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## TANK SIZING AND OPTIMIZING LOOP PLACEMENT IN A BRANCHED WATER DISTRIBUTION SYSTEM

Colin G. McCorkle  
*Michigan Technological University*

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TANK SIZING AND OPTIMIZING LOOP PLACEMENT IN A BRANCHED WATER  
DISTRIBUTION SYSTEM

By

Colin G. McCorkle

A REPORT

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

In Environmental Engineering

MICHIGAN TECHNOLOGICAL UNIVERSITY

2014

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

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## Abstract

More than eighteen percent of the world's population lives without reliable access to clean water, forced to walk long distances to get small amounts of contaminated surface water. Carrying heavy loads of water long distances and ingesting contaminated water can lead to long-term health problems and even death. These problems affect the most vulnerable populations, women, children, and the elderly, more than anyone else. Water access is one of the most pressing issues in development today.

Boajibu, a small village in Sierra Leone, where the author served in Peace Corps for two years, lacks access to clean water. Construction of a water distribution system was halted when a civil war broke out in 1992 and has not been continued since. The community currently relies on hand-dug and borehole wells that can become dirty during the dry season, which forces people to drink contaminated water or to travel a far distance to collect clean water. This report is intended to provide a design the system as it was meant to be built.

The water system design was completed based on the taps present, interviews with local community leaders, local surveying, and points taken with a GPS. The design is a gravity-fed branched water system, supplied by a natural spring on a hill adjacent to Boajibu.

The system's source is a natural spring on a hill above Boajibu, but the flow rate of the spring is unknown. There has to be enough flow from the spring over a 24-hour period to meet the demands of the users on a daily basis, or what is called providing continuous flow. If the spring has less than this amount of flow, the system must provide intermittent flow, flow that is restricted to a few hours a day. A minimum flow rate of 2.1 liters per second was found to be necessary to provide continuous flow to the users of Boajibu. If this flow is not met, intermittent flow can be provided to the users.

In order to aid the construction of a distribution system in the absence of someone with formal engineering training, a table was created detailing water storage tank sizing based on possible source flow rates. A builder can interpolate using the source flow rate found to get the tank size from the table. However, any flow rate below 2.1 liters per second cannot be used in the table. In this case, the builder should size the tank such that it can take in the water that will be supplied overnight, as all the water will be drained during the day because the users will demand more than the spring can supply through the night.

In the developing world, there is often a problem collecting enough money to fund large infrastructure projects, such as a water distribution system. Often there is only enough money to add only one or two loops to a water distribution system. It is helpful to know where these one or two loops can be most effectively placed in the system. Various possible loops were designated for the Boajibu water distribution system and the Adaptive Greedy Heuristic Loop Addition Selection Algorithm (AGHLASA) was used to rank the effectiveness of the possible loops to construct. Loop 1 which was furthest upstream was selected because it benefitted the most people for the least cost. While loops which were further downstream were found to be less effective because they would benefit fewer people.

Further studies should be conducted on the water use habits of the people of Boajibu to more accurately predict the demands that will be placed on the system. Further population surveying should also be conducted to predict population change over time so that the appropriate capacity can be built into the system to accommodate future growth. The flow at the spring should be measured using a V-notch weir and the system adjusted accordingly.

Future studies can be completed adjusting the loop ranking method so that two users who may be using the water system for different lengths of time are not counted the same and vulnerable users are weighted more heavily than more robust users.

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# 1.0 Introduction

## 1.1 Problem Statement

### 1.1A Project Introduction

In 2010, the United Nations declared access to clean water as a human right (UN 2010). Clean water is one of the most important factors in improving quality of life for people in developing nations and can be easily provided given the developed world's wealth of resources. The village of Boajibu, in Sierra Leone, lacks access to clean water and their quality of life suffers accordingly. The people of Boajibu rely on draw wells and a few borehole wells, which can become contaminated during the dry season. This can cause serious problems as ingesting water-borne pathogens leads to diarrhea and other illnesses. Women, children, and the elderly are especially at risk to dying from these diseases. There was an attempt to improve the village's water access by constructing a gravity-fed water distribution system but construction was halted when a civil war broke out. This report is intended to aid in the continued construction of that system by providing the design for the gravity-fed water system, which was lost during the war.

### 1.1B Water Access and Poverty

Clean water is fundamental to human life and health. According to the World Health Organization, lack of access to water supply and sanitation accounts for 1.73 million deaths each year, most of these deaths being children (Howard 2003). In 2000, 1,069 million people did not have consistent access to clean water; that's 18% of the world's population (Howard 2003). Unsurprisingly, the people of the poorest countries of the world are most affected by this issue. Having to pay for water or walk to collect water creates a cycle of poverty, as it wastes the time, energy, and resources of a people already deficient in all three (Howard 2003). The governments of these countries are often ill-equipped to provide good water access for their citizens, and the foreign aid provided cannot solve the problem, due to corruption and a lack of effective project management and planning.

### 1.1C Health Effects of Lack of Good Water Access

Getting water from a tap is a luxury many in the world can't afford. In developing countries, many people get their water from a lake, river, or swamp. In Sierra Leone, this can be dangerous especially in the dry season when the water levels drop or the water dries up all together. Having at least a basic level of access to water, be it a pump or tap, is enough to ensure safe hygiene and consumption. While access to water is a help to the community as a whole, it is particularly helpful to the more vulnerable parts of the community, women, children, and the elderly. Women and children are often the ones tasked with carrying water, which makes them vulnerable to malnutrition and can cause scoliosis (Figure 1). Carrying water can also cause issues with the growth of a fetus during pregnancy (Dufant 1988). Collecting water from a far distance may not leave enough



*Figure 1 - Woman carrying water, showing the strain it puts on her neck and back (Otero 2011)*

water for proper hygiene or the water may be dirty already, leading to a fecal-oral transmission of disease (Howard 2003). Allowing people to have just a basic level of water access can save countless lives in the future.

### **1.1D Boajibu's Current Water Access**

The community of Boajibu is a village of 7,000 people in southeastern Sierra Leone. Its economy is primarily based on mining and agriculture. It is rich in diamonds and gold and has plenty of arable land surrounding it. Boajibu lacks basic amenities like reliable, clean water access because it is in a very rural area. The community is currently relying on hand-dug and borehole wells, but the water can become dirty in the dry season. Community members can become ill from drinking this contaminated water, which is especially dangerous for women, children, and the elderly. A gravity-fed water distribution system could provide safe drinking water year round and would greatly improve the health of the community members, especially pregnant women, children, and the elderly (Howard 2003). Boajibu began the construction of a gravity-flow water system before the outbreak of the civil war in 1991. The taps were constructed and some of the piping was laid, but the rest of the system was unfinished before work had to be abandoned because of the violence (Figure 2). The system in this report was designed based off of that unfinished system. To design the system, interviews with community leaders, the layout of the water taps, and local surveying was used.



*Figure 2 - Tap in Boajibu, the water system in Boajibu remains unfinished to this day - Picture by Author*

### **1.1E Objective of this Report**

The objective of this report is to provide a design for a water distribution system in the village of Boajibu. Three questions about that design will be addressed. First, the report will determine the source flow rate that will allow the system to provide continuous flow. Second, the report will create a table by which a builder could size a water storage tank based on the measured flow rate of the source. Third, it will assess where loop can be added at its most effective point in regards to the number of people it benefits

### **1.1F Explanation of Continuous vs. Intermittent Flow**

The system was designed but the flow rate of the natural spring that will be used to supply the town is unknown. The flow rate of the spring needs to supply enough water over a 24-hour period to meet the users' daily needs. If the spring cannot do this, the system will have to provide intermittent flow, or flow that is less than what the users are demanding and is provided only periodically throughout the day. The minimum flow rate which will provide continuous flow, meet all the user's demands, will have to be specified so that the builder can know which situation they are dealing with.

