Water Distribution System Design: Village of Idunda

Design for Life: Water in Tanzania
January 2019

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March 15th, 2019

Executive Summary

The purpose of this project is to provide a preliminary design for a water distribution system to serve the water needs of the village of Idunda. Idunda is a farming community located southwest of Iringa Town. Four sub-villages exist within Idunda, with a total village population of 1,869 people. Currently, villagers living on the south end of the village gather water from three main surface sources: Mukaravadanda, Kalengakelu, and Mdetema. Because the water sources are located at significantly lower elevations than most of the village infrastructure, villagers must descend and ascend steep slopes to gather water. Along with accessibility concerns, the current water sources also present health risks. All three water sources tested positive for coliform bacteria and two of the sources contained E. coli.

To improve both water quality and water collection safety, a water distribution system was designed. The Mdetema spring water source, found to produce an adequate flow rate of about 59,000 L/day, was chosen as the system source. The proposed design consists of a collection point at the water source, a gravity main servicing a proposed dispensary and the south end of the village, and a pumped system carrying water to the village high point with two gravity mains distributing water to the primary school and the Mavinga sub-village. Water goes through a settling basin at the source and is collected near the source in two SIM tanks. From the storage tanks, a 50 mm pipe will run for 479 m down a 32 m change of elevation to the proposed dispensary location. From the dispensary, a 50 mm pipe continues for 602 m with a 5 m elevation drop to Ukimbilizi, nicknamed Mall of America. A 50 mm pipe continues for 508 m, traversing a low point and ending at the same elevation as the Ukimbilizi ("Mall of America") distribution point near the Msasi preaching point. To serve the upper portion of the village, a three horsepower pump carries water from the SIM tanks at the source to two SIM tanks located at the Village Office. The 40 mm pipe runs 334 m up 94 m of elevation change. From there, a 40 mm gravity main runs for 623 m down 30 m of elevation change to a row of stores to the north in Mavinga, nicknamed Rosedale. A 40 mm gravity main also runs to the south from the Village Office servicing the Lutheran church and the school. The pipe covers 1,202 m and drops 86 m in elevation. The proposed project design also details a suggestion for a second phase to distribute water to the north entrance of the village, specifically the sub-village of Lugoli.

Idunda villagers never dreamed they would be considered for a water distribution system. The community is willing to run a previously organized water committee, provide labor to install the system, and ensure security of the system. The water committee did not have a method of collecting funds for the system in place, but they did express their commitment to developing a means of collecting these funds. The cost of the system, including materials, labor, shipping, and a 10% contingency, was estimated to be $33,376. With the implementation of a water distribution system, the villagers of Idunda will benefit from improved water quality and safer conditions for obtaining water.

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2.0 | Project Profile

2.1 | Purpose

In Tanzania, a motto to live by is, "*Maji ni Uhai*," or "*Water is Life.*" As important as water is to livelihood, many people have limited access to safe water sources. Adults and children across the country must dedicate hours of their day to walking great distances to obtain water. Many water sources are unfit for drinking, as indicated by bacterial contamination. Inadequate access to the resource is a driving cause of poverty. When basic needs fail to be met, people cannot reasonably progress in society. The purpose of the water distribution system design presented in this proposal is to suggest a course of action to bring water closer to the doors of the inhabitants of Idunda.

2.2 | Location

The village of Idunda is in the Iringa region of Tanzania. Although located roughly 100 kilometers from Iringa, it can take upwards of four hours to reach the village due to extreme road conditions and mountainous terrain. Idunda sits at an elevation of about 1,550 meters, spans approximately five kilometers, and is positioned along a road. Main points of reference include a primary school, a proposed dispensary, six churches, and a village office. Approximately 1,900 people live within the village limits. Figure 1 illustrates the village layout (next page).

