rainy day data was scaled up and down to meet the projected values. The resulting climate change adjusted precipitation data can be seen below in figure 11:

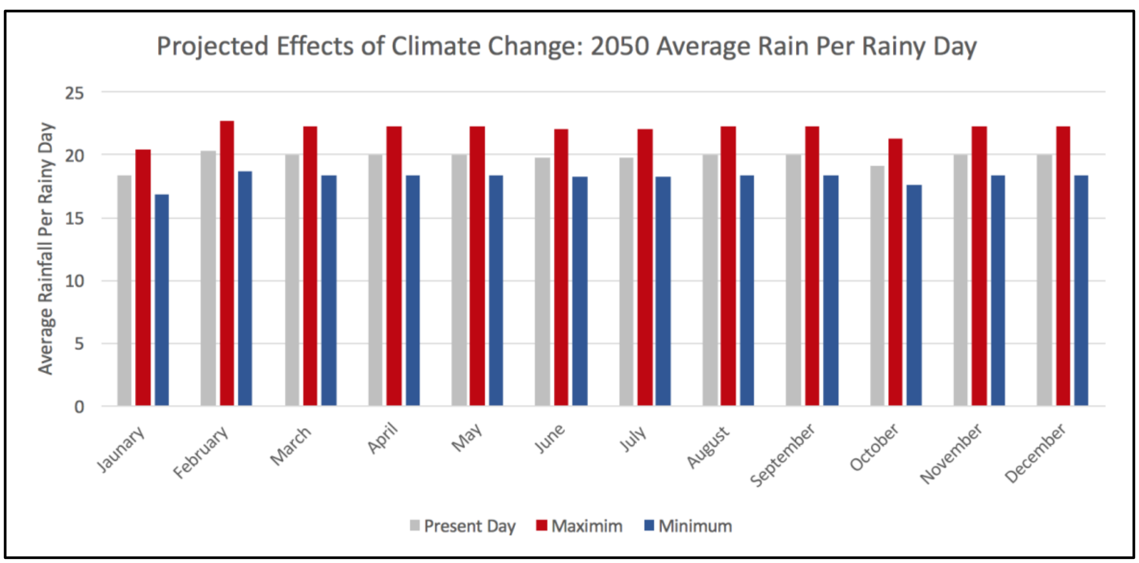


Figure 11: Average Rain Per Rainy Day, Climate Change Effects

4.3 Captured Water

The data obtained from the sections above was used in calculations to determine the amount of anticipated water to be collected from the rainwater catchment system. Using values provided for the size of the school roof and the angle of inclination, as seen in Figure 12, the projected effective area of the catchment was calculated to be 89.5 m^2. As seen in figure 13, the maximum amount of water captured in any month occurred in May at approximately 14,493 L. When scaled up to the maximum climate change prediction, the largest volume captured was 16,175 L - a fairly significant difference in terms of total capacity of the system. An increase in the volume of the capture tank may be an aspect of future consideration.

Figure 12: Estimation of roof dimensions and slope and rainwater capture area at TWSB's school in Mbale. (TWSB, 2018)

