Water Delivery for the Sub-Village of Manyigi

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Executive Summary

The purpose of this project is to design a water distribution system to supply clean well water to an area of the Mwatasi village. Mwatasi has three sub-villages: Manyigi, South Mwatasi and Ibwange with a total population of 7,720. The area of Manyigi is the only sub-village without water distribution infrastructure in place. The 1,500 people living in Manyigi retrieve all of their water from two local natural sources. The surface water from various natural sources was tested and found to contain harmful levels of bacteria. Another source that the village uses was located near farmland, and was assumed to contain harmful chemical runoff from the use of fertilizer. In both cases, a source of clean water is needed due to the adverse health effects resulting from the poor water quality.

The current design plan proposes to supply 43,500 liters of potable water per day to the village of Manyigi. This amount of water was chosen to adhere to Tanzanian water guidelines that state that every villager should be able to obtain 25 liters per day[1]. The system will have gravity fed distribution points, supplied by a submersible pump in a borehole located near one of the natural sources. Two 10,000 liter tanks will be placed at a high point in the village to store and supply adequate amounts of water during morning and afternoon peak water collection times. Seven distribution points will be placed throughout the village so that there are no more than 250 people per location. This design plan for the sub-village Manyigi is Phase 1 of a two-phase proposal and is based on the village water committee's priorities for water. A Phase 2 plan has been created for South Mwatasi, where the current water system only supplies 20% of water needs according to the water committee. The Phase 2 plan proposes addition of larger storage tanks and new distribution points.

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1. Background

1.1 Village Overview

Mwatasi is located 33 miles southeast of Iringa Town. Marching through the three sub-villages of Mwatasi, our group was met by a mix of generosity, friendliness, and curiosity from many of the villages' roughly 7,720 members. This once small village is projected to grow to a population of 8,950 in ten years' time, based on a 1.5% yearly growth rate[1]. Within the Manyigi area the estimated population will be 1,740. Figure 1.1.1 depicts the locations of each sub-village within Mwatasi. Table 1.1.1 displays the current and projected population values for each sub-village. A larger, hand-drawn map of the area is included as Appendix B.

Figure 1.1.1 Mwatasi Village with Sub-Villages Shown

Table 1.1.1 Population of Mwatasi

Sub-Village	Current Population	Expected Population[1] (10 Years)
South Mwatasi 8.269 S, 35.816 E	3,200	3,700
Ibwange 8.256 S, 35.809 E	3,020	3,510
Manyigi 8.258 S, 35.818 E	1,500	1,740
Total	7,720	8,950

[1]Population growth of 1.5%/year assumed

1.2 Existing Systems

The village Mwatasi (referring to the collective of the sub-villages) has a water committee to govern and maintain the current water system. The water committee is composed of 15 representative community members from the three sub-villages. The water committee charges 100 shillings per 20 liter bucket to pay for basic maintenance and upkeep of the current system. This is a relatively affordable amount for villagers, who are happy to pay for the peace of mind and convenience of clean tap water. Only 20% of water needs are being met in South Mwatasi, as stated by the water committee, and 0% of needs are being met in Manyigi. The water committee did not discuss any large concerns with the amount of water being supplied to Ibwange. The three sub-villages have contrasting ways of accessing water based on the different systems available, with Mwatasi and Ibwange retrieving water from taps while Manyigi is sourced completely by surface water.

1.2.1 Ibwange

Ibwange currently has two wells that supply water to distribution taps around the sub-village. A primary school was built in 2016 in northern Ibwange that currently uses rainwater to fill a 5,000 liter tank seen in figure 1.2.1(a). Piping routed from a well in Ibwange is already in place, but the water supply has been shut off. The previous supply tank from the piping system was broken. Unfortunately, this system could have provided the children and teachers of the school with sufficient water for a school day, which would surely strengthen the education situation in Mwatasi. A view of the area where the piping is and the tank used to be is provided in Figure 1.2.1(b). The committee stated that the water needs of Ibwange are otherwise met.

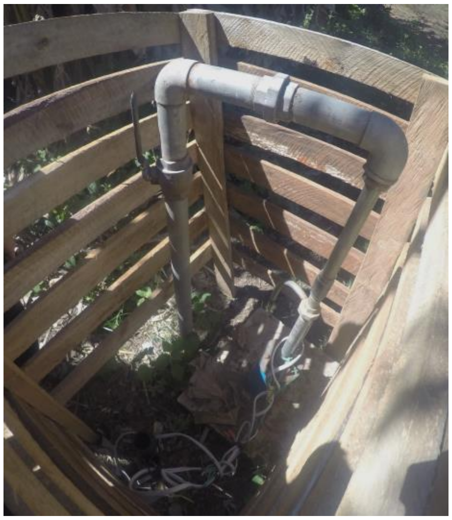
(a) **(b)**

Figure 1.2.1 Ibwange Primary School. The school currently uses a **(a)** rainwater collection system to provide water to the school. The piping is laid along the treeline in image **(b)** that could be used to fill a water tank. **(a) 8°14’45.97”S 35°48’18.59”E (b) 8°14’47.47”S 35°48’17.97”E**

3.2.2 South Mwatasi

The current system in South Mwatasi supplies water from a well to a 2,000 liter tank. The water is then moved to distribution taps around the sub-village. A 1.5 hp pump is placed in the borehole, and an additional 1.5 hp pump is located at the pumphouse in the pipeline to act as a booster pump to supply additional head to the system. Currently the two pumps run off of diesel fuel. Well water is pumped out of the borehole to the pump house. Figure 1.2.2(a) displays a picture of the well. The pipeline entering the pump house can either be directed to fill the 2,000 L tank located in the pump house or directed to fill a 2,000 L tank by the secondary school that is uphill in central Mwatasi. This design is depicted in Figure 1.2.2(b).

(a) (b)



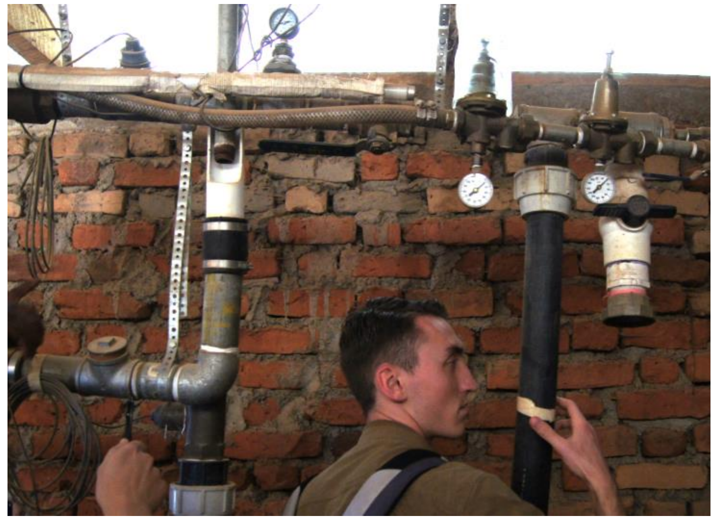


Figure 1.2.2 Water Distribution System in South Mwatasi. The **(a)** well has a wooden fence that is locked and monitored by the water committee. Inside the **(b)** pump house, valves can be adjusted to direct the water to the secondary school. **(a) 8°16'2.30"S 35°48'58.84"E. (b) 8°16'0.47"S 35°49'1.00"E.**

Four distribution taps are used to deliver well water to the community members in South Mwatasi. An example of one of these taps in included as Figure 1.2.3(b). One tap was damaged from road construction, but the pipeline is still in place to supply water to a new potential distribution point. Damage has also occurred to piping leading up to the pump house since pipes were not buried 1 meter deep, which is the Tanzanian standard. This is why it is important for our future design to follow the Tanzanian guidelines for water systems. The growing population in South Mwatasi has put strain on the current water distribution system, leading to only 20% of villagers in receiving enough water. The villagers eagerly accepted buckets of water that we filled when inspecting the taps. In addition, this lack of water is unnecessary, since the well has sufficient output, but the current tank is too small to hold daily water needs. The well water was tested out of a distribution tap and was determined to be free of harmful bacteria that cause waterborne diseases. When the 2,000 L supply tank is empty, villagers hike down 22 meters to the valley where the well is located and obtain water from a surface source, seen in Figure 1.2.3(a). Surface water sources that villagers are currently using were also tested and were found to contain potentially harmful bacteria. Figure 1.2.3(c) displays the water tests that were completed. Water from the sources was collected and a nutrient packet was placed into them. These tests were allowed to incubate for 24 hours at body temperature. Tests that returned a dark color indicated that a large presence bacteria was present in the water that could be harmful if consumed.