### **1.1G Explanation of Tank Sizing**

If the spring's flow rate is not able to directly meet the water demands of the people

in Boajibu, a water storage tank should be constructed to store water overnight. However, there are not many people in Sierra Leone with the knowledge to design such a tank. In order to assist a builder without the engineering knowledge to size such a tank, a table was created detailing the different sizes of tanks to build based on possible source flow rates. Thus, when the system is built, they will not need a consultant to finish it.

### ***1.1H Ranking of Loops***

In the developed world, loops are placed throughout the system to maximize the redundancy in the system. If there is a rupture in one of the pipes or a need for maintenance, there is always another path through which the water can flow. In the developing world, there is only enough money to place one or two loops in the system. The engineer must decide where said loops should be placed to be most effective. A simple algorithm using people benefitted versus the cost of the loop will be used to rank the effectiveness of loop placement in the water distribution system in Boajibu (Abbott 2014).

## 1.2 Geography & Climate



Figure 3 - Map of Sierra Leone - (Embassy 2014)

### 1.2A General Geography

Sierra Leone is a small country in West Africa with a population of 5.7 million people (CIA 2014). It has four distinct regions: Coastal mangroves, wooded hill areas, an upland plateau, and the mountains in the east. It is bordered on the south by Liberia and on the north and east by Guinea (Figure 3).

### 1.2B Local Geography

Boajibu, the site where the study takes place, is a wooded and hilly area in Kenema District (Figure 4). It is bordered on two sides by the Sewa River, which is the second largest river in Sierra Leone. It sits below Boaji Hill and has many swamps in the area. Boajibu has a population of 7,000 people. The town center has a concentrated population density, while houses are spread out farther away from the center. Boajibu is surrounded by arable land and swamps where its residents practice agriculture. About seven miles east of Boajibu is a Hydro-Electric dam that provides power to Bo and Kenema, the second and third largest cities in Sierra Leone.



## **1.2C Climate**

Sierra Leone has a tropical climate that is moderated by its proximity to the Atlantic Ocean. Two seasons are present in Sierra Leone: the rainy season (from June to September) and the dry season (October to April). The Harmattan is a subset of the dry season that contains much colder weather because of the winds blowing off of the Sahara Desert to the North. Boajibu's water access issues are most acute during the dry season, as the water table is lowered allowing the water to become more dirty. The average temperature can vary from 60°F to 96°F, with the hotter weather in the dry season (except for the Harmattan) and the colder in the rainy season. The annual precipitation is 101 inches with most coming during the rainy season (Weatherbase 2014).



*Figure 4 – Landscape of Boajibu showing the local geography of the area – photo by Author*

## **1.3 Social & Economic Background**

### **1.3A Countrywide Social and Economic Background**

Sierra Leone is one of the poorest nations in the world, with 70% of its population below the poverty line (CIA 2014). Sierra Leone's GDP is growing at a rate of 13.3%, which is second in the world (CIA 2014). However, Sierra Leone is 208<sup>th</sup> in the world in GDP per capita. The economy relies primarily on agriculture and mining. More than 80% of the population in Sierra Leone is employed in agriculture, mainly subsistence farming with rice being the staple crop (Konig 2008). Most rural Sierra Leoneans live off what is grown through subsistence farming and make their money by providing local services, such as providing transportation, construction, and selling goods or food. Cocoa and coffee are also grown as cash crops. Sierra Leone is rich in diamonds, gold, iron ore, rutile, and bauxite, and mining is becoming one of its biggest industries. Some mining is done at a community or small business level, but the bulk of the mining in the country is done by large multi-national companies. Mining continues to play a larger part in the economy as more companies move in to take advantage of the mineral-rich country.

### 1.3B Local Social and Economic Background

Simbaru Chiefdom, of which Boajibu is the capital, is heavily involved in diamond and gold mining (Figure 6). Most of the mining done in the area is small in scale, either being done by a community or by a small business. Boajibu's other main industry is farming with rice being the staple crop (Figure 5). Mining does not significantly affect water use, but a large amount of water is used to grow crops in the dry season. Most people in Boajibu practice subsistence farming and have another job, such as working for a miner, providing transportation, construction, or selling goods, to make money. Before the war, electricity was present in Boajibu due to the proximity of a hydroelectric dam, but the power lines have not been reconstructed since the rebels destroyed them.



Figure 5 - Farmer drying rice outside Boajibu, shows agriculture as an economic activity - Photo approved for use by Bryan Gastonguay



Figure 6 - Local diamond mining in Boajibu, shows mining as an economic activity - Photo approved for use by Kat Buxton

### 1.3C Mende Culture

Boajibu is predominantly Mende by tribe. The Mende people originally came out of an area east of Sierra Leone. They were a war-like people who drove out the original inhabitants of the south Sierra Leone and still reside there (Fage and Oliver 1975). They speak a local tribal language with the same name as the tribe, Mende. The Mende tribe is the second largest tribe in Sierra Leone. The Temne tribe, who occupy the north of the country, is the largest. Politically, the Mende people traditionally support the Sierra Leone People's Party (SLPP) party while the Temnes support the All People's Congress (APC) party.

The Mende people are mostly Muslim by religion with the rest being Christian. This has an effect on water use because of the ablutions, ritual washing of the hands and feet, necessary to the religion before each prayer, which occurs four times a day. The Mendes also use a lot of water to launder their clothing, believing that washing it more than once is necessary to get it clean.

The Mende people mainly practice subsistence farming with rice being the staple crop. They grow cassava, yams, sesame, potatoes, and corn as supplementary crops. Palm nuts are harvested and made into palm oil for cooking. Domestic animals are kept for

cooking, including chickens, goats, and sheep. To make money, they sell the excess food, work for local mining companies, or provide transportation with either a car or motorcycle to fellow villagers.

### **1.3D History of the War**

Sierra Leone is still recovering from a decade-long, brutal civil war. The war began in 1991 when rebels from the Liberian civil war entered the country in search of diamonds to help fund their struggle in Liberia. The Sierra Leonean people then spent 10 years attempting to drive those rebels out of their country and were only able to end the conflict by negotiating a peace in 2002. During this time, there were multiple military governments established by coups, which led to even more confusion and prolonged the war (Sesay 2014).

The main issue at stake during the civil war were the diamond fields in the center and east of the country. At the start of the civil war, the Liberian rebels entered the country to get control of those fields and fund their own struggle in Liberia. Some members of the Sierra Leonean Army then used those fields for their own gain when the government was not supporting them with a salary, leading to a back and forth struggle over the diamond fields with both sides committing atrocities against the local populace to keep them in check (Watch 1999). Looting was also very commonplace as a means to fund the conflict. Tensions between tribes, especially the Mendes and Temnes, was only worsened by the arming of local militias, also known as “kamajors”. The kamajors often extended their defense of local areas to persecution of anyone not native to the area. This tension has lessened, but is still present in today’s politics, which features a Mende political party against a Temne political party.

This war has come to shape modern day policy and society. Many people lost almost everything they had and tend to think in the short-term, not saving or investing. The war’s atrocities also worsened tribal differences dividing the country into two political parties. This has led to mistrust in the government, as one group is in power over the other, only made worse by the corruption endemic in government officials. The country has yet to fully recover from the war and has taken yet another step backwards with the recent Ebola outbreak.



## 1.4 Water Access

### 1.4A Current Water Access

After the war, Sierra Leone received large amounts of aid and development through governments and NGOs. Foremost among these developments, was the installation of wells in a large number of communities (Figure 7). Only the most remote villages in Sierra Leone are without at least one well. However, there is still a problem with water access in the dry season, when many of the wells become dirty.



*Figure 7 – Well in Kamakwie, showing current water access for Sierra Leoneans- Photo approved for use by Michael Gibbs*

### 1.4B Current Water Systems

While there are many wells in Sierra Leonean villages, there are almost no running water systems to public taps or to households. Even the major cities of Sierra Leone have no municipal water distribution systems. A few systems were installed in the 1970s but have since fallen into disrepair, due to a lack of maintenance and engineering knowledge. The water division of the Sierra Leonean government, SALWACO, constructs and maintains pumps in the rural areas, but does not have the resources to install a municipal water system in any major city. SALWACO has claimed that they will be building a new system for each of the major cities with money from a large grant, but nothing has been done as of yet.