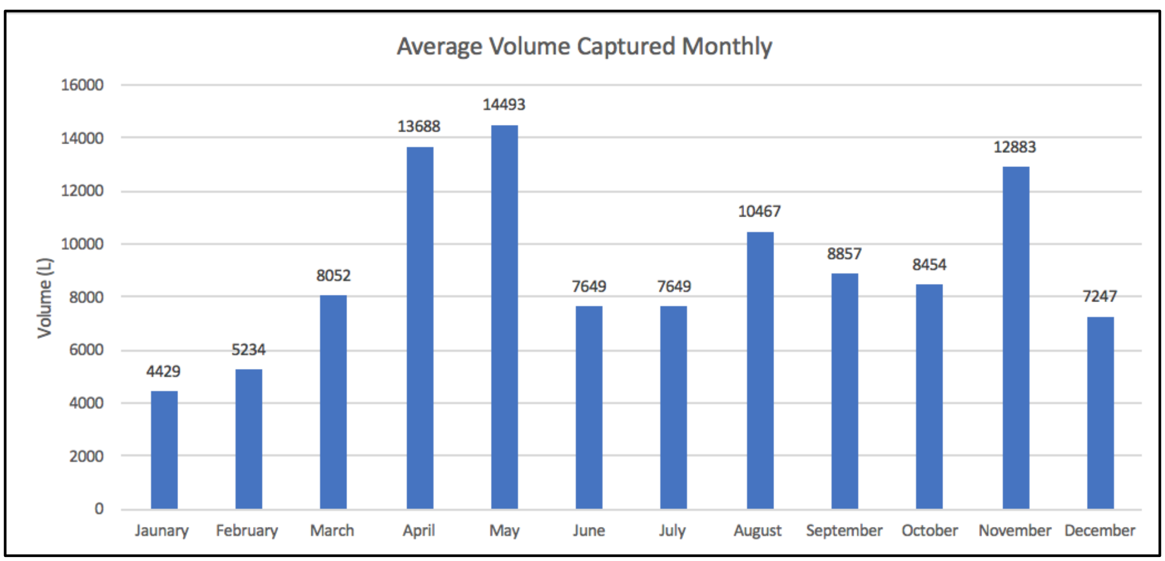


Figure 13: Average Rainfall Captured Monthly

5.0 DESIGN

The final design consists of three main components: first flush system, sand filter, and chlorine treatment. Together, these methods can decrease the percentage of contaminants and improve overall water quality. Contributing factors in this design are: rainfall, contaminants, and consumption, all of which may vary based on the desired location of installation.

5.1 System Overview

The general system overview outlined in figure 14 below. The rainwater moves past an initial screen and into the first flush system where the dirty water moves to a waste tank, and the clean water enters the filtration system. The water flows through the sand filter and into the chlorination tank below.

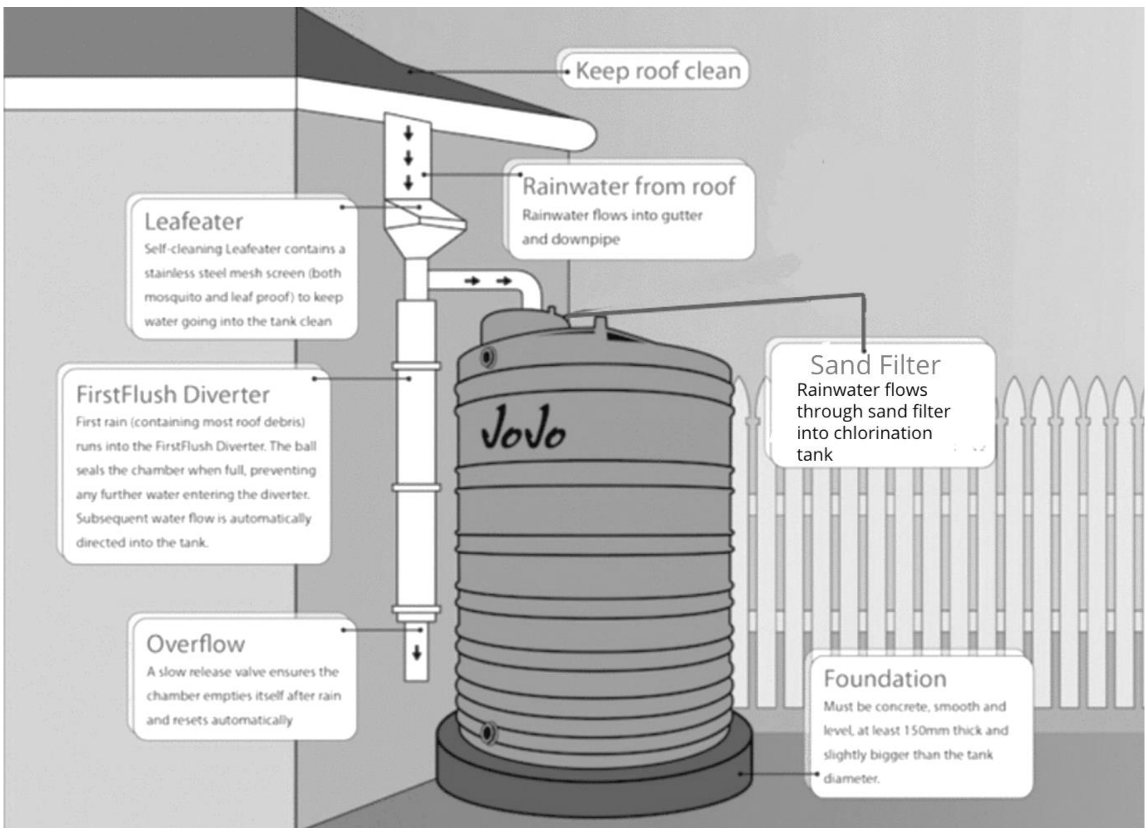


Figure 14: General system components ("Rwh Roofing Equipment", 2018)

5.2 Components

As described in section 5.1, the components of the system complete the suggested assembly pictured below in figure 15. This figure acts as a support of the above CAD drawing and does not include the leaf-diverter component explained below.