(a)

(b)

(c)

Figure 1.2.3 South Mwatasi Water System. The distribution tap **(b)** located adjacent to the pump house, supplies water from a 2,000 L storage tank. When the tank is empty, villagers go down to a surface source **(a)** to obtain water. A water test **(c)** was performed to determine water quality. Black water indicates bacteria levels higher than what is suitable for potable water while yellow indicates potability.

1.2.3 Manyigi

Currently, the sub-village of Manyigi does not have a working water distribution system in place. All water comes from surface water near plots of agriculture in various valleys around Manyigi. Despite this, the children of the village were full of energy and curiosity as Professor Strykowski chased them throughout the village. Various distribution points exist, but were never connected to a distribution pipeline. Distribution points shown as Figure 1.2.4(a) were constructed to be supplied by a water tower, located near the secondary school, that was never usable by the villagers. Figure 1.2.4(b) displays the taps that were installed by The World Bank in a failed project. After construction of The World Bank taps, the connecting pipes were never installed due to a corrupt contractor that stole millions of shillings from the villagers.

(a)

(b)

Figure 1.2.4 Distribution Taps in Manyigi. The older distribution taps **(a)** in Manyigi never were able to deliver water. The newer taps **(b)** were never connected to a water source.

1.3 Village Needs

The Mwatasi water committee communicated that a water system designed for Manyigi would be the highest priority for them. Currently, there is no distribution system located in the sub-village of Manyigi and water is being collected from standing water near farmland. This leaves villagers and animals alike dry and dusty while trying to find a suitable source of water, that could be several kilometers away. Figure 1.2.3(c) displays water tests that were performed at various water sources in Mwatasi. The standing water tests from the natural sources both displayed having potentially harmful bacteria. Not only are the citizens of Manyigi far from suitable water sources, but the water sources they currently have access to could be causing significant diseases, especially among children and infants. In contrast, the water tested from the well in South Mwatasi was determined to not contain these bacteria. It was concluded that a well drilled in Manyigi would be the first necessary design aspect to deliver safe and clean water to the villagers.

As we trekked through South Mwatasi and Manyigi with Menas, and several other water committee members, we had great conversation about the failure of past projects and history of corruption of government projects. These heart-breaking failures were motivation for our team to carry out our due diligence, and avoid the pitfalls of others. We began by examining a destroyed water tap followed by a complex and undersized tank system that supplies a small fraction of the water needed in Mwatasi. On our roughly 5-hour hike of the village we empathized with the women who would have to carry water across great elevation changes and distances. After climbing down into the valley that marks the start of Manyigi, suddenly we were surrounded by the curious eyes of young Tanzanians. Ever timid, they scattered as Paul chased them throughout the village. Finally, we were treated to a delicious traditional lunch of rice, beans, gristly goat meat, and tea to at the pastor's house after our journey. Our meeting with the water committee followed, where we learned a great deal about the struggles and priorities of the village. After a day in the life of a Mwatasi villager, it was utterly clear that this village and its inhabitants had been through years of strife, and we are overjoyed to be able to help improve the standard of living here, even by a small amount.

(a)

(b)

(c)

Figure 1.3.1 Observations while Exploring Mwatasi. This is what women and children must hike through each day for water **(a)**. Rachel, a student from University of Iringa who acted as our translator, hiking up a large hill from the natural water source people retrieve water from in South Mwatasi **(b)**. Paul playing with the children as we hiked throughout the village **(c)**.

2. Project Design

2.1 Water Needs

Currently, there are approximately 1,500 people living in the sub-village of Manyigi. The proposed water distribution system's capacity is required to provide water to the growing population for the next ten years. Assuming a 1.5% per year growth rate there is expected to be 1,740 people in ten years time. The Tanzanian water design guidelines state every person requires 25 L per day. Therefore, the water system for Manyigi should supply at least 43,500 L per day, with a capacity of 50% of the total or ~20,000 liters.

2.2 Proposed Phase 1 Design

We propose to drill a borehole in an area of low elevation were villagers currently obtain surface water. Current assumptions for a 60 meter borehole depth came from the current well located in South Mwatasi. Figure 2.2.1 displays the suggested location for the well. This spot is believed to be a successful location for drilling, because the various natural sources scattered around the valley lead us to believe groundwater is present. However, other sources that were considered were located near farmland. The use of fertilizer raises the potential for chemicals to affect the water supply. We have proposed mud-rotary drilling initially, followed by air hammer if necessary. The selected location is the closest location to grid power, has the best access to the main road for drilling equipment if necessary and is not near farmland, which could contaminate the water from fertilizer use.

Figure 2.2.1 Proposed Well Site-Phase 1; 8°15'46.73"S 35°48'55.06"E.

(a) **(b)**

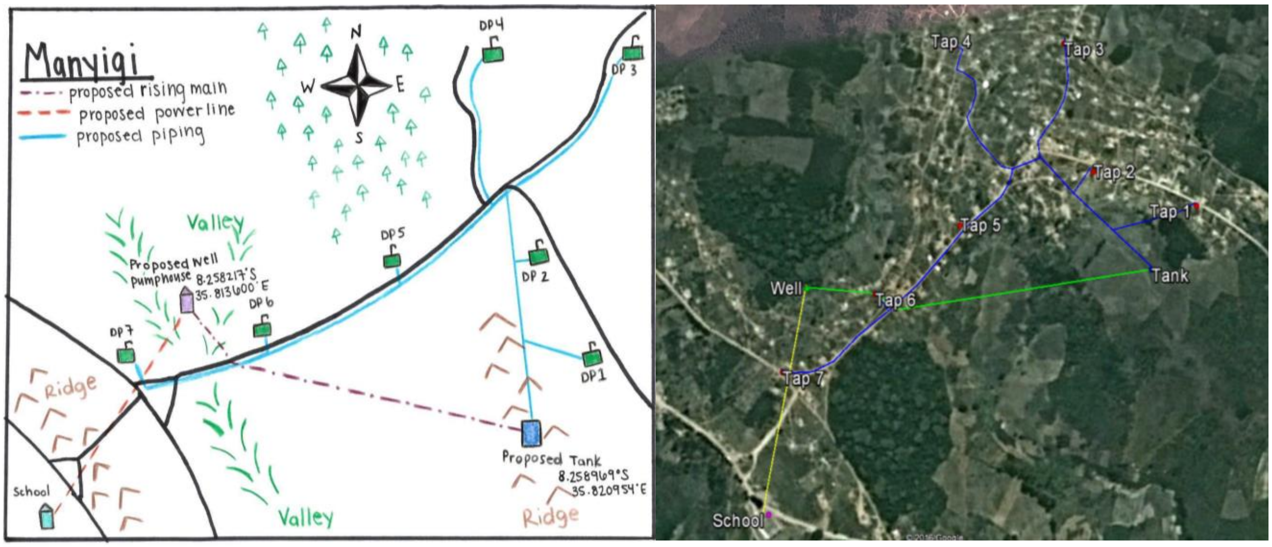


Figure 2.2.2 Maps of System for Manyigi. (a). The ridgelines and valleys are used to help show the elevation differences between locations. The orange line represents the powerline, blue for piping, and purple for rising main. **(b).** The yellow line connected from the school to the well is the powerline. The green line is the rising main connecting the well source to the 10,000 L tank at the highest elevation in the village. The blue lines are the piping to the distribution taps from the water storage tanks.