### 1.4C Boajibu's Situation

A variety of community analysis of techniques were used within the community of Boajibu to determine what the priorities for development were. The PACA tools, which are community analysis tools taught during Peace Corps training, were especially helpful to prioritize community needs. Community mapping is one of those tools. With community mapping, the community members are asked to draw their village and rank the most important parts. The ranking is the most obvious help to prioritizing, but what the community members put on the map can also be important. Using this form of community analysis and others, it was determined that water access was the first priority in Boajibu.

Boajibu had begun construction of a gravity-flow water system just before the war (it is assumed in the late 80s or early 90s), but had to halt construction when the war began in 1991. All the taps were built and the reservoir and spring were sited, but none of the pipes were laid and nothing else was built. No one from the village has been able to produce plans or say anything about who was doing the work. GOAL, an Irish NGO, began work on the system again, but halted work without explanation or warning. GOAL does work on water access in the area around Boajibu, repairing and installing wells. They have yet to come back to Boajibu again. It is the author's intention to provide GOAL, the community leaders, and Peace Corps with a copy of this report in hopes that the water system will be constructed in the future.

## 1.5 System Design

### 1.5A How Systems are Designed in the Developed World

When water supply systems are created in the developed world, engineers want to have a lot of connectivity to make a system as robust as possible. Robustness is defined as, “the optimal connectivity of a network to reduce the probability of hydraulic failures or to reduce the consequences of component failures” (Yazdani 2012). To do this, they design their systems in loops, which would leave at least two pipes at every junction. This is called having redundancy in the system, and it increases the system's reliability. If one pipe has a rupture, the water can pass around through the other pipe (Figure 8). While the pipe is repaired, the people at the junction will continue to receive water. To the end user, the system has never failed at all and continues to be reliable.

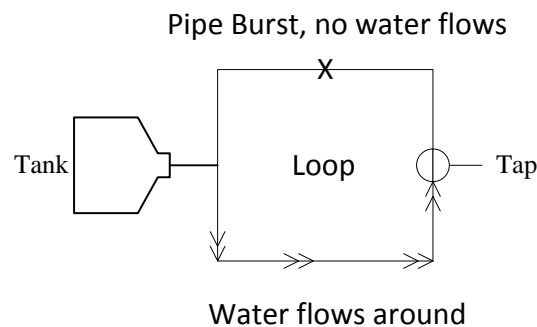


Figure 8 - Diagram of how loops provide redundancy - Drawn by Author

### 1.5B How Systems are Designed in the Developing World

In the developing world, branched systems are used to save money. This type of system still gets the water to the end users, but it has none of the redundancy of the systems of the developed world. However, there is sometimes enough money in the budget for the construction of one or two loops. Currently, there is no established method for finding the most effective place for a loop within a system.

### **1.5.1 Field Data Collection**

#### **1.5.1A Taking Points and Interviewing Local Leaders**

To design a water system for Boajibu, data needed to be collected. Data collection began with interviews with local community leaders and community members on local water access and the history of development in Boajibu. The village was then surveyed to assess where taps, junctions, the spring box and the reservoir would be placed. GPS points were taken at all these points so that elevation and location would be known. The distances between points were measured using GPS software and the information was entered into EPANET 2.0.

#### **1.5.1B Assumptions Made**

Houses within one hundred meters of any tap were designated as draw points for those houses. If a house was within one hundred meters of two taps, it was assigned to the closest tap. Each house was given a designation and the number of men, women, and children in each house was noted. A demand for each person using the tap was estimated using the WHO guidelines for improved access, fifty liters per capita per day (Howard 2003). Churches, mosques, and schools were estimated differently depending on their use patterns. Population growth was not accounted for at this time as it was not determined if Boajibu's population was growing or shrinking. The construction of a system may cause an influx of people due to the easy access to clean water that system would provide, but this was not provided for either. The demands based on the current population were totaled and entered into the EPANET 2.0 software.

### **1.5.2 Creating a Continuous Service Model**

#### **1.5.2A Explanation of EPANET 2.0 and Its Capabilities**

EPANET 2.0 software is a freely available software created by the EPA that models water distribution systems. It takes inputs, such as, elevations of system components, junction demands, pipe lengths, tank sizes, friction factors, and many other variables and models the results over a specified length of time (EPA 2008).

#### **1.5.2B Explanation of Pipe Sizing**

All pipe sizes were found using the Darcy-Weisbach equation. The demands, elevations, and distances were put into an Excel file labeled "Pipe Sizing". The demands were found using the WHO guideline assuming an eight-hour day. The friction factors were estimated and checked using the Moody diagram till the correct friction factor was found. The next largest available diameter was then chosen for that pipe. An available head of thirty two feet was assumed to be the minimum pressure needed at each tap (Mihelcic, et al., 2009). Any time the head dropped below thirty two feet, the pipes upstream were increased in diameter till it was above thirty two feet of head again. When all the pipes were sized correctly, they were entered into the EPANET 2.0 software and a simulation was run to check that no pressures below our thirty two feet of head (13.87 psi) resulted (Figure 10).



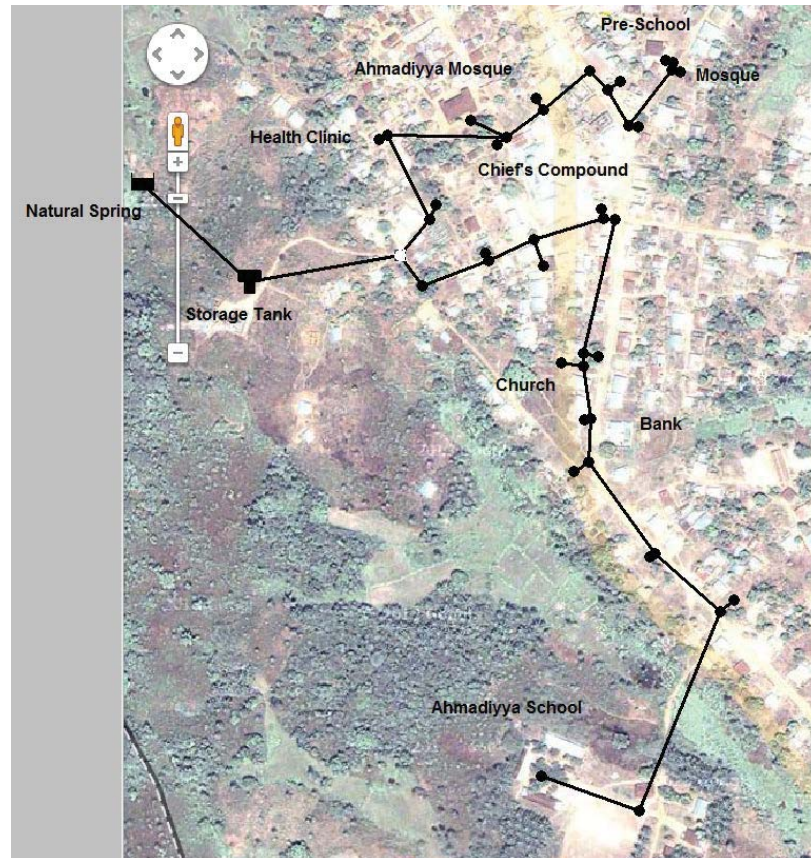


Figure 9 - System design by author superimposed on aerial photo (Google Earth)