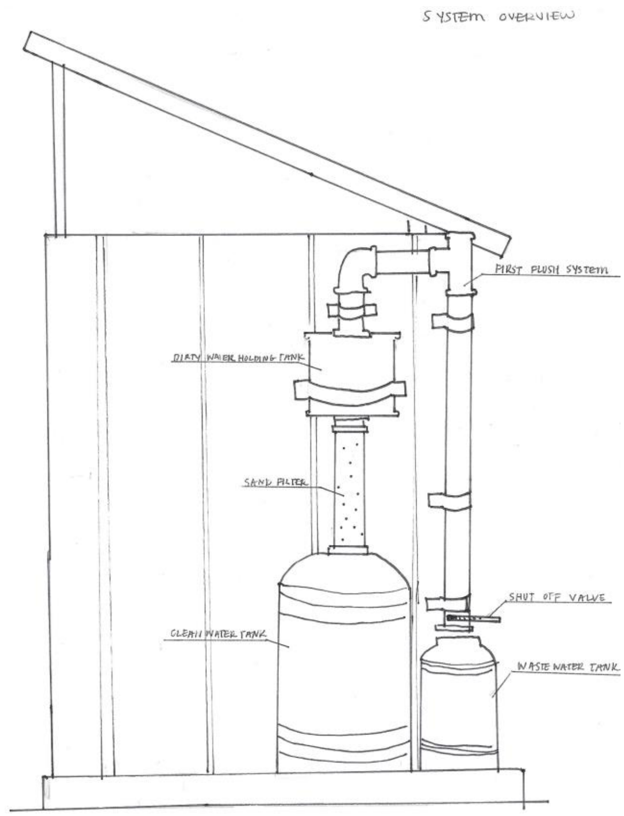


Figure 15: System Components

5.2.1 Leaf Diverter System

When the water leaves the gutter, it will pass through a slanted piece of chicken wire or similar perforated material. This will allow leaves and other large bebris to be removed from the system and automatically deposited onto the adjacent ground. Removing the large debris prior to filtration and diversion will prevent the system from clogging, hence, reducing the frequency of system maintenance.

5.2.2 First Flush System

As discussed in detail in section 3.1.4, the most effective first flush system is a diversion tube arrangement. In this system, the first flush water enters a downspout to a waste tank below. At the bottom of the diversion tube a slider will be in place which can be pulled out to release the diverted water. This method allows for the separation between water first contacting the roof and the filtered water entering main holding tank. The first flush water will be collected in a waste tank. This water can then be used for activities that do not require high-quality water such as watering plants and providing water to animals in TWSB's nutrition program.

5.2.3 Sand Filtration

As shown in Figure 16, the sand filtration process occurs after the first flush system. Pre-filtration, prevents the nutrients that breed insects and bacteria from reaching the tank, and requires less frequent maintenance and cleaning. Additionally, the tank water is prevented from becoming anaerobic and odorous when combined with good tank ventilation (Thomas & Martinson, 2007).

Due to its cleanliness Silica sand is recommended. This sand is mined in the Mbale region and can be found in local markets. Urban, unmined sand could potentially be polluted. A simple mechanical filter consists of a 1 m tall column (a PVC pipe of local dimension available to the area with a 15-20 cm diameter, though other diameters will also suffice) filled with this sand, and with a cloth tucked into the PVC pipe at the bottom. 1 m column heights are recommended in order to minimize contaminants and increase the effective surface area. The column is suggested to be filled with sand of a size distribution ranging from 0.15-0.35 mm and with a uniformity coefficient less than 2. As this coefficient increases in size, the differentiation becomes greater and the quality of the sand becomes less desirable (Clark, 2012). Uniformity entails maximum filter effectiveness; conversely, higher variability in the sand grain size distribution results in the smaller sand particles filling in the spaces between the larger particles, potentially clogging the filter and reducing filter efficiency.