The main goal for Phase 1 of the design is to supply water to the sub-village of Manyigi, because it is currently the only sub-village with no access to clean well water. We are designing a system that will be able to provide water to areas where the population is the most dense, and allow for people to walk as short of distance as possible in order to retrieve the water. Also, in order to not overload a tap with traffic, we are distributing points so that each only serves 250 people. With this being said, the system will have seven distribution points, five of which have been constructed by the World Bank in an earlier project (Figure 2.2.2)

According to villagers, the World Bank proposed a water system for the entire village of Mwatasi that was to bring water to areas that currently don't have any, specifically Manyigi and the expanding areas of South Mwatasi. The village raised money for the project and then secured it with the government, who then partnered with World Bank to build the system. The World Bank provided money to the central government who hired a contractor and built well-designed water taps in the areas in need, and then never completed the project. According to village leaders, the World Bank taps are not connected by piping and have never been used. Since they have never been connected to a system it will be easy to incorporate them into our design and reduce the cost of the overall project by using infrastructure that is already in place.

The gravity main will be 75 mm PN10 piping and offshoots will be 50mm PN10 piping. These pipes were sized to ensure the system could achieve the necessary water distribution capacity as defined in the Design Manual for Water Supply[1]. All distribution points will be designed to have concrete pads and copper spigots. The World Bank designed taps satisfy these specifications set out by the Tanzanian design guidelines[1]. The well will be drilled using a mud rotary drill at natural source 1, as displayed in Figure 2.2.1 and marked as well in Figure 2.2.2 The well is approximated to be 60 meters deep. The well is estimated to provide 3000 L/hr of flow based on a similar well output in South Mwatasi. It was approximated that these two wells were in a similar aquifer and therefore will behave similarly. A well output test will be conducted to confirm the well's recharge rate. The drawdown of the well was designed to be 20 meters. The well output test will also determine this exact drawdown value.

Two 10,000 L tanks will be installed at the coordinates 8.258969 ^{o}S and 35.820954 ^{o}E, one of the highest elevation in Manyigi. This size of storage was chosen in accordance with Tanzanian guidelines that the system should be able to hold approximately half of the total daily water requirement of the village. The rising main design sample calculations are located in Appendix C.2. An EES code used for these calculations is included in Appendix A.2. For the rising main, piping from the borehole to the 10,000 L tanks will be 50mm PN12 HDPE. The PN12 piping is necessary to account for the calculated maximum pressure in the system of 9.0 bar. Based on initial assumptions of borehole performance, a 2.0 hp pump will be placed into the borehole to provide the necessary power to fill the tank. The pump will be powered by electricity grid power. The nearest known point where there is an electrical line is the school. The system was designed by extending that line, shown in yellow in Figure 2.2.2, to the pump house located at the well location. A secure structure will be constructed to house the pump controller. This ensures that the system can only be turned on by the water committee, and it protects the pump controller from animals or vandalism.

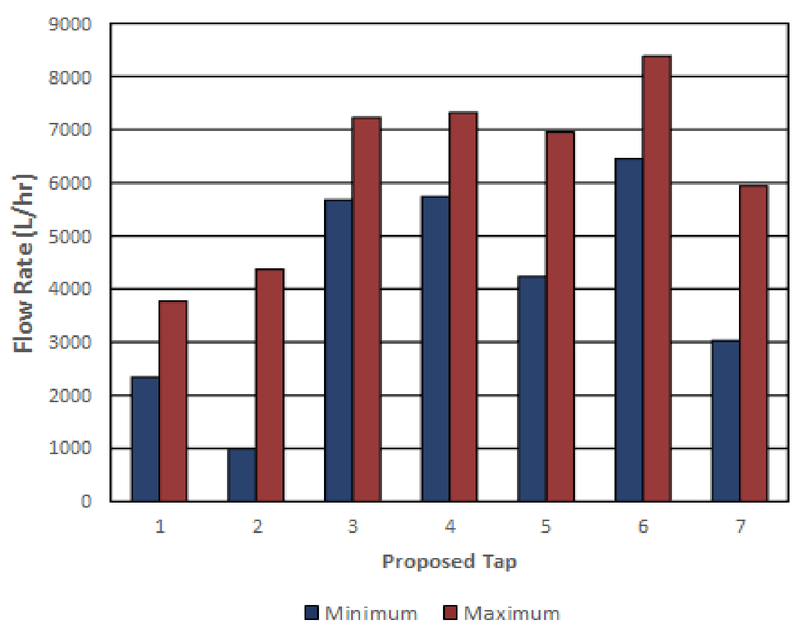


Figure 2.2.3 Maximum and Minimum Flow Rates at Distribution Points. The maximum flow rates were calculated for the case where only one tap is open, and the minimum flow rates were calculated for the case where all taps are open.

The maximum and minimum flow rates available at each of the distribution points is given in Figure 2.2.3. The minimum flow rates correspond to all of the taps being open at the same time. This would occur if the Water Committee decided to only open the distribution taps at peak demand hours. This displays that even in the worst-case scenario where all taps are in use, the system is able to provide enough water at each tap for the Tanzanian guidelines to be met.

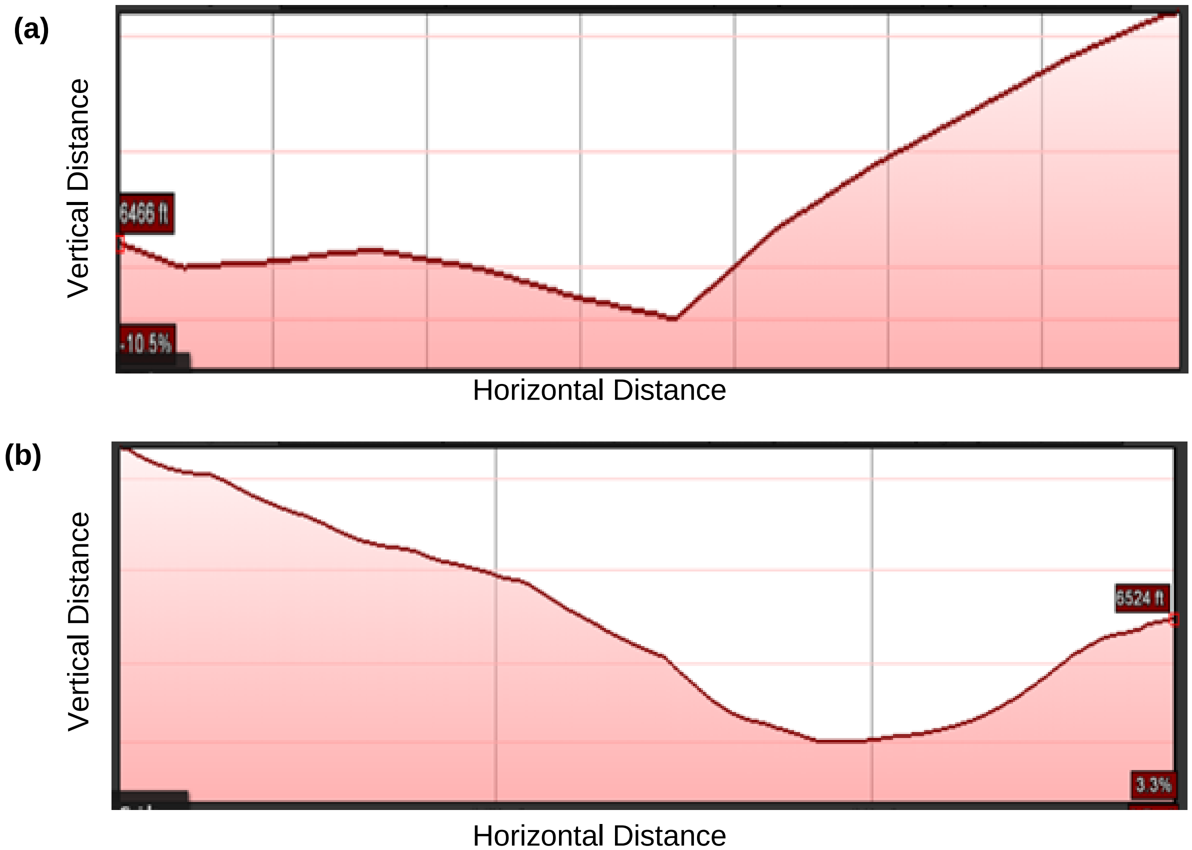


Figure 2.2.4 Elevation Profiles of the Proposed Water Delivery System. Included are the elevation profiles for the rising main **(a)** and the gravity main **(b)** of the proposed water delivery system. Height is included on the y-axis and horizontal distance is on the x-axis

The elevation profile of the rising main for the proposed water delivery system is displayed in Figure 2.2.4**(a)**. The elevation profile of the gravity main of the proposed system is included as Figure 2.2.4**(b)**. The gravity main system includes water distribution from the two 10,000 L tanks to the seven taps located around Manyigi. The profile of the gravity main displays that there is an overall downward slope of the distribution system which allows for the system to be powered by gravity. Calculations for the gravity main were done using EES code as included in Appendix A.1. Sample Calculations for this system are included in Appendix C.1.