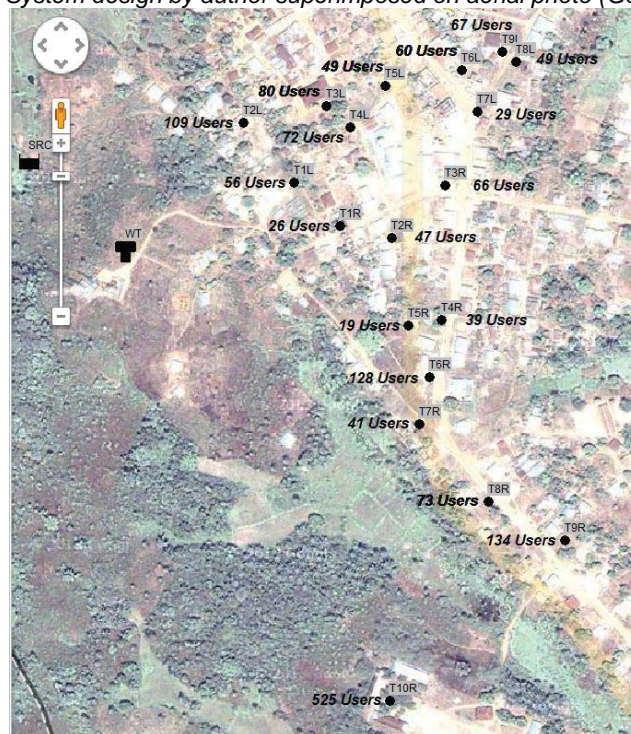


Figure 10 – Water taps and corresponding population superimposed on aerial photo (Google Earth)

## **2.0 Minimum Source Flow Rate for Continuous Flow**

### **2.0A Providing Continuous Flow**

Continuous flow can only be provided if the total flow out of the spring over a 24-hour period is equal to the village's demands over 24 hours. If it cannot, the system will have to provide intermittent flow, meaning flow will be restricted. This is achieved by only allowing water collection for a few hours a day. This process of providing a supply of water and cutting it off over and over again can cause contamination in the system (Vairavamoorthy 2004).

### **2.0B Intermittent Flow Problems**

Intermittent flow can cause many issues beyond not fulfilling the users' water demands. Having to wait until the water is turned on can be inconvenient for the users responsible for fetching water, often the women. The women would then have less time to cook proper food, care for and educate the children, receive an education, and other productive activities. Intermittent flow also creates inequity within the system, as the users upstream will take the majority of the flow all at once leaving less flow for the users downstream or the first people to the tap take the bulk of the water.

### **2.0C Health Concerns with Intermittent Flow**

The biggest issue with intermittent flow is the health concerns it can cause. When the water system is off, it allows a biofilm and bacteria to grow in the stagnant water in the low points of the system. When the water system is then switched back on, this biofilm and bacteria is flushed out of the system. The users often collect this flush water, which is full of contaminants that lead to illnesses such as diarrhea. Valves can be added before each tap that when opened will allow this film to flush out of the system before the users come and collect. Another issue is the low level of pressures that happen while all the users come to collect at once. Studies have shown that at low levels of pressure (<17 psi) pipes have high concentrations of bacteria, which could again lead to illness (Kumpel and Nelson 2014). Intermittent flow would not be ideal for the village as it would not result in a marked improvement in health versus what is already present in the village. If intermittent flow is necessary, the system should be flushed for fifteen minutes before the users start to collect water to clear out the biofilm that has accumulated (Geldreich 1996). If funds allowed and a reliable individual can be trained, the system can be periodically disinfected to deal with the issue of contamination in the system.

## **2.1 Methods**

### **2.1.1 Providing Continuous Flow**

The source's flow rate must be high enough to equal the maximum water demanded in a day. A table was created in Excel to find the minimum source flow rate that could fulfill these conditions. Any flow rate below that minimum amount could only provide intermittent flow.

To calculate the minimum flow rate that could provide continuous flow, a method

was used from *A Handbook of Gravity-Flow Water Systems* (Jordan Jnr 1980). First, a daily water demand schedule based on observation of the water-fetching habits of villagers in Boajibu. Using this schedule, tables are made comparing supply to the demand throughout the day, based on varying levels of flow at the source. The supply throughout the day should total up to more than the demand to be able to supply continuous flow.

## 2.2 Results

### 2.2.1 Results from Providing Continuous Flow

Different source flows were checked for the water supply they provided, using a demand schedule shown below:

#### Boajibu Daily Water Demand Schedule

7:00 AM – 10:00 AM..... 45% of total daily water demand  
 10:00 AM – 4:00 PM ..... 10% of total daily water demand  
 4:00 PM – 7:00 PM..... 45% of total daily water demand

*Table 1 - Checking the Source for Ability to Provide Continuous Flow*

Flow At Source 2.10 L/s			
Time	Supply (L)	Demand (L)	Difference
7:00 PM-7:00 AM	90,752	0	90,752
7:00 AM-10:00 AM	22,688	81,677	-58,989
10:00 AM-4:00 PM	45,376	18,150	27,226
4:00 PM-7:00 PM	22,688	81,677	-58,989
<b>Total Difference</b>			<b>0</b>

Using the Goal Seek function in Excel, to iterate the source flow until the total difference between inflows and outflows was zero, the minimum flow rate to provide continuous service at the maximum daily usage to the users is 2.1 liters per second. This minimum flow could store enough water during low-demand hours to satisfy all the users demands daily. If said flow is not met, the system can only provide intermittent flow and will then have the corresponding issues mentioned in the introduction.

## 2.3 Conclusion

If the source flow rate is below 2.1 liters per second, continuous flow cannot be provided. The demand of the users is more than the source can supply even if all the water is stored overnight. The water supplied will have to be limited using valves either at the source or at the point of use by community leaders. The users will have to take as much water as they can get and supplement the rest using existing wells or pumps in the area.

This situation is not ideal as it can lead to contamination in the pipes and would result in inequity among water collection for the users.

If the source flow rate is above 2.1 liters per second, continuous flow can be provided.

## 2.4 Recommendations

A source flow rate below 2.1 liters per second would force the designer to provide intermittent flow. This can lead to contamination of the water system due to low pressures and a multitude of other problems. Thus, any designer encountering flow rates below this should either scale down the initial design or not build the system altogether. If the designer finds they must use intermittent flow, the following flow schedule should be used:

*Table 2 - Intermittent Flow Schedule*

Time of Day	Water on?	Collection Allowed?
6:45-7:00 AM	Yes	No, Flush Water
7:00-9:00 AM	Yes	Yes
9:00 AM-4:00 PM	No	No
4:00-6:00 PM	Yes	Yes
6:00 PM-6:45 AM	No	No

The schedule above permits water collection for four hours per day, which will keep the amount of water the users can collect below what they would normally demand. Also included in the schedule is fifteen minutes flush time before each collection. This will allow the biofilm which has accumulated on the pipe walls to flush out before the users begin to collect water as referenced in the introduction. To flush the system, some simple valves are installed on the pipes before each tap. These valves are opened to let water flow freely before users are allowed to collect water. This is not an ideal situation, as the pipes will likely still have some contamination due to the pressure rising and falling every day. Adding a chlorine residual to the system would help to combat this contamination, or scaling back the system to allow for continuous flow.

### 3.0 Sizing the Tank for the System based on the Source

As of now, the flow rate of the source has yet to be determined. In an effort to help the builders of said system in the future, an analysis of tank sizing that would be needed depending upon the flow rate was completed. This table and model could be used by the community to finish the system when the funds, manpower, and materials are available.

#### 3.1 Methods

##### 3.1.1 Calculating the Size of the Tank

To size the water storage tanks, a method from *Field Guide to Environmental Engineering for Development Workers* was used (Mihelcic 2009). First, a population needs to be projected for the last year of the design life of the storage tank.