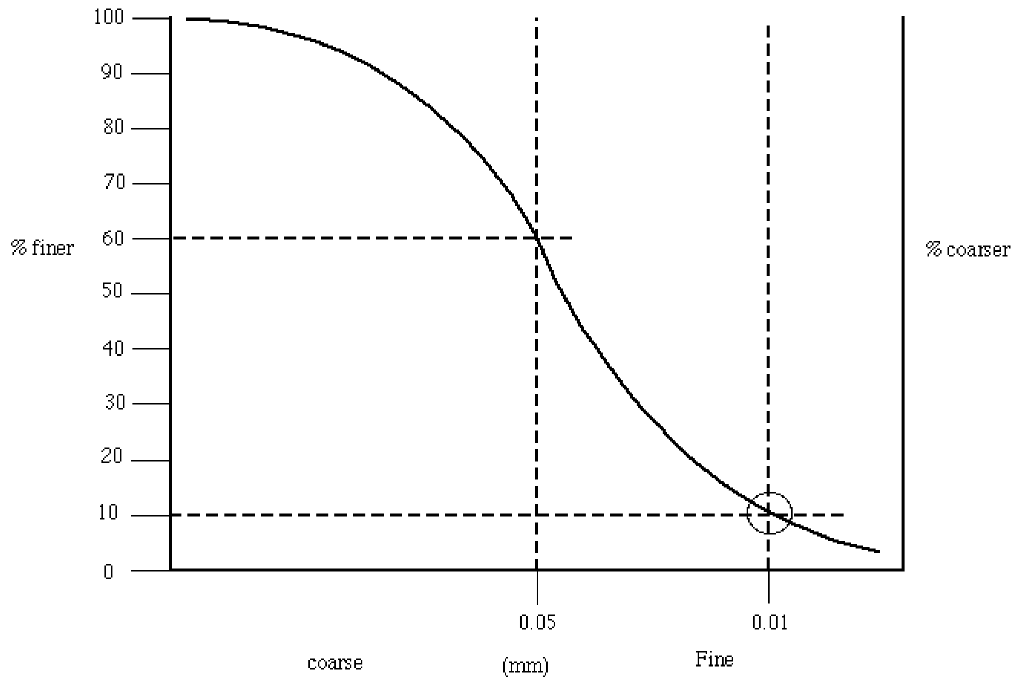


Figure 16: Example grain size distribution graph.

The uniformity coefficient is defined as the ratio of the size at which 60% by weight (upper horizontal dotted line) of a sand sample passes through a sieve, divided by the size at which 10% of the same sample by weight (lower horizontal dotted line) passes through a sieve.

5.2.4 Chlorination

Currently TWSB uses a chlorine ball in their 1000 L tanks for disinfection. The team has been tasked with reviewing this process, its effectiveness, and possible alternatives. It is important to note that for disinfection to be effective, through chlorination or otherwise, the water must be clear and free of any particulates (i.e. properly filtered). Any material present in the water can shield the microorganisms for the disinfection process, and large aggregates of bacteria increases their resistance to the disinfectant (Stewart & Olson, 1992).

Three factors need to be considered for the use of this process: dosage, tank volume, and contact time. Additional factors that affect disinfection are the pH and temperature of the water. The dosage is determined based on water quality and to ensure an adequate amount of residuals is leftover (chlorination breakpoint). A field test needs to be performed to determine accurately the breakeven point, but since this is a highly variable water source this isn't practical. Therefore certain assumptions will be made. Considering the source water and the filtration step beforehand, the breakeven point for this system is likely to be very low.

It is stated that chlorine is applied in solid form, it is likely calcium hypochlorite. Typically the dosage should range within 4-10 mg/L, or 4-10 g if the tank is completely full. The desired residual should be around 0.2 - 1 mg/L at the furthest point in the distribution system. In this case the distribution system is very short so less chlorine is required. Contact time is generally inversely and linearly related to concentration of free chlorine.

Note that 2-log indicates 99% disinfection and the CT value refers to the combination of concentration (dosage) and contact time. Based on this information, and assuming the lowest water temperature is 10 C and the highest pH is 7.5, the desired CT value is 126 mg/L.min^{-1} for a free residual of 0.4 mg/L. This means that for 4 - 10 g addition, a contact time is of 12 - 32 minutes is required, respectively. This was obtained using for a 3-log (99.9%) inactivation of Giarda, one of the more resistant microorganisms that can be present in the water. At higher temperatures and/or lower pH values, the Ct value is smaller.

Chlorine can also be applied in liquid form through sodium hypochlorite or directly as chlorine gas. Although it's quite cheap and highly effective, it is highly inadvisable to use the gas form in this setting. Chlorine gas requires special handling, as it is highly toxic.

Ultraviolet (UV) and solar disinfection were not analyzed since UV is fairly energy intensive and solar is not consistently reliable. The last method for disinfection is boiling the water which is quite effective at killing the majority of microorganisms present, but also requires some form of energy.

5.3 Materials of Construction

All materials in the design can be purchased locally. The first flush piping system can made using the pre-existing PVC pipe size; the system does not rely on one individual pipe size. Sand used in filtration is locally mined along Lake Victoria, and large bags are sold in Kampala, the capital of Uganda. The sand must be clean and pre-washed before installation. This can be accomplished by leaving the cap off the first flush system for approximately half an hour, allowing the sand to rinse. The waste bucket, used in the first flush system, may be of any desired size and material. The shut off slider, at the bottom of the first flush system can be constructed from sheet metal.

5.4 Maintenance Requirements

Each component of the system has specific maintenance requirements and are detailed below. Maintenance frequency should be altered based on need of the Mbale community.