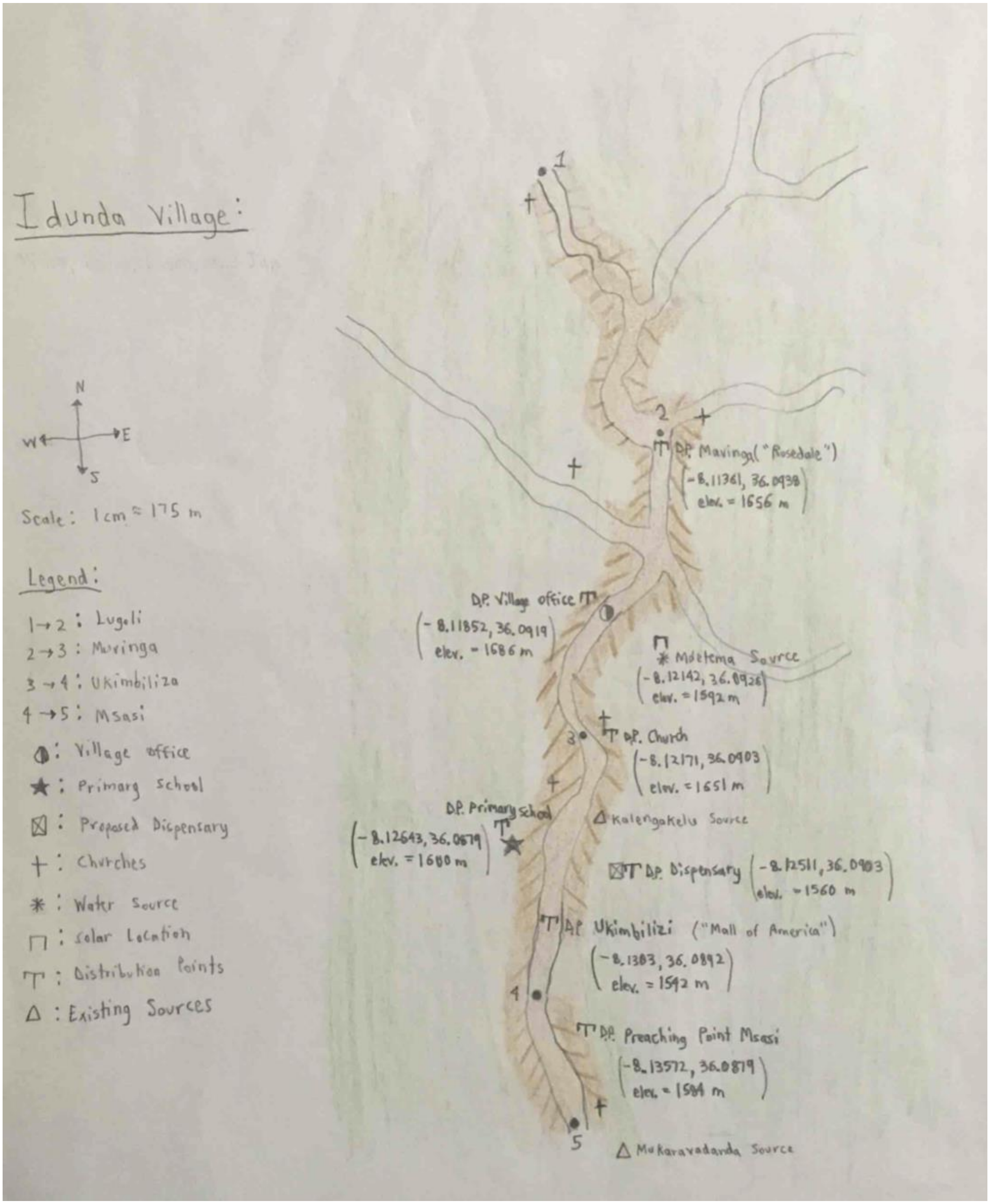

Figure 1: Map of Idunda

2.3 | Current Water Sources

Idunda villagers gather water from several water sources throughout the valley. On the southern end of the village, sources include Mukaravadanda, Kalengakelu, and Mdetema springs as seen on Figure 1. Water quality tests were performed on each of the sources, and all sources tested positive for coliform bacteria, with both Mukaravadanda and Kalengakelu testing positive for E. coli. Based on the water test results, the current water sources are unsafe for drinking per standards set by the World Health Organization, which state that no evidence of coliform or E. coli should be found in drinking water sources (World Health Organization, 1997). To obtain water from the sources, villagers must traverse steep slopes. Since many of the houses are located on the ridgeline, this makes gathering water from the valley a time-consuming and dangerous task.

2.4 | Needs

Water is an essential resource for life. The villagers of Idunda understand the importance of water and emphasized the need for a water distribution system in the village. The water committee unanimously agreed upon three priority locations that should have access to water: the primary school, proposed dispensary, and six village churches. Access to water at the primary school is the first priority because the youth are the future of Idunda. Their health is paramount for a successful society. The proposed dispensary should be reached by the water distribution system because water is needed to adequately treat illness. Servicing the village churches with water is important because churches are a gathering point for villagers and, thus, serve as locations accessed by a large percentage of the village population. The ultimate goal of the water distribution system is to service the entire village of Idunda with water.