The following equation is used to predict the population in twenty years:

$$P_N = P_O \left( 1 + \frac{r*N}{100} \right) \quad \text{Equation 1}$$

where  $P_O$  = original population (*People*)

$r$  = percentage population growth rate (*Percent*)

$N$  = number of years in design life (*Years*)

Once a projected population is found, the average daily water demand can be calculated, but only by assuming a demand per person.

$$Q_{ave} = [P_N * \omega_R] \quad \text{Equation 2}$$

where  $Q_{ave}$  = average daily usage (*Liters/day*)

$P_N$  = projected population (*people*)

$\omega_R$  = volume of water demanded (*Liters/person/day*)

From there, we can calculate a maximum daily water demand by simply multiplying by a safety factor (1.25-1.5).

$$Q_{max} = Q_{ave} * \text{safety factor (1.25 - 1.5)} \quad \text{Equation 3}$$

where  $Q_{max}$  = maximum daily usage (*Liters/day*)



The average and maximum daily use are good to have. They tell us the kinds of demands the users are putting on the system, but how should we size the tank? In this case, the water will most likely be demanded in a shorter amount of time, as the people of Boajibu only collect water for eight hours out of a twenty four hour day. Thus, it would be good to design the tank using for those peak flow conditions. To do this, we use a peaking factor. This tells us how many times greater than our maximum demand daily our peak demand will be. Our equation is:

$$Q_{peak} = Q_{max} * peaking\ factor \quad \text{Equation 4}$$

where  $Q_{peak}$  = peak demand of the system (*Liters/day*)

$Q_{max}$  = maximum daily usage (*Liters/day*)

We will estimate the amount of time that the peak flow would be demanded in any one day with the following equation:

$$\tau_{peak} = Q_{max}/Q_{peak} \quad \text{Equation 5}$$

where  $\tau_{peak}$  = time to draw  $Q_{max}$  at  $Q_{peak}$  (*days*)

We take the peak flow minus our source's flow rate and multiply it by the amount of time that flow will be demanded to get the size of our tank. This will give us a tank that can supply continuous flow even if the users demand peak flow for our entire estimated time calculated in Equation 5.

$$V_{tank} = (Q_{peak} - Q_{min-source}) * \tau_{peak} \quad \text{Equation 6}$$

where  $V_{tank}$  = volume of the tank (*Liters*)

$Q_{min-source}$  = minimum flow at the source (*Liters/day*)

An excel sheet was created using this method that sizes tanks based on different source flow rates. A designer or builder without knowledge of engineering could use this sheet as an aid while finishing the system in Boajibu. The tanks are all set at a height of 7 feet so as not to be too difficult to build. The site of the tank has also already been selected based on a variety of characteristics: proximity to the town and the source, height, grade, and security.

An alternative method was also used for comparison (Viessman Jr. 1998). The inflows and outflows of the system are looked at for each hour of the day. The cumulative inflows and cumulative outflows are then graphed on the same chart over the hours of the day. A tangent line with the slope of the inflows is drawn at the greatest and least cumulative outflow. The difference between these two tangent lines vertically is the size storage tank wanted.

## 3.2 Results

### 3.2.1 Results from Sizing the Tank based on Source Flow Rate

Ideal tank sizes were calculated in Excel for various flow rates starting from 1 L/s and assuming a constant demand of 181,104 liters per day. Each tank's ideal volume in liters was calculated first, which was then converted to cubic feet. After this, the diameter in feet was calculated based on an assumed height of 7 feet (for ease of construction) and a circular construction. This table is intended to aid any builder or designer without engineering knowledge, in the construction of a gravity-flow water system in the village of Boajibu, Sierra Leone.

*Table 3 - Tank Sizing based on Source Flow Rate*

Flow At Source (L/s)	Volume of Tank (L)	Volume of Tank (ft <sup>3</sup> )	Diameter of Tank (ft)
1	N/A	N/A	N/A
2	N/A	N/A	N/A
2.1	121,024	4,274	27.88
3	95,104	3,359	24.72
4	66,304	2,341	20.64
5	37,504	1,324	15.52
6	8,704	307	7.48

The design above is a conservative one and should be considered on the high-end of storage tank sizing. The volumes of the tanks at 1 L/s and 2 L/s are assuming continuous flow, but we have seen from Table 1 above that at those flow rates, intermittent flow would result. Thus, we must reformulate our estimates for tank volume based on intermittent flow. Our tanks in an intermittent flow system will be drained completely every day of what they have stored because the users will demand more than what can be provided by the spring overnight and to ensure no microbial growth in the tanks or pipes. Thus, the tanks would be given the capacity to store as much water as would come in from the source overnight.

#### Tank Sizing if Source Flow is 1 L/s

$$1 \frac{\text{Liter}}{\text{second}} * \frac{60\text{seconds}}{\text{minute}} * \frac{60\text{minutes}}{\text{hour}} * 12 \text{ hours} = 43,200 \text{ liters}$$

#### Tank Sizing if Source Flow is 2 L/s

$$2 \frac{\text{Liter}}{\text{second}} * \frac{60\text{seconds}}{\text{minute}} * \frac{60\text{minutes}}{\text{hour}} * 12 \text{ hours} = 86,400 \text{ liters}$$

If the source flow is 1 liter/second, the tank should be sized at 43,200 liters. Any bigger tank would be a waste of money because the water would never fill it. For a source flow of 2 liters/second, the tank should be 86,400 liters. Again, this will never fill past this mark, so a bigger tank would not be useful.

*Table 4 - Tank Sizing based on Source Flow Rate*

Flow At Source (L/s)	Volume of Tank (L)	Volume of Tank (ft <sup>3</sup> )	Diameter of Tank (ft)
1	43,200	1,526	16.67
2	86,400	3,051	23.56
2.1	121,024	4,274	27.88
3	95,104	3,359	24.72
4	66,304	2,341	20.64
5	37,504	1,324	15.52
6	8,704	307	7.48

An example of the alternative method is provided for the flow of 2.1 liters per second.

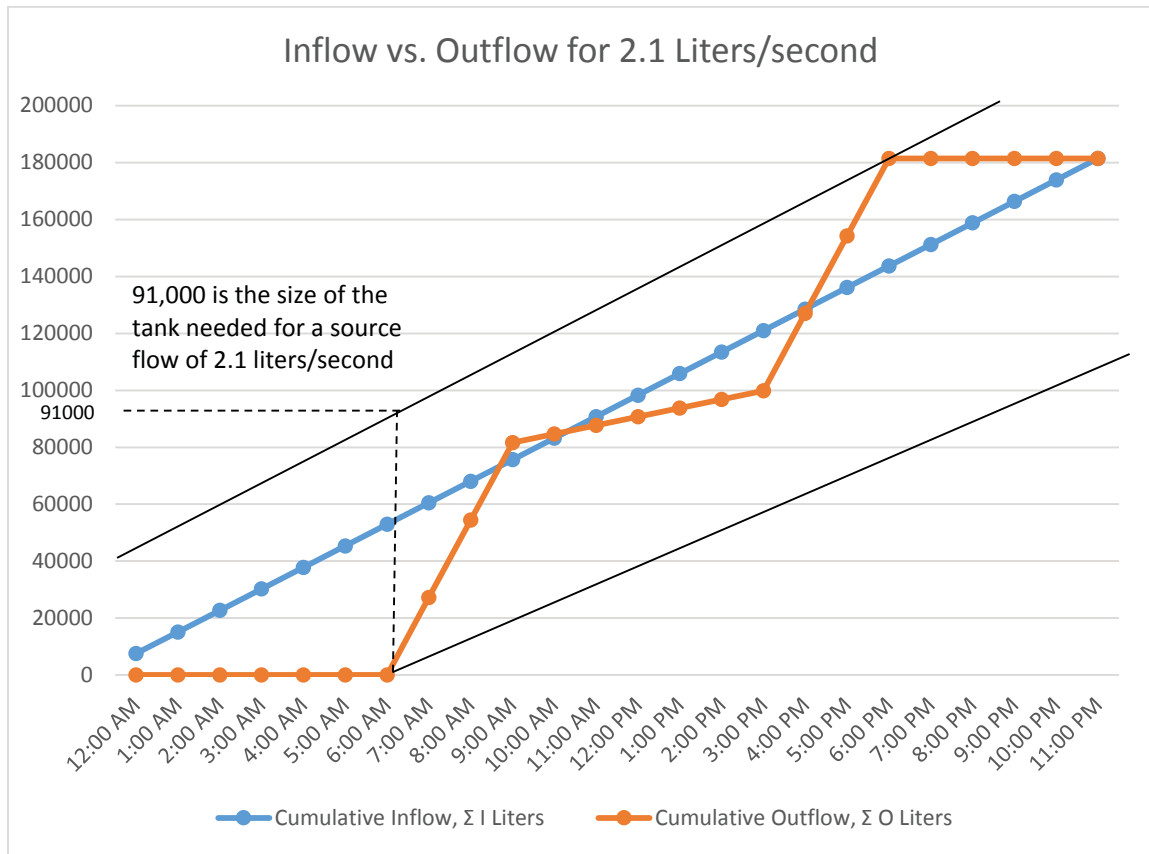


Figure 11 – Chart Showing Alternative Tank Sizing Method – by Author

### 3.3 Conclusion

Table 3 could be used by a builder without formal engineering training to size a water storage tank only by measuring the source flow rate using the table to size the tank. The tank sizes at 1 and 2 liters per second are sized for intermittent flow, while the rest are sized for continuous flow. If any flows are measured that are between the flows shown, the builder should interpolate to get the size of the tank.