5.4.1 First Flush System

The key consideration for the first flush system is that the diverter needs to be manually emptied before a rainstorm to make room for the new volume of dirty water. Provided that a slow drip alternative is not used to automatically drain the diversion tube. However, the diverter must not be emptied immediately after a rainstorm, because then clean water would be unnecessarily (and wastefully) diverted into it. Rather, ideally after 3 days without rain, or at the time when the user feels the roof is dirty, it should be emptied (Doyle, 2006).

5.4.2 Sand filter

Dirty filters will not allow water to flow efficiently and could themselves contaminate the water. As sand filters become dirty, they increasingly impede the flow of water. When this occurs, the filter needs to be emptied and the sand thoroughly rinsed or replaced before being put back.

5.4.3 Roof

The roof is the largest single source of contamination in the rainwater harvesting system. To mitigate this, the roof itself should be cleaned of any and all dust and debris before the rains begin. To perform this, the roof should be swept off using a broom or rags. This should be performed periodically during a dry spell in the anticipation of coming rains.

5.4.4 Gutter

Maintenance of gutter should also not be ignored. Over time, the gutter will fill with dust and debris, contaminating the water and potentially clogging the run-off. This presents the additional hazard of providing a prime breeding ground for mosquitoes. Gutters must be cleaned out periodically; the frequency should be dictated primarily by the levels of dust blown into the gutter and the presence of overhanging trees. It is recommended that the gutter is cleaned at the same time and in the same way as the roof to maintain consistency.

5.4.5 Water Holding Tank

Assuming that the guidelines outlined in Section 5.2.2 are followed, the tank will rarely require cleaning. Commonly, the tank is the most cleaned component in many rainwater harvesting systems.

However, excessive tank cleaning can destroy the layer of beneficial bacteria that forms a film on the walls and kills pathogenic bacteria. In light of these precautions, tank cleaning should be limited to washing settled matter once a year, and only performed when the sludge level is approaching the outlet connection, or when a discernible odour can be detected from the water (Thomas & Martinson, 2007).

6.0 RECOMMENDATIONS

At this time, the state of contamination of the water in the holding tank is largely unknown. If the water in the holding tank proves to be relatively clean, the methods outlined in this report may not be considered. To determine the contamination levels, water sampling and testing should be conducted. Based on these results a more thorough and precise recommendation may be made. Specifically, if the water is deemed to be clean, the sand filter would become redundant and unnecessary; this is up to the discretion of Walking School bus personnel and may vary with each case. Due to the low cost and high effectiveness, the first flush system should always be installed. The main concern is to remove particles in the water that contain bacteria that would grow in the holding tanks. This system will require time and costs not outlined in this report, and the benefits of this system should be considered by Walking School Bus prior to installation

APPENDIX A: LITERATURE REVIEW

Appendix A: Literature Review:
Water Filtration Techniques for Potential Use in Mbale, Uganda

I: INTRODUCTION

There are a myriad of filtration techniques available for the removal of contaminants and the improvement of water quality. In this paper, we review several of the most common water filtration methods with the aim of facilitating the prioritization of a specific method for use and implementation at the Walking School Bus's field site in Mbale, Uganda, elaborating upon the basic physical/chemical principles, primary applications, and relative advantages and disadvantages pertaining to each. The methods reviewed include: sand, glass medium, ceramic medium, carbon, membrane, reverse osmosis, plant xylem, and fruit waste filtration methods.

Regarding the specific requirements of filtration at our field area, we seek to develop a low cost, technical, simple filtration solution that will supplement the pre-existing chicken wire filter at a rainwater catchment system with a 1000 L holding tank. The filter should be easily capable of being constructed at large scale and maintained by local peoples using local materials, which include (though are not limited to) rebar, aluminum, pvc piping, charcoal, and chlorine balls.

II: REVIEW OF FILTRATION METHODS

Sand Filtration

Sand filtration is a type of gravity filtration which utilizes sand, typically silica sand, to act as the filtration medium. Sand filtration works by using clean, sieved sand which matches a predetermined grain size distribution to physically entrain particulate that passes through it. The sand is arranged within a cylindrical housing in layers based on grain size and particle density.

The filtration itself occurs by trapping particles between the sand grains, removing them from the water. A downside of sand filtration is that it is not effective at removing very small particles such as bacteria or dissolved chemical contaminants such as arsenic. Sand filtration is effective in the removal of small organisms, algae and other physical particles like dirt or pollen. A downside of silica sand is a known carcinogen and therefore precautions must be taken when preparing the sand to protect from the silica dust.