2.3 Proposed Phase 2 Design

A second phase of the Mwatasi design is proposed to provide additional drinking water resources to the two other sub-villages. The water committee estimated only 20% of the water needs are met for both South Mwatasi and Ibwange. By adding on to the existing systems, and utilizing what is already in South Mwatasi, the water needs could be completely met.

In South Mwatasi, the only water storage vessel is the 2,000 L tank that is located inside the pumphouse. Manyigi is half the population of South Mwatasi, but is designed to have two 10,000 L tanks to fill twice during the day. Therefore, the 2,000 L tank is not a reasonable size to provide water to over 3,000 villagers. Adding two 10,000 L tanks near the pumphouse is proposed for the Phase-2 design. A suggested location for theses tanks is by the current pump house, shown in Figure 2.3.1. Building a concrete structure and attaching additional piping to the tanks and distribution taps will also be required.

Figure 2.3.1 Phase-2 Tank Location in South Mwatasi. This is the proposed location to put the new 10,000 L distribution tanks. The pump house is directly behind where this photo is taken. The valley where the well is located is directly to the left of this photo.

Four distribution taps are already available and in use in South Mwatasi. The water committee mentioned that a distribution tap was broken from road construction in the sub-village. Another necessary project is to fix that distribution tap because piping is already in place from the pumphouse. An additional distribution tap would be added to account for population growth towards the edge of South Mwatasi. The current system runs on diesel. Extending the powerline from the secondary school to the pump house is also recommended to improve the existing system by eliminating the dependence on the diesel fuel.

Finally, fixing the current system at the primary school in Ibwange would be beneficial to the village. The placement of a 5,000 L tank for the school would provide water throughout the day to the students. The piping and water source is already available in Ibwange. A tank and PVC piping to attach to the tank would be the necessities for fixing the system. This new tank would be located in a similar place as the old one, shown in Figure 2.3.2. This would be a huge benefit to the more than 50 students that go to school here. Not only would they have clean water while at school, but it would improve their learning as well since it would increase attendance.

Figure 2.3.2 New Tank Location in Ibwange. The piping is currently connected to a collection ditch. The placement of the tank would be near this location which is on the south side of the school.

2.4 Project Sustainability

Critical to project sustainability is significant buy-in from the community. It important to distinguish that the people of Mwatasi are going to see the water systems as their own, and not as belonging to "the foreigners". This is often the downfall of many projects in the developing world, so in order to incent the villagers to maintain, repair, and treat their system with care, they will need to contribute to and take ownership of the system.

To maintain the water distribution system, the village will need to create a payment system for the water being provided. This payment will need to cover both the cost of electricity that is necessary for the pumping system and contingency costs for the pump. The contingency cost should be able to cover the cost of pump replacement once the pump warranty expires after about three years. The cost of electricity will be approximately $760 USD each year. The pump has a capital cost of $2,000 USD. Therefore, agreements must be made within the water committee to determine a way to raise these funds each year for the electricity and for the pump cost in three years.

Currently, the cost for a bucket of water in south Mwatasi is 100 TSh. A similar amount could be collected in Manyigi. However, it is up to the water committee to ensure that enough is being collected for coverage of costs and savings are being made for repairs.

A final piece of sustainability comes in the form of St. Paul Partners' relationship with the villages. If approved for funding, St. Paul Partners will be taking the designs within this report and implementing the necessary organizational and technical aspects of the project. This entails working with St. Paul Partners' Tanzanian employees to ensure the accountability is at a suitable level, in-kind contributions are made, contractors are lined up, and that all work is completed. While the design work done by students is a helpful first step and in-kind contributions are critical for accountability's sake, it is truly the dedicated effort of those at St. Paul Partners that allows for the success of this project.

3. Project Implementation Budget

The budget for Phase 1 and 2 is given in Table 3.1 and Table 3.2, respectively. The in-kind contributions are to be provided by the village, usually in the form of manual labor, and are calculated from the cost of labor for digging and laying the piping. For current costs that were not known, a 10% yearly inflation was added to historical costs from past projects.

Table 3.1: Phase 1 Budget

No.	Item Description	Qty.	Unit Cost (TSH)	Unit Cost (USD)	Total Cost (USD)
1	2.0 hp Grundfos Pump[5]	1	4,468,000	$2,000	$2,000
2	Pump Controller[4]	1	2,149,868	$962	$962
3	ARJE2 - Pump Controller[4]	1	48,400	$22	$22
4	Pump House Construction (in-kind contribution)	1	1,117,000	$500	$500
5	LT line extension cost[2]	500 m	2,833,864	$1,267	$1,267
6	Service line cost[2]	1	385,300	$172	$172
7	VAT (18%)[2]	1	365,233	$163	$163
8	Submersible Drop Cable[4]	60 m	12,668/m	$5.67/m	$340
9	Safety Rope[4]	1 roll	100,000	$45	$45
10	Borehole Cover Plate, 7”[4]	1	160,000	$72	$72
11	Distribution pipe Class C (75mm PN10) (Main)[3]	1120 m	1,884,317/150 m	$843.48/150 m	$6,298
12	Distribution Pipe Class C (50mm PN10) (Offshoots)[3]	1026 m	786,159/150 m	$351.91/150 m	$2,407
13	Rising Main Pipe Class D (50mm PN12)[3]	826 m	906,593/150 m	$405.82/150 m	$2,235
14	Tank Foundation[5]	2	1,100,000	$500	$1,000
15	Tank Construction (in-kind contribution)[5]	2	1,100,000	$500	$1,000
16	10,000 L Tank[3]	2	2,640,000	$1,181.22	$2,362
17	Well Drilling (Mud Rotary)	60 m	10,052,000	$4,500	$4,500
18	Digging trenches/laying pipe[5] (in-kind contribution)	2972 m	4,467/m	$2/m	$5,944
19	Shipping Costs[5]		2,234,000	$1,000	$1,000
20	Contingencies[5]	~10% total			$3,200
	Phase 1 Sub-Total:				$35,489
	Phase 1 In-Kind Contribution:				$7,444
	Phase 1 Total:				**$28,045**

Table 3.2: Phase 2 Budget

No.	Item Description	Qty.	Unit Price (TZS)	Unit Price (USD)	Total Cost (USD)
1	10,000 L Tank (S. Mwatasi Pumphouse)[3]	2	2,640,000	$1,181.22	$2,362
2	5,000 L Tank (Ibwange school)[3]	1	1,014,200	$454	$454
3	New tap construction	2	6,705,000	$1,500	$3,000
4	Tap fittings[5]	4	102,000	$60	$240
5	Tank Foundation[5]	3	1,100,000	$500	$1,500
6	Tank Construction (in-kind contribution)[5]	3	1,100,000	$500	$1,500
7	LT line extension cost[2]	700 m	3,963,000	$1,774	$1,774
8	Service line cost[2]	1	385,300	$172	$172
9	VAT (18%)[2]	1	365,233	$163	$163
10	Shipping Costs		2,234,000	$1,000	$1,000
11	Contingencies[5]	~10% of total			$1,000
	Phase 2 Sub-Total:				$13,165
	Phase 2 In-Kind Contribution:				$1,500
	Phase 2 Total:				**$11,665**

References

[1] *Design Manual for Water Supply*. Ministry of Water and Irrigation. 3rd Ed. March 2009

[2] Tanzania Electric Supply Company Limited (personal communication, January 25, 2017)

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[4] Byemerwa, A.M.S. (2015, August 20). *TransAfrica Water* [Profama Invoice]. Tanzania, Dar es Salaam

[5] Barrett, H., Harvieux, J., Kirkeide, L., & Thole, S. (n.d.). *Ihemi Village: Community Effort for Implementing a Large-Scale Water Distribution System* (pp. 1-40, Tech.).