The alternative method is also effective but is less conservative as it uses no peaking factor.

## 4.0 Loop Algorithm Analysis

### 4.1 Methods

#### 4.1.1 Modeling and Ranking each Loop

##### 4.1.1A How Loops were Chosen and How They will be Modeled and Ranked

Loops were connected according to different communities within the town of Boajibu, to help foster a sense of ownership of the system (Figure 11). Another loop, Loop 8, was designated, but is not shown in the figure pictured below. It connects the two endpoints of the top and bottom of the system making one big loop for the entire system. The Adaptive Greedy-Heuristic Algorithm for Redundancy Augmentation designed by (Abbott 2014) was used to rank the loops.

##### 4.1.1B Process by Which They are Ranked

**Step 1** Each loop was numbered and the number of users downstream of each loop was calculated (Figure 11).

**Step 2** A separate EPAnet file was made for each loop to ease in calculation and organization. The new pipe was added to make the loop and the simulation was run again to check for pressures below 13.87 psi at the taps (32 feet of head).

**Step 3** Each pipe in the loop was “broken” (closed in EPAnet), and the simulation was run again to check for pressures below 13.87 psi. If pressures below 13.87 psi resulted, the other pipes in the loop were increased in size to handle the additional flow.

**Step 4** The cost of this increase in size and the new pipe that creates the loop were totaled. That was the total cost of the loop.

**Step 5** The number of users downstream of the loop divided by the total cost of the loop gave the loop ranking parameter all the loops were ranked.

Use the following equation:

$$\beta = n/c$$

where  $\beta$  = Loop Ranking Parameter

$n$  = Number of users benefitted downstream

$c$  = Cost of adding the loop

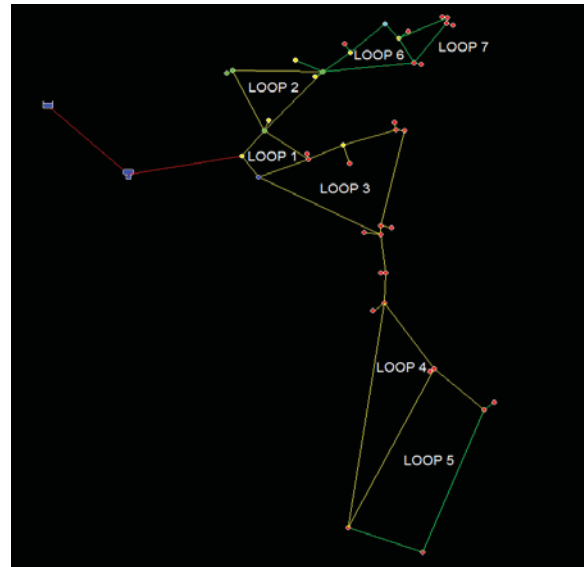


Figure 12 - Loops designated, shown in EPAnet 2.0 - Drawn by Author

For example, Loop 2 had one pipe added to make a loop. With a length of 297 feet and a diameter of 1.5 inches, it would cost \$66.74 to add.

*Table 5 - Measures of pipe added to Loop 2*

<b>Loop 2</b>	<b>Length (ft)</b>	<b>Diameter (in)</b>	<b>Cost (\$)</b>
<i>One pipe added</i>	297	1.5	\$66.74

Now we close each pipe in the loop and run the EPAnet simulation checking for pressures below 13.87 psi. In this case, we found no pressures below 13.87 psi at the taps meaning that we don't need to increase the size of any of the other pipes.

*Table 6 - Cost and Benefit of Loop 2*

<b>Pipes to Close</b>			<b>Ranking Parameter</b>
<i>(Bottom left, clockwise)</i>	<b>People Benefitted (n)</b>	<b>Cost ( c)</b>	<b>(<math>\theta</math>)</b>
1	571.00	\$66.74	8.56
2	571.00	\$66.74	8.56
3	571.00	\$66.74	8.56

The loop would benefit 571 people and cost \$66.74 to add because no other pipes needed to be increased in size. The smallest Ranking Parameter is taken as the rank of the loop. Here, they are all 8.56, so 8.56 is the parameter we use for Loop 2. This process is repeated for each loop until they are all ranked.

## 4.2 Results

### 4.2.1 Results of Ranking each Loop

The method devised by (Abbott 2014) was used for each of the 7 loops chosen, and the results are shown below.

*Table 7 - Cost of Loops in Boajibu Water Distribution System*

<b>Loop Number</b>	<b>New Pipe Length ft</b>	<b>New Pipe Diameter in</b>	<b>Replaced Pipe Length ft</b>	<b>Replaced Pipe Diameter in</b>	<b>Cost</b>
1	250	1.5	606	2.0	\$ 90.22
2	297	1.5	-	-	\$ 66.74
3	528	1.5	-	-	\$ 118.65
4	1056	1.5	919	1.5	\$ 288.93
5	792	1.5	-	-	\$ 177.98
6	252	1.0	-	-	\$ 42.47
7	251	1.0	-	-	\$ 42.30

In Table 6, the costs of adding each loop to the system are shown. The first two columns after the loop designation dealing with the pipe that is added to make the loop, and the two after that deal with any pipes that had to be increased in size due to a need for more flow capacity in case of a break in the loop. The cost of replacing the broken pipe is not included because said pipe would need to be replaced regardless of the loop being in place. Loops 1 and 4 were the only loops needing an increase in the pipe size of the other pipes in the loop to handle the extra demand in case of a rupture. The other loops simply had the cost of the one added pipe. Loop 8 is not shown because the pipe diameters could not be made large enough to allow tap pressures to remain above the minimum of 13.87 psi; this is due to the water having to flow downhill then back uphill all the way to the other side of the system. There is not enough pressure head for the water to reach the other side of the system, regardless of the pipe size.

*Table 8 - Ranking each Loop according to its Benefit-Cost Ratio*

Rank	Loop Number	People Benefitted	Cost	Ranking Parameter, $\beta$
1	1	1,669	\$ 90.22	18.50
2	3	1,098	\$ 118.65	9.25
3	2	571	\$ 66.74	8.56
4	6	254	\$ 42.47	5.98
5	7	205	\$ 42.30	4.85
6	5	732	\$ 229.61	3.19
7	4	773	\$ 288.93	2.68

The two loops which benefitted the most people, had the highest ranking. The two loops which required enlarging of the surrounding pipes due to increased flow, and thus the highest cost, were the lowest ranked. In all, it is better to connect smaller loops upstream because it benefits more people at the cost of only one small pipe. Once again, Loop 8 was not viable because the water could not reach all the taps when water was shut off at one end.

The following is not an issue in this system because the system is designed correctly. One possible issue with the loop ranking happens when a loop is either under designed or over designed. In other words, under designed means when the pipes are smaller than they should be, and over designed means when the pipes are larger than they should be. The cost of an under designed loop will be high because the pipes will need to be increased in size a lot to make up for the flow they were already not carrying properly, which doesn't necessarily mean the loop is in a bad place, just that it was designed badly to begin with. The cost of an over designed loop will be below what it should be because the pipes were too big to start and won't need to be increased in size. In the case of the system in this report, all the pipes were sized correctly, so the loop ranking did not have this issue, but it deserves to be mentioned for future work.