One of the large advantages of sand filtration is the widespread availability of sand. While effectively any available sand can be used, it must be passed through a set of basic sieves to ensure a correct grain size distribution. This cheap, reliable and time tested method may be one of the most effective filtration methods at removing particulate from the water, however, the water must still be treated with a disinfectant such as chlorine before the water can be consumed.

Glass Medium

A relatively new method of gravity filtration has arisen in the recent years which utilizes crushed glass as the medium of filtration. This method is very similar to sand filtration but has proven to be a cheaper and cleaner alternative. This method has been gaining traction in both residential and industrial uses in recent years as its popularity continues to increase.

A huge benefit of the glass medium is that any type of glass can be used. This means it is usually a readily available option for most people. Additionally, this repurposed glass usually comes at little to no cost making it a cheaper alternative to silica sand. As with the sand, a set of sieves must be used to ensure a proper grain size distribution, ensuring proper filtration.

The benefits of using crushed glass as the filtration medium over silica sand have been researched by many individuals including, Elif Soyer from the department of Civil Engineering at Istanbul Technical University and Omer Akgiray from the department of Environmental Engineering at Marmara University. Their findings have been published in a research article "Crushed recycled glass as a filter medium and comparison with silica sand" (Soyer, Akgiray, Eldem & Saatçı, 2010).

One of the main benefits of using crushed glass over silica sand is the effectiveness of backwashing. When silica sand is backwashed, microscopic pores entrain bacteria and algae which promotes the growth of unwanted organisms, resulting in a shortened time of use between backwashes. The advantage of glass is the fractured glass contains smooth sheared surfaces which do not allow bacteria to hide in the pores. This results in a longer time between backwashing, and overall, safer, cleaner water.

As for the effectiveness of the glass medium, it was found that "The crushed glass medium generated both a smaller clean-bed head loss and smaller clogging head losses than those of the sand filter" (Soyer, Akgiray, Eldem & Saatçı, 2010). The medium proved to filter the water equally as well, if not better when compared to the silica sand and it was concluded that "crushed glass shows significant promise as an alternative to silica sand in rapid filtration." (Soyer, Akgiray, Eldem & Saatçı, 2010).

Ceramic Medium

Ceramic filters remove contaminants via physical filtration and chemical disinfection. Water seeps through microscopic pores where organic and inorganic particulates too large to pass through accumulate on the ceramic surface. The small pore size membrane has been shown to physically filter E. coli and turbidity by over 99.99% and 94%, respectively. (National Water Quality Reference Laboratory Test Results). Ceramic filters are able to remove bacteria including vibrio-cholera, giardia, streptococcus, total coliforms, and cryptosporidium. Many ceramic filters also incorporate a colloidal silver compound to act as a bacteriostatic agent to repel bacterial growth in and on the filter (SPROUTS of Water, 2015).

Ceramic filtration is most appropriate in areas where there is a capacity for quality ceramic filter production. These filters may be produced locally at ceramics facilities using local clay material. Along with reducing bacteria in the water, additional advantages of ceramic filtration include simplicity, acceptability and a low one-time cost. (Centers for Disease Control and Prevention, 2012)

One drawback of ceramic filtration is its low production flow rate of 1-3 liters per hour for non-turbid waters. In turbid water, this number significantly decreases. Additional disadvantages for ceramic filter include an ineffectiveness against viruses and variable quality control. There is a significant variety of filter quality depending on local production and material. Filters must also be cleaned regularly, especially after filtering turbid water. (CDC, 2012). Proper cleaning, maintenance, and monitoring are essential for this filter to provide potable water.

Carbon Filtration

A typical carbon filter has numerous pores that exhibit a high degree of porosity and an extended surface area. Carbon becomes activated through a carbonization step when feedstock such as wood, bones, or nut shells are heated to several hundred degrees Celsius under restricted oxygen conditions. Commercial charcoal filters are subsequently “activated” in an additional step that requires processing not usually available in rural areas (Kearns, 2012).

During water filtration through activated carbon, contaminants bind to the char surface or become trapped in the small pores of the activated carbon. This method is effective in removing certain organics (such as unwanted taste and odors, micropollutants), chlorine, fluorine or radon from drinking water or wastewater. However, it is not effective for microbial contaminants, metals, nitrates and other inorganic contaminants (Mazille, 2011).

The main advantage of using carbon filters is that activated carbon can be produced relatively easily with a wide variety of locally sourced materials. In addition, operating costs are usually limited to filter replacement (Mazille, 2011).

A significant disadvantage of rural-produced char filters is that they may contain substantial proportions of incompletely carbonized compounds (especially if the char is created at a temperature under 600 °C). In addition, the high absorption potential of activated carbon can lead to the binding of non-problematic dissolved organic matter in addition to the targeted hazardous contaminants (Kearns, 2012). This organic matter can clog the char pores and make it less effective resulting in an increase of filter replacement.