Appendix

A.1 Distribution System EES Code

The EES code used to design the distribution system from the tank is provided below. This code represents the distribution system for Manyigi. Comments have been inserted to outline the function of each code block.

```
{Function to solve for Reynolds Number if it's laminar or turbulent}
Function ff(Re,ed)
If (Re>2300) Then
{ff:=0.025}
ff:=1/((1.8*log10((ed/3.7)^1.11+6.9/Re))^2)
Else
ff:=64/Re
{ff:=0.025}
Endif
End

{Constants & Elevations}
e=0.00001
mu=0.00011
Z_T = 2019  [m] {check back for this}
Z_A = 2014 [m]
Z_1 = 2007 [m]
Z_B = 2007 [m]
Z_2 = 2005 [m]
Z_C = 2001 [m]
Z_3 = 1978 [m]
Z_D = 1999 [m]
Z_4 = 1974 [m]
Z_E = 1983 [m]
Z_5 = 1987 [m]
Z_F = 1972 [m]
Z_6 = 1971 [m]
Z_7 = 1989 [m]

{Converting flow rates to liters per hour}
Q_faucet1=Q_11a*3600*1000
Q_faucet2=Q_22a*3600*1000
Q_faucet3=Q_33a*3600*1000
Q_faucet4=Q_44a*3600*1000
Q_faucet5=Q_55a*3600*1000
Q_faucet6=Q_66a*3600*1000
```

```
Q_faucet7=Q_77a*3600*1000
Q_main=Q_TA*1000*3600

{Converting pressure to Bar}
P_1s=P_1/100000
P_As=P_A/100000
P_1as=P_1a/100000
P_2s=P_2/100000
P_Bs=P_B/100000
P_2as=P_2a/100000
P_3s=P_3/100000
P_Cs=P_C/100000
P_3as=P_3a/100000
P_4s=P_4/100000
P_Ds=P_D/100000
P_4as=P_4a/100000
P_5s=P_5/100000
P_Es=P_E/100000
P_5as=P_5a/100000
P_6s=P_6/100000
P_Fs=P_F/100000
P_6as=P_6a/100000
P_7s=P_7/100000
P_7as=P_7a/100000

{From tank to point A}
D_TA = .075 [m]
t_TA =  .0036 [m]
A_TA = pi*(D_TA -2* t_TA)^2/4
Q_TA = (A_TA)*(V_TA)
P_T = 0
L_TA = 118 [m]
Re_TA=(rho*V_TA*(D_TA-2*t_TA))/(mu)
ed_TA=e/(D_TA-2*t_TA)
f_TA = ff(Re_TA,ed_TA)
g = 9.81 [m/s^2]
rho = 1000 [kg/m^3]

(P_A - P_T)/(rho*g) + (Z_A - Z_T) = - (V_TA^2/(2*g))*(f_TA*L_TA/(D_TA - 2*t_TA))*1.05

{From A to 1}
D_A1 = .05 [m]
t_A1 =  .0024 [m]
A_A1 = pi*(D_A1 -2* t_A1)^2/4
Q_A1 = Q_TA-Q_AB
Q_A1 = (A_A1)*(V_A1)
L_A1 = 209 [m]
Re_A1=(rho*V_A1*(D_A1-2*t_A1))/(mu)
ed_A1=e/(D_A1-2*t_A1)
f_A1 = ff(Re_A1,ed_A1)

(P_1 - P_A)/(rho*g) + (Z_1 - Z_A) = - (V_A1^2/(2*g))*(f_A1*L_A1/(D_A1 - 2*t_A1))*1.05

{From 1 to 1a, tap}
```

```
switch_1=1 {1 for on, 1000000000 for off}
Z_tap = 2 [m]
D_11a = .0254 [m]
t_11a =  .0027 [m]
A_11a = pi*(D_11a -2* t_11a)^2/4
Q_11a = Q_A1
Q_11a = (A_11a)*(V_11a)
L_11a = 5 [m]
Re_11a=(rho*V_11a*(D_11a-2*t_11a))/(mu)
ed_11a=e/(D_11a-2*t_11a)
f_11a = ff(Re_11a,ed_11a)
k_d=10
P_1a=0

(P_1a - P_1)/(rho*g) + (Z_tap) =  - (V_11a^2/(2*g))*(f_11a*L_11a/(D_11a - 2*t_11a)+k_d*switch_1)

{From point A to point B}
D_AB = .075 [m]
t_AB =  .0036 [m]
A_AB = pi*(D_AB -2* t_AB)^2/4
Q_AB = Q_BC+Q_B2
Q_AB = (A_AB)*(V_AB)
L_AB = 119 [m]
Re_AB=(rho*V_AB*(D_AB-2*t_AB))/(mu)
ed_AB=e/(D_AB-2*t_AB)
f_AB = ff(Re_AB,ed_AB)

(P_B - P_A)/(rho*g) + (Z_B - Z_A) =  - (V_AB^2/(2*g))*(f_AB*L_AB/(D_AB - 2*t_AB))*1.05

{From B to 2}
D_B2 = .05 [m]
t_B2 =  .0024 [m]
A_B2 = pi*(D_B2 -2* t_B2)^2/4
Q_B2 = (A_B2)*(V_B2)
L_B2 = 68 [m]
Re_B2=(rho*V_B2*(D_B2-2*t_B2))/(mu)
ed_B2=e/(D_B2-2*t_B2)
f_B2 = ff(Re_B2,ed_B2)

(P_2 - P_B)/(rho*g) + (Z_2 - Z_B) =  - (V_B2^2/(2*g))*(f_B2*L_B2/(D_B2 - 2*t_B2))*1.05

{From 2 to 2a, tap}
switch_2=1 {1 for on, 1000000000 for off}
D_22a = .0254 [m]
t_22a =  .0027 [m]
A_22a = pi*(D_22a -2* t_22a)^2/4
Q_22a = Q_B2
Q_22a = (A_22a)*(V_22a)
L_22a = 5 [m]
Re_22a=(rho*V_22a*(D_22a-2*t_22a))/(mu)
ed_22a=e/(D_22a-2*t_22a)
f_22a = ff(Re_22a,ed_22a)
P_2a=0
```

```
(P_2a - P_2)/(rho*g) + (Z_tap) =  - (V_22a^2/(2*g))*(f_22a*L_22a/(D_22a - 2*t_22a)+k_d*switch_2)

{From point B to point C}
D_BC = .075 [m]
t_BC =  .0036 [m]
A_BC = pi*(D_BC -2* t_BC)^2/4
Q_BC = Q_CD+Q_C3
Q_BC = (A_BC)*(V_BC)
L_BC = 104 [m]
Re_BC=(rho*V_BC*(D_BC-2*t_BC))/(mu)
ed_BC=e/(D_BC-2*t_BC)
f_BC = ff(Re_BC,ed_BC)
K_val=0

(P_C - P_B)/(rho*g) + (Z_C - Z_B) =  - (V_BC^2/(2*g))*(f_BC*L_BC/(D_BC - 2*t_BC)+K_val)*1.05

{From C to 3}
D_C3 = .05 [m]
t_C3 =  .0024 [m]
A_C3 = pi*(D_C3 -2* t_C3)^2/4
Q_C3 = (A_C3)*(V_C3)
L_C3 = 280 [m]
Re_C3=(rho*V_C3*(D_C3-2*t_C3))/(mu)
ed_C3=e/(D_C3-2*t_C3)
f_C3 = ff(Re_C3,ed_C3)

(P_3 - P_C)/(rho*g) + (Z_3 - Z_C) =  - (V_C3^2/(2*g))*(f_C3*L_C3/(D_C3 - 2*t_C3))*1.05