### **4.3 Conclusions**

The water distribution system in Boajibu as designed would benefit most from a small loop at the start of the system designated as Loop 1. The second most beneficial loop was the next loop downstream in the direction of the school, which has our biggest population by far, making loops upstream of it very important. The four lowest ranked loops were also the four loops that were farthest from the source.

The general trend of the loop rankings is that the closer the loop is to the source, the more beneficial a loop will be. This is because the number of users benefitted is very high when it is close to the source and very low when it is far away, whereas cost does not vary as much. Thus, a designer should look at creating loops near to the source, or upstream, first because this will have a beneficial impact for the most people, even if the cost is a little bit more than downstream loops.

### **4.4 Recommendations**

The water distribution system in Boajibu would benefit most from Loop 1, or any other loop that is very near to the source and will benefit most of the users without being too cost-prohibitive. Any loop that is too far downstream will not benefit enough users to be useful and should not be prioritized for construction.



## 5.0 Future Work/Limitations

There were many constraints under which this research was conducted, which limited the quantity and quality of data that could be collected. A more extensive population survey could have been completed. The current survey only asked one member of each household how many people resided within that house. A future survey could note the changes in population over time, and could also attempt to estimate the effects of a water system being installed. A new water system may cause more people to move into town from outside town increasing demand on the system. A new population survey should also look at the transient nature of people in a Sierra Leonean culture.

With more time, a more extensive water use and habits survey could be conducted. For a population that is 60% Muslim, the daily ablutions, washing of feet and hands, will have an effect on water use, as well as, the local religious beliefs which use water. A study of local cultural habits and how they affect water use could also be very important, such as how people launder their clothes, wash their dishes, and wash their bodies. Water is also used to water crops during the dry season, as there is not enough rainfall.

The flow at the spring which is the source for the water system is unknown. Measuring the flow at the spring with a V-notch weir would allow a designer to optimize the system for the source flow rate measured. The system was designed based on the existing taps built, but an entirely new system could be designed ignoring these taps if the engineer felt this was prudent. If the source flow rate was found to be much higher than anticipated or much lower than anticipated, the system could be scaled up or down accordingly.

An environmental assessment of the spring should also be completed to see what impact stopping it will have on the surrounding hydrology or peoples. It's possible that the spring feeds a swamp or wetland that could be destroyed when the spring is diverted for the distribution system. People in the area may depend on the spring as their source of water for drinking, crops, or for their domestic animals. The environmental and social impacts of stopping this source should be considered before construction is begun.

The method for loop ranking can be further refined based on a few salient points. The method only looks at the number of users benefitted, but some of the users will be utilizing the water every day, while some will only use it once a week, like a churchgoer. The method will count these two types of users the same regardless of how much they utilize the water system. A possible way to circumvent this method is to count how many hours the user will utilize the water, using number of user-hours benefitted over cost.

Another way to refine the loop ranking method is to weigh vulnerable users as more important than regular users when calculating the benefit of a loop. Vulnerable users are pregnant women, the elderly, and children because they are more susceptible to death from diseases commonly contracted by consumption of contaminated water, such as diarrhea. Weighing them more heavily in the loop ranking method will take into account not just the economic but the social constraints of the situation.

One other issue with the loop ranking method is the likelihood that a pipe will break. In the method used in this report, the assumption is that every pipe has the same likelihood

of breaking, but some pipes are longer than others and some pipes go through rougher terrain. The addition of an adjusting factor that accounts for one pipe being more likely to break than another would model the real-life situation more accurately.

## References

- Abbott, M. O. N., Jennifer; Barkdoll, Brian (2014). "Adaptive Greedy-Heuristic Algorithm for Redundancy Augmentation by Loop Addition in Branched Water Distribution Systems." Journal of Water Resources Planning and Management: 6.
- CIA (2014, 2004). "CIA World Factbook Sierra Leone." World Factbook. Retrieved 10/21/2014, 2014, from <https://www.cia.gov/library/publications/the-world-factbook/geos/sl.html>.
- Dufant, A. (1988). "Women carrying water: how it affects their health." Waterlines **6**(3): 3.
- Embassy, U. (2014). "Map of Sierra Leone." from [http://freetown.usembassy.gov/map\\_of\\_sierra\\_leone\\_.html](http://freetown.usembassy.gov/map_of_sierra_leone_.html).
- EPA (2008, 2008). "EPAnet: Software That Models the Hydraulic and Water Quality Behavior of Water Distribution Piping Systems." Retrieved 10/21/2014, 2014, from <http://www.epa.gov/nrmrl/wswrd/dw/epanet.html>.
- Fage, J. D. and R. A. Oliver (1975). The Cambridge history of Africa. Cambridge ; New York, Cambridge University Press.
- Geldreich, E. E. (1996). Microbial quality of water supply in distribution systems. Boca Raton, CRC Lewis Publishers.
- Howard, G. B., Jamie (2003). Domestic Water Quantity, Service Level and Health, World Health Organization: 33.
- Jordan Jnr, T. (1980). A Handbook of Gravity-Flow Water Systems. India, Intermediat Technology Publications Ltd.
- Konig, D. (2008). Linking Agriculture to Tourism in Sierra Leone - a Preliminary Research, GRIN Verlag.
- Kumpel, E. and K. L. Nelson (2014). "Mechanisms Affecting Water Quality in an Intermittent Piped Water Supply." Environmental Science & Technology **48**(5): 2766-2775.
- Mihelcic, J. F., Lauren; Myre, Elizabeth; Phillips, Linda; Barkdoll, Brian (2009). Field guide to environmental engineering for development workers : water, sanitation, and indoor air. Reston, Va., ASCE.
- Otero, M. (2011, 04/27/2011). "Walking in The Footsteps of Women in the Developing

World to Celebrate Earth Day 2011." US Mission Geneva. Retrieved 10/21/2014, 2014, from <https://geneva.usmission.gov/2011/04/28/walking-in-the-footsteps-of-women-in-the-developing-world-to-celebrate-earth-day-2011/>.

Sesay, S. M. (2014). Sierra Leone - Civil War. Encyclopedia Britannica.

UN (2010). "General Assembly declares access to clean water and sanitation is a human right." UN News Centre. from <http://www.un.org/apps/news/story.asp?NewsID=35456#.VH3As4ujNsI>.

Vairavamoorthy, K. (2004). Design of sustainable water distribution systems in developing countries. Briding the Gap: Meeting the Worlds Water and Environmental Resources Challenges, World Health Organization. **111**: 10.

Viessman Jr., W. (1998). Water Supply and Pollution Control. Menlo Park, California, Addison Wesley Longman, Inc.

Watch, H. R. (1999). "IV. HUMAN RIGHTS ABUSES COMMITTED BY RUF REBELS." Human Rights Watch. from <http://www.hrw.org/legacy/reports/1999/sierra/SIERLE99-03.htm>.

Weatherbase (2014, 10/21/2014). "Boajibu Sierra Leone." Weatherbase. Retrieved 10/21/2014, 2014, from <http://www.weatherbase.com/weather/weather.php3?s=604761&cityname=Boajibu-Sierra-Leone>.

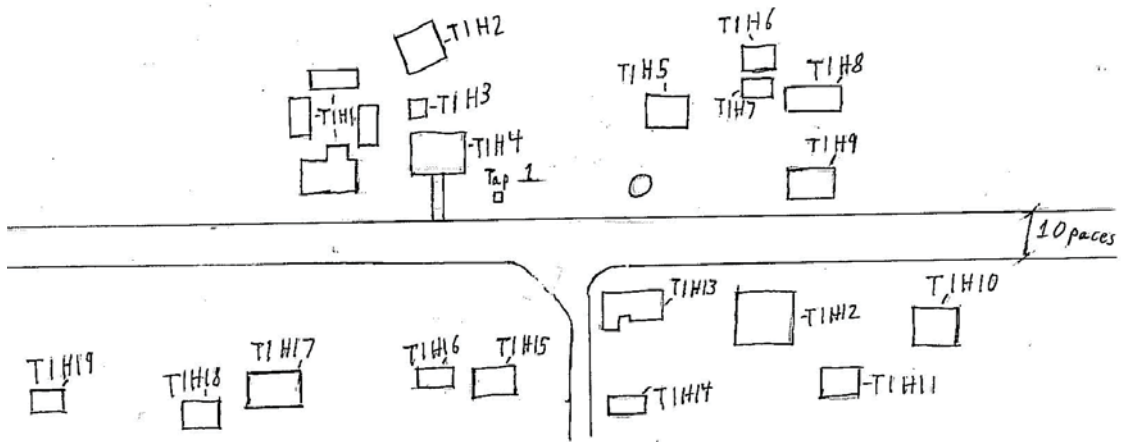
Yazdani, A. J., P. (2012). "Applying Network Theory to Quantify the Redundancy and Structural Robustness of Water Distribution Systems." Journal of Water Resources Planning and Management **138**(2): 153-161.