An important note: often to mitigate the frequent occurrence of clogged char pores an additional filtration system is installed before the water encounters the char (Mazille, 2011). Sand filters and gravel filtration systems are added to remove a large portion of the organic matter (Kearns, 2012).

Membrane

Membrane filtration refers to the use of any thin layer of semi-permeable material that selectively allows particles of certain sizes or properties through (Figure 1). Membranes can be used in water treatment to remove particulates, organic matter, various chemicals, bacteria and even viruses. The four major types of membrane filtration, defined by their pore size, are microfiltration, ultrafiltration, nanofiltration and reverse osmosis (Figure 2). Fouling is the main challenge to efficiency using any membrane technology. These membranes are generally synthetically manufactured and are relatively expensive so replacement is therefore an issue. Furthermore certain methods like backwashing could be used to recover the filter but that introduces an element of maintenance that might create issues when used by non-technical individuals. Another challenge is damage to the membranes during installation and operation that significantly lower water quality; however significant research has been done to produce self-healing membranes. Overall this is an emerging technology that is relatively costly and could potentially be complicated, however it is a very effective treatment method that removes the majority of contaminants in one step. A potential design option is combining a membrane with another treatment technology upstream that removes larger particles. This way the membrane only removes the very small particles and microorganisms, thereby reducing fouling and increasing its lifespan.

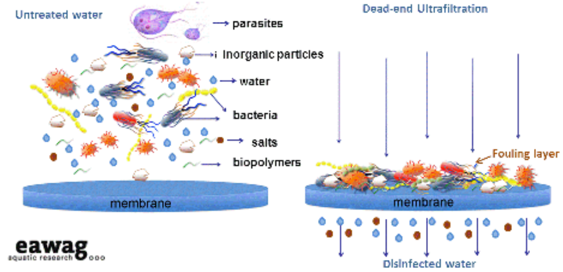


Figure 1: Overview of membrane filtration mechanism

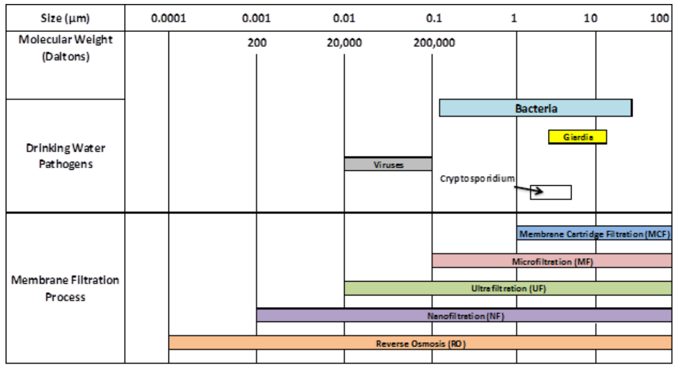


Figure 2: Filtration method removal efficiency based on size and molecular weight.

Reverse Osmosis

RO is a membrane treatment process used primarily to separate dissolved solutes from water via a semi-permeable membrane. They are a subclass of more general membrane treatment processes, which also include microfiltration (MF), ultrafiltration (UF), and nanofiltration (NF) (Crittenden et. al., 2012). While household reverse osmosis drinking water purification systems are ubiquitous around the world, industrial-scale systems are also common. Reverse osmosis is also commonly employed for desalination purposes, owing from its ability to remove salt from water, with over 1100 reverse osmosis plants operating in the US by 2008.

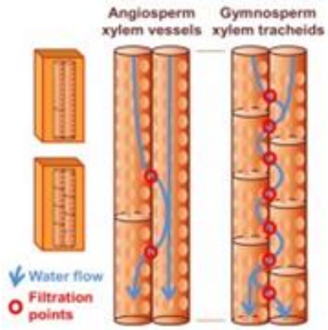
Mechanistically, reverse osmosis occurs via inducing a pressure gradient (the creation of which requires electricity), which drives the flow in the reverse direction of normal osmosis, such that particles move from a solution of of low concentration to that of high concentration. Typically, this is accomplished via use of a semi-permeable membrane, which removes ions and molecules, inorganic particles (antinomy, arsenic, barium, fluoride, nitrate, nitrite, selenium, and radionuclides), bacteria, salts, biopolymers, and even pesticides (Baier et. al, 1987). Semi-permeable membranes are defined as materials that are permeable to some components in the feed stream and permeable to others, with overall thicknesses of less than 1 mm.