{From 3 to 3a, tap}
switch_3=1 {1 for on, 1000000000 for off}
D_33a = .0254 [m]
t_33a =  .0027 [m]
A_33a = pi*(D_33a -2* t_33a)^2/4
Q_33a = Q_C3
Q_33a = (A_33a)*(V_33a)
L_33a = 5 [m]
Re_33a=(rho*V_33a*(D_33a-2*t_33a))/(mu)
ed_33a=e/(D_33a-2*t_33a)
f_33a = ff(Re_33a,ed_33a)
P_3a=0

(P_3a - P_3)/(rho*g) + (Z_tap) =  - (V_33a^2/(2*g))*(f_33a*L_33a/(D_33a - 2*t_33a)+k_d*switch_3)

{From point C to point D}
D_CD = .075 [m]
t_CD =  .0036 [m]
A_CD = pi*(D_CD -2* t_CD)^2/4
Q_CD = Q_DE+Q_D4
Q_CD = (A_CD)*(V_CD)
L_CD = 72 [m]
Re_CD=(rho*V_CD*(D_CD-2*t_CD))/(mu)
ed_CD=e/(D_CD-2*t_CD)
f_CD = ff(Re_CD,ed_CD)
```

```
(P_D - P_C)/(rho*g) + (Z_D - Z_C) =  - (V_CD^2/(2*g))*(f_CD*L_CD/(D_CD - 2*t_CD))*1.05

{From D to 4}
D_D4 = .05 [m]
t_D4 =  .0024 [m]
A_D4 = pi*(D_D4 -2* t_D4)^2/4
Q_D4 = (A_D4)*(V_D4)
L_D4 = 372 [m]
Re_D4=(rho*V_D4*(D_D4-2*t_D4))/(mu)
ed_D4=e/(D_D4-2*t_D4)
f_D4 = ff(Re_D4,ed_D4)

(P_4 - P_D)/(rho*g) + (Z_4 - Z_D) =  - (V_D4^2/(2*g))*(f_D4*L_D4/(D_D4 - 2*t_D4))*1.05

{From 4 to 4a, tap}
switch_4=1 {1 for on, 1000000000 for off}
D_44a = .0254 [m]
t_44a =  .0027 [m]
A_44a = pi*(D_44a -2* t_44a)^2/4
Q_44a = Q_D4
Q_44a = (A_44a)*(V_44a)
L_44a = 5 [m]
Re_44a=(rho*V_44a*(D_44a-2*t_44a))/(mu)
ed_44a=e/(D_44a-2*t_44a)
f_44a = ff(Re_44a,ed_44a)
P_4a=0

(P_4a - P_4)/(rho*g) + (Z_tap) =  - (V_44a^2/(2*g))*(f_44a*L_44a/(D_44a - 2*t_44a)+k_d*switch_4)


{From point D to point E}
D_DE = .075 [m]
t_DE =  .0036 [m]
A_DE = pi*(D_DE -2* t_DE)^2/4
Q_DE = Q_EF+Q_E5
Q_DE = (A_DE)*(V_DE)
L_DE = 172 [m]
Re_DE=(rho*V_DE*(D_DE-2*t_DE))/(mu)
ed_DE=e/(D_DE-2*t_DE)
f_DE = ff(Re_DE,ed_DE)

(P_E - P_D)/(rho*g) + (Z_E - Z_D) =  - (V_DE^2/(2*g))*(f_DE*L_DE/(D_DE - 2*t_DE))*1.05

{From E to 5}
D_E5 = .05 [m]
t_E5 =  .0024 [m]
A_E5 = pi*(D_E5 -2* t_E5)^2/4
Q_E5 = (A_E5)*(V_E5)
L_E5 = 16 [m]
Re_E5=(rho*V_E5*(D_E5-2*t_E5))/(mu)
ed_E5=e/(D_E5-2*t_E5)
f_E5 = ff(Re_E5,ed_E5)

(P_5 - P_E)/(rho*g) + (Z_5 - Z_E) =  - (V_E5^2/(2*g))*(f_E5*L_E5/(D_E5 - 2*t_E5))*1.05
```

```
{From 5 to 5a, tap}
switch_5=1 {1 for on, 1000000000 for off}
D_55a = .0254 [m]
t_55a =  .0027 [m]
A_55a = pi*(D_55a -2* t_55a)^2/4
Q_55a = Q_E5
Q_55a = (A_55a)*(V_55a)
L_55a = 5 [m]
Re_55a=(rho*V_55a*(D_55a-2*t_55a))/(mu)
ed_55a=e/(D_55a-2*t_55a)
f_55a = ff(Re_55a,ed_55a)
P_5a=0

(P_5a - P_5)/(rho*g) + (Z_tap) =  - (V_55a^2/(2*g))*(f_55a*L_55a/(D_55a - 2*t_55a)+k_d*switch_5)

{From point E to point F}
D_EF = .075 [m]
t_EF =  .0036 [m]
A_EF = pi*(D_EF -2* t_EF)^2/4
Q_EF = Q_F7+Q_F6
Q_EF = (A_EF)*(V_EF)
L_EF = 250 [m]
Re_EF=(rho*V_EF*(D_EF-2*t_EF))/(mu)
ed_EF=e/(D_EF-2*t_EF)
f_EF = ff(Re_EF,ed_EF)

(P_F - P_E)/(rho*g) + (Z_F - Z_E) =  - (V_EF^2/(2*g))*(f_EF*L_EF/(D_EF - 2*t_EF))*1.05

{From F to 6}
D_F6 = .05 [m]
t_F6 =  .0024 [m]
A_F6 = pi*(D_F6 -2* t_F6)^2/4
Q_F6 = (A_F6)*(V_F6)
L_F6 = 50 [m]
Re_F6=(rho*V_F6*(D_F6-2*t_F6))/(mu)
ed_F6=e/(D_F6-2*t_F6)
f_F6 = ff(Re_F6,ed_F6)

(P_6 - P_F)/(rho*g) + (Z_6 - Z_F) =  - (V_F6^2/(2*g))*(f_F6*L_F6/(D_F6 - 2*t_F6))*1.05

{From 6 to 6a, tap}
switch_6=1 {1 for on, 1000000000 for off}
D_66a = .0254 [m]
t_66a =  .0027 [m]
A_66a = pi*(D_66a -2* t_66a)^2/4
Q_66a = Q_F6
Q_66a = (A_66a)*(V_66a)
L_66a = 5 [m]
Re_66a=(rho*V_66a*(D_66a-2*t_66a))/(mu)
ed_66a=e/(D_66a-2*t_66a)
f_66a = ff(Re_66a,ed_66a)
P_6a=0
```

```
(P_6a - P_6)/(rho*g) + (Z_tap) =  - (V_66a^2/(2*g))*(f_66a*L_66a/(D_66a - 2*t_66a)+k_d*switch_6)

{From F to 7}
D_F7 = .05 [m]
t_F7 =  .0024 [m]
A_F7 = pi*(D_F7 -2* t_F7)^2/4
Q_F7 = (A_F7)*(V_F7)
L_F7 = 290 [m]
Re_F7=(rho*V_F7*(D_F7-2*t_F7))/(mu)
ed_F7=e/(D_F7-2*t_F7)
f_F7 = ff(Re_F7,ed_F7)

(P_7 - P_F)/(rho*g) + (Z_7 - Z_F) =  - (V_F7^2/(2*g))*(f_F7*L_F7/(D_F7 - 2*t_F7))*1.05

{From 7 to 7a, tap}
switch_7=1 {1 for on, 1000000000 for off}
D_77a = .0254 [m]
t_77a =  .0027 [m]
A_77a = pi*(D_77a -2* t_77a)^2/4
Q_77a = Q_F7
Q_77a = (A_77a)*(V_77a)
L_77a = 5 [m]
Re_77a=(rho*V_77a*(D_77a-2*t_77a))/(mu)
ed_77a=e/(D_77a-2*t_77a)
f_77a = ff(Re_77a,ed_77a)
P_7a=0

(P_7a - P_7)/(rho*g) + (Z_tap) =  - (V_77a^2/(2*g))*(f_77a*L_77a/(D_77a - 2*t_77a)+k_d*switch_7)
```