# Appendices

## Appendix A: Community Census Data

<b>Tap 1R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	3	5
House 2	1	1	2
House 3	0	2	7
House 4	2	1	1
<b>Tap 2R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	2	5
House 2	3	2	4
House 3	1	1	1
House 4	2	1	3
House 5	1	2	4
House 6	1	2	2
House 7	1	1	2
House 8	1	1	3
<b>Tap 3R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	4	2	2
House 2	0	0	0
House 3	1	1	5
House 4	0	3	10
House 5	7	10	21
<b>Tap 4R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	0	0	0
House 2	1	5	7
House 3	2	4	8
House 4	1	2	4
House 5	1	1	3
<b>Tap 5R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	0	3
House 2	1	0	2
House 3	3	2	7
<b>Tap 6R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	2	2	4
House 2	1	2	5
House 3	12	0	0
Church	30	50	20
<b>Tap 7R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	4	1	0
House 2	4	7	5
House 3	1	2	5
House 4	1	2	5
House 5	3	1	0
<b>Tap 8R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	0	5	10
House 2	2	2	3
House 3	2	4	7
House 4	1	3	7
House 5	1	3	5
House 6	2	2	3
House 7	1	1	1
House 8	1	1	3
House 9	0	1	2
<b>Tap 9R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	3	5	10
House 2	2	3	5
House 3	1	0	0
House 4	1	0	0
House 5	3	2	3
House 6	1	1	2
House 7	0	1	3
House 8	1	3	5
House 9	0	4	4
House 10	2	3	2
House 11	1	2	5
House 12	1	3	5
House 13	1	3	5
House 14	0	2	3
House 15	4	1	0
House 16	2	2	10
House 17	1	1	1
House 18	1	1	4
House 19	1	1	3
<b>Tap 10R</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
School	15	10	500

<b>Tap 1L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	2	5
House 2	2	4	4
House 3	1	1	2
House 4	3	1	2
House 5	2	3	5
House 6	1	2	3
House 7	1	2	5
House 8	3	1	0
<b>Tap 2L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	1	4
House 2	2	2	7
House 3	3	4	7
House 4	2	3	4
House 5	1	1	3
Clinic	5	20	30
House 7	1	2	6
<b>Tap 3L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
Mosque	40	30	10
<b>Tap 4L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	2	3	5
House 2	1	2	4
House 3	1	1	2
House 4	5	10	22
House 5	3	1	4
House 6	0	2	4
<b>Tap 5L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	1	1	5
House 2	1	2	3
House 3	2	1	4
House 4	1	1	1
House 5	1	2	5
House 6	3	5	10
<b>Tap 6L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
Pre-School	2	2	30
House 2	1	0	0
House 3	10	0	4
House 4	0	0	0
House 5	5	1	0
House 6	1	1	3
<b>Tap 7L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	2	5	0
House 2	1	2	5
House 3	1	3	5
House 4	5	0	0
House 5	0	0	0
<b>Tap 8L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	2	2	4
House 2	1	2	5
House 3	1	1	2
House 4	2	2	5
House 5	1	3	7
House 6	3	1	5
<b>Tap 9L</b>			
	<i>Men</i>	<i>Women</i>	<i>Children</i>
House 1	0	3	5
Mosque	20	15	0
House 3	2	2	1
House 4	1	2	5
House 5	1	3	7



<u>T1H1</u> M W C 3 5 10	<u>T1H5</u> M W C 3 2 3	<u>T1H9</u> M W C 0 4 4	<u>T1H13</u> M W C 1 3 5	<u>T1H17</u> M W C 1 1 1
<u>T1H2</u> M W C 2 3 5	<u>T1H6</u> M W C 1 1 2	<u>T1H10</u> M W C 2 3 2	<u>T1H14</u> M W C 0 2 3	<u>T1H18</u> M W C 1 1 4
<u>T1H3</u> M W C 1 0 0	<u>T1H7</u> M W C 0 1 3	<u>T1H11</u> M W C 1 2 5	<u>T1H15</u> M W C 4 1 0	<u>T1H19</u> M W C 1 1 3
<u>T1H4</u> M W C 4 0 0	<u>T1H8</u> M W C 1 3 5	<u>T1H12</u> M W C 1 3 5	<u>T1H16</u> M W C 2 2 10	

Typical sheet used for surveying the local populace.

## Appendix B: Piping Costs

Pipe Size	Cost ( <i>per 20'</i> )	Length ( <i>ft</i> )	Total Cost
1" Pipe	\$3.37	2000	\$337.08
1 1/2" Pipe	\$4.49	3700	\$831.46
2" Pipe	\$5.62	500	\$140.45
<b>Total Piping Costs</b>			<b>\$1,308.99</b>



## Appendix C: Supporting Files

File Name	Tab Name (for Excel)	Contents of File
Boajibu Loop Anaylsis Loop 1.net	N/A	EPAnet Analysis of Loop 1 in the system
Boajibu Loop Anaylsis Loop 2.net	N/A	EPAnet Analysis of Loop 2 in the system
Boajibu Loop Anaylsis Loop 3.net	N/A	EPAnet Analysis of Loop 3 in the system
Boajibu Loop Anaylsis Loop 4.net	N/A	EPAnet Analysis of Loop 4 in the system
Boajibu Loop Anaylsis Loop 5.net	N/A	EPAnet Analysis of Loop 5 in the system
Boajibu Loop Anaylsis Loop 6.net	N/A	EPAnet Analysis of Loop 6 in the system
Boajibu Loop Anaylsis Loop 7.net	N/A	EPAnet Analysis of Loop 7 in the system
Boajibu Tank Sizing 7.5 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 7.5 foot diameter.
Boajibu Tank Sizing 15.5 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 15.5 foot diameter.
Boajibu Tank Sizing 20.5 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 20.5 foot diameter.
Boajibu Tank Sizing 24.75 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 24.75 foot diameter.
Boajibu Tank Sizing 28.2 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 28.2 foot diameter.
Boajibu Tank Sizing 31.3 feet.net	N/A	EPAnet Analysis of the system with a Water Storage Tank with a 31.3 foot diameter.
Pipe Sizing.xlsx	Tap Demands	The Results of the Initial Survey
Pipe Sizing.xlsx	Tap Demands 2	The Results of the Survey Organized into an easy to read Table
Pipe Sizing.xlsx	Design Demands	Calculations of the Demands at Each Tap and Junction and the Elevation Differences between each.

Pipe Sizing.xlsx	Pipe Sizing	The Darcy-Weisbach Calculations for the left side of the water system
Pipe Sizing.xlsx	Pipe Sizing 2	The Darcy-Weisbach Calculations for the right side of the water system
Pipe Sizing.xlsx	Costing	The Costs of the PVC Piping in Sierra Leone
Loop Ranking.xlsx	Overall Piping Cost	The Total Cost of Piping in the System
Loop Ranking.xlsx	Loop Costing	Analysis of the Cost and Benefit of each Loop based on EPAnet Analysis
Loop Ranking.xlsx	Loop Ranking	The Rank of each of the Loops in the System
Tank Sizing.xlsx	Tank Sizing	A Table relating Tank Size to Source Flow Rate
Tank Sizing.xlsx	Intermittent Flow	A Set of Tables determining the Minimum Source Flow to provide Continuous Flow