Reverse osmosis holds an advantage over carbon systems, as they remove salt, minerals, metals, and chloride that carbon fails to remove, and reverse osmosis treatment systems are valued for their ability to remove virtually all contaminants in water, including many synthetic organic chemicals. However, they suffer from relatively low filtration rates. They also require electricity in order to create the pressure gradient necessary to drive the reverse osmosis process, rendering them ineffective in disaster areas and in humanitarian situations when electricity may be intermittent or even unavailable. While reverse osmosis can (and is recommended by the EPA) be used for specific contaminant removal, it is less common because alternative technologies are frequently more cost effective (a home reverse osmosis system costs upwards of $100US (EPA, 2015)), and the disposal of the resultant contaminant stream may present challenges (Crittenden et. al., 2012).

Plant Xylem

Plant xylem tissue from the sapwood of coniferous trees has been shown to be an effective water filtration mechanism (Figure 3), with a size cutoff of about 100 nm and a bacterial rejection rate of 99.9%. The pore sizes however are not small enough to filter viruses. These filters can be created by simply cutting and peeling sections from a branch (~1 cm diameter in experiments). This piece is then inserted into the end of a tube, sealed with epoxy, and the entire system flushed with water. One challenge is that the filter needs to remain damp, as dry branches may introduce cracks that allow contaminated water to flow through. Another challenge is the use of the right type of plant. As shown in Figure 4 the use of angiosperm (flowering trees) cells allows water to flow through the vessels without filtration through the cells. Finally this filtration method is limited to a few liters per day so it is a bit slow (4 L/d at 5 psi). Flowrate increases with increased pressure difference across the filter, however a rupture analysis has not been conducted to test the durability of the filter. These filters, like many nanofiltration methods, are susceptible to clogging quite rapidly, however due to the ease of construction and low cost and wide availability of the materials, this isn't an issue as the filters could be easily replaced. The setup process is also quite simple allowing people without a technical background to assemble the filters. Overall this method is cheap and effective for point-of-use systems provided that the right type of plant is available in the region.

Figure 3: Instructions on filter creation.

a) 

b) 

Figure 4: a) Water flow in angiosperm vs gymnosperm xylem cells and b) photo of branch used (gymnosperm).

Chemical Oxidation-Reduction Filtration

Metallic alloys (such as cooper and zinc) can be used, when placed, in electrolytic cells, to run oxidation-reduction (redox) reactions that convert ionic (charged) contaminants (either organic or inorganic) into physiologically inert forms. Whereas organic compounds are converted into harmless forms (eg. toxic organic compounds can be oxidized into carbon dioxide), inorganic metal species are oxidized into insoluble forms and removed via precipitation (eg. iron, manganese, hydrogen sulfide, etc.). These methods can be subdivided into three main sub-methods: a) conventional oxidation processes, b) oxidation processes carried out at elevated temperature and/or pressures, and c) advanced oxidation processes (Crittenden et. al., 2012). Conventional oxidation processes employ oxidants such as (predominantly) chlorine, ozone, chlorine dioxide, potassium permanganate, or hydrogen peroxide, which are usually added at either the beginning (peroxidation) or end (disinfection) of the water treatment process. The latter two sub-methods, owing from their complexity, are likely unfeasible for our study purposes.

Conceptually, these methods utilize the potential difference between ionized copper and zinc to drive electron flow from zinc to copper, facilitating the removal of charged particles such as chlorine, hydrogen sulfide, iron, and other metals. For this reason, their main uses include: taste and odor control (eg. naturally occurring organic compounds produced by algal blooms and bacteria), hydrogen sulfide removal (‘rotten egg’ odor), colour removal (eg. from degradation of dead plant matter), iron and manganese removal, and disinfection (Crittenden et. al., 2012). However, redox filtration methods are ineffective at removing bacteria and organic chemicals, as they are not necessarily charged particles susceptible to the reaction. For this reason, they are not typically employed for household filtration, unless combined with carbon-based systems, which account for this deficiency.

Cloth and Paper

Cloth and paper are simple and cost effective filtration methods. Both can be composed of a variety of materials and thicknesses to achieve desired effectiveness. Materials must be changed often in order to minimize waste particle build up. For the purposes of reusable filtration techniques, paper should not be considered due to its one-time usability. Cloth filters are effective in areas where other materials are not readily available (Hug et. al. 2010).

Fruit waste

The use of various fruit waste, such as banana, kiwi, and tangerine peels can remove toxic metals from wastewater. Peels must be washed, dried and turned to a powder to eliminate excess NaOH. These powders then can be used to treat wastewater. This is not a filtration technique, but rather a purification technique to be noted in this review. The removal of these metals is enacted by a process called biosorption. Smaller particle sizes result in higher biosorption effect, and each fruit cortex removes different types of metals. (Khairia 2016). These methods are cost effective and readily available. However, they require the drying of fruit and lengthy preparation time.

APPENDIX B: References

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