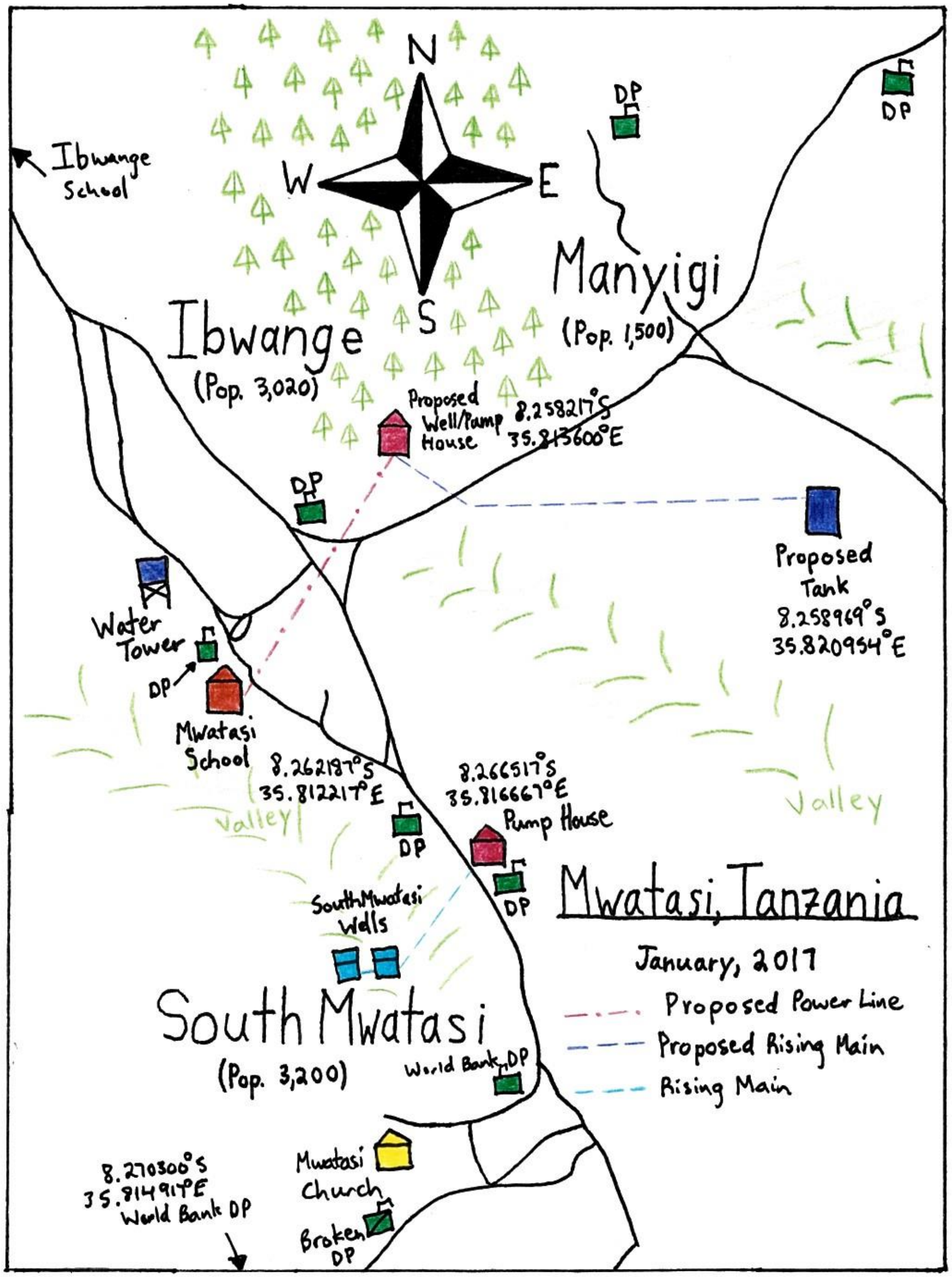
A.2 Rising Main EES Code

The following code analyzes the well/pump system in order to determine the pump size necessary to bring water to the elevated storage tank. Upon knowing the depth of the well being drilled, this code can be used to determine the required pump strength for the system.

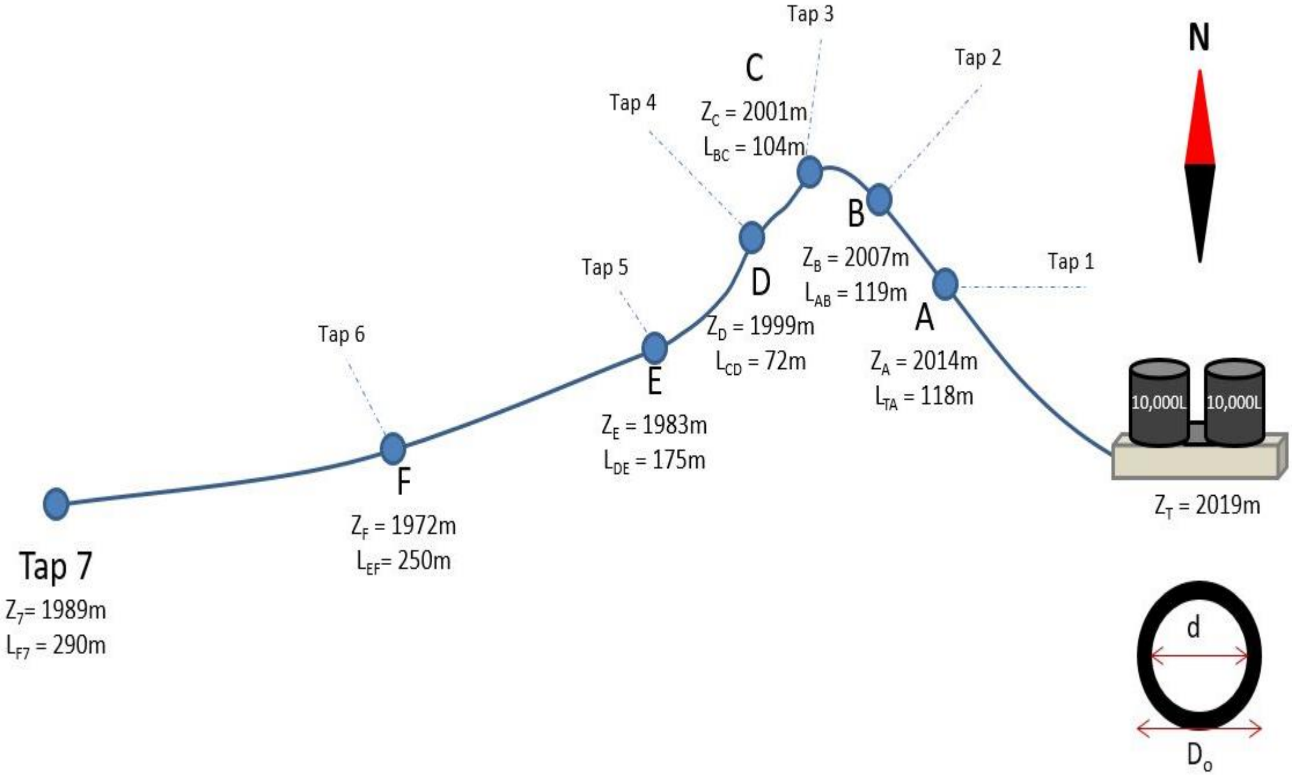
```
{Code for Pumping System from Well to Tank}

z_pump=60 [m] {distance_of_pump_below_ground}
z_ground=1958 [m] {absolute_height_of_ground}
z_tank=2019 [m] {absolute_height_of_tank}
z_dd=20 [m] {height_of_drawdown}
q=3000 [L/hr] {flow_rate_needed}
D_o=0.05 [m] {outer_diameter_of_pipe}
w_t=0.0046 [m] {wall_thickness_of_pipe}
f=0.025 {friction_factor}
L_pipe=826 [m] {length_of_piping}
eta_pump=0.65 {efficiency_of_pump}
eta_motor=1 {efficiency_of_motor}
c_energy=0.1 {cost of energy per kilowat_hr}
p_time=7 {hours for running pump}
days=365 {days for pump to be run per year}

P_1=0 [Pa]
P_4=0 [Pa]
```

```
rho=1000 [kg/m^3]
g=9.81 [m/s^2]
z_1=z_ground-z_dd
z_2=z_ground-z_pump
z_3=z_1
z_4=z_tank
d=D_o-2*w_t
q_real=q/(3600000)
A=pi*(d/2)^2
V=q_real/A
L_12=0 [m]
L_23=z_pump-z_dd
L_34=L_pipe+z_dd
W_required=W/eta_pump
W_electricity=W_required/eta_motor
H_provided=W/(g*rho*q_real)
P_max=P_3/(100000)
cost_electricity=(W_electricity/1000)*p_time*days

(P_2-P_1)/(rho*g)+z_2-z_1=W/(rho*q_real*g)-(V^2)/(2*g)*(1.05*f*L_12/d) {energy balance between top of drawdown outside of pipe to exit of pump}
(P_3-P_2)/(rho*g)+z_3-z_2=-(V^2)/(2*g)*(1.05*f*L_23/d) {no work done by pump in this}{energy balance for exit of pump to top of drawdown inside of pipe}
(P_4-P_3)/(rho*g)+z_4-z_3=-(V^2)/(2*g)*(1.05*f*L_34/d) {no work done by pump in this}{energy balance for top of drawdown inside of pump to exit of pipe into tank}
```