2.5 | Challenges

The design solution for a water distribution system in a mountainous region was not immediately apparent. Present challenges include elevation changes, the location of the water sources, longitudinal distances, the remote location, and access to power. Because the village is situated along a ridgeline with water sources in the valley, calculations were done to determine the necessary pumping power to deliver water from the source to the highest point in the village. The elevation variation also raises concerns about high pressures in the gravity mains as well as possible vacuums in the pipes. The population of Idunda is sparsely distributed within the village so distance between households are large. Servicing all the villagers is difficult because the current surface water sources have a limited yield. Due to the roads being difficult to maneuver, driving an air hammer to drill a borehole in Idunda was not an option, and the rocky soil has prevented the use of a mud rotary borehole in the past. The lack of grid power currently and into the foreseeable future made deciding upon a reliable power source a challenge. Idunda experiences cloud cover and inconsistent sun exposure, presenting uncertainties in the use of solar power. Finding a usable water source at a high elevation and central location in the village was the greatest project challenge.

2.6 | Proposed Solution

The water distribution system presented in this proposal contains several components. Water from the Mdetema spring source is first sent through a sedimentation basin and collected in a series of SIM tanks positioned near the source on the side of a mountain. A portion of the water is pumped via solar power to SIM tanks located at the highest point in the village, the Village Office. From there, a gravity main feeds water to the primary school and another to a strip of stores to the north in Mavinga (nicknamed Rosedale). A portion of the water from the source SIM tanks is also sent by gravity to the proposed dispensary location, a strip of stores in Ukimbilizi (nicknamed Mall of America), and a southern preaching point (Msasi Preaching Point). During Phase I, approximately 70% of the village will have access to the distribution system. Phase II describes an independent second system to serve the remaining population.

2.7 | Design Guidelines

When designing a water distribution system in Tanzania, guidelines apply (Ministry of Water and Irrigation, 2009). The system proposed in this report was designed for the expected population in 2029. Using a 2.7% population growth rate, a water demand of 25 L/person/day for the entire village, 10 L/person/day for the primary school, and 10 L/person/day for the dispensary. This led to a total water demand of 52,000 L/day. Because the design source is estimated to produce roughly 59,000 L/day, the 10-year design period demand guidelines were met. Phase I of the system was designed to place distribution points within 400 meters of approximately 70% of the villagers. Tanzanian design guidelines call for the entire village population to be within 400 meters of a distribution point. This guideline will be met with a proposed Phase II design. Other considerations include designing the pipes to accommodate peak hourly demands, account for water losses, and produce certain flow rates from the spigots (full list in Appendix A).

3.0 | Background

3.1 | Village Overview

Idunda village is located approximately 100 kilometers southwest of Iringa Town in a mountainous region. The roads leading to the village are very hazardous, impassable during the rainy season, and impossible to maneuver with large machinery. The village itself is primarily located on a ridge of a mountain with steep slopes on either side. According to the village committee, the total population of the village is 1,869 people with 346 households. Idunda is divided into four sub-villages: Lugoli, Mavinga, Ukimbilizi, and Msasi, with populations shown in Table 1. Lugoli, located on the north end of Idunda, is the most densely populated sub-village. The extents of the sub-villages are shown in Figure 2.

Table 1: Sub-village populations, as provided by the village committee [1]

Sub Village Name	Population	Number of Households
Lugoli	511	106
Mavinga	473	82
Ukimbilizi	362	51
Msasi	504	93

[1] Data obtained on January 11, 2019.

Governmental decisions in Idunda are made by a committee headed by a village executive. A village chairman also contributes to decisions that impact the community. For extra initiatives, committees are formed. For example, a water committee is the governmental body that manages decisions relating to water. As seen in Section 1.4, ten members make up the water committee. The group was formed to initiate the conversation about installing a water distribution system in Idunda.

The people of Idunda are subsistence farmers. Common crops include corn, pumpkins, potatoes, plantains, and bananas. Many villagers raise chickens for eggs and meat; however, other livestock is not commonly found in the village. Other professions Idunda villagers hold include roles within the Lutheran or Protestant churches, teaching at the primary school, and owning stores. Village children assist with farming and attend primary school while they are young. After primary school, some young adults leave the village to attend secondary school in nearby villages.