B. Overview Map of Mwatasi



C.1 Sample Calculations for the Gravity Distribution System



Energy Balances

-From tank level (z_T) to a point in the gravity main (z_A)

$$\frac{P_A - P_T}{\rho g} + (z_A - z_T) = \frac{V_{TA}^2}{2g}[1.05\frac{f \times L_{TA}}{d}]$$

This can be applied to any point on the gravity main as shown in Figure #

Results

-The results represent the system with all taps wide open, and were found by using Engineering Equation Solver. The code is in section A.1 Distribution System EES Code

$$P_F = P_{max} = 4.605\ bar$$
$$V_{TA} = V_{max} = 1.406\ m/s$$
$$Q_{TA} = Q_{max} = 18{,}275\ L/hr$$

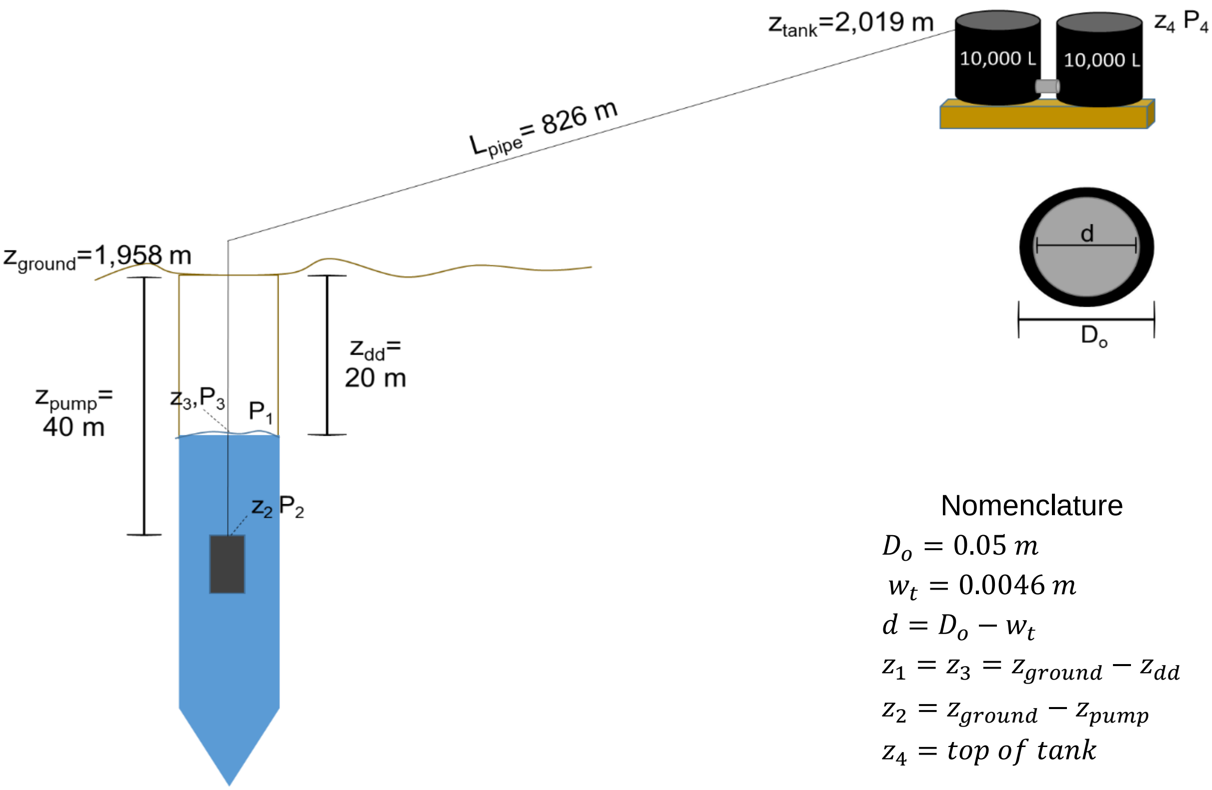
Nomenclature

$D_o = 0.075\ m$

$w_t = 0.0036\ m$

$d = D_o - w_t$

C.2 Sample Calculations for the Rising Main System



Nomenclature

$D_o = 0.05\ m$

$w_t = 0.0046\ m$

$d = D_o - w_t$

$z_1 = z_3 = z_{ground} - z_{dd}$

$z_2 = z_{ground} - z_{pump}$

$z_4 = top\ of\ tank$

Energy Balances

-From water level (z_1) to outside of pump (z_2)

$$\frac{P_2 - P_1}{\rho g} + (z_2 - z_1) = \frac{W}{\rho g Q} - \frac{V^2}{2g}\left[1.05\frac{f\times(0\ meters)}{d}\right]$$

-From outside of pump (z_2) to top of drawdown inside the pipe (z_3)

$$\frac{P_3 - P_2}{\rho g} + (z_3 - z_2) = \frac{V^2}{2g}\left[1.05\frac{f\times(z_{pump} - z_{dd})}{d}\right]$$

-From top of drawdown inside the pipe (z_3) to exit of pipe at top of tanks (z_4)

$$\frac{P_4 - P_3}{\rho g} + (z_4 - z_3) = \frac{V^2}{2g}\left[1.05\frac{f\times(L_{pipe} - z_{dd})}{d}\right]$$

-Assuming pump efficiency is 65%, the work required for the pump was found as follows,

$$W_{required} = \frac{W}{\eta_{pump}}$$

Results

-The following results were found by using Engineering Equation Solver. The code used can be found in section A.2 Pump to Tank EES Code

$$W_{required} = 1{,}164\ W$$

$$W_{required} = 1.56\ hp$$

$$P_3 = P_{max} = 9.1\ bar$$

$$V = 0.64\ m/s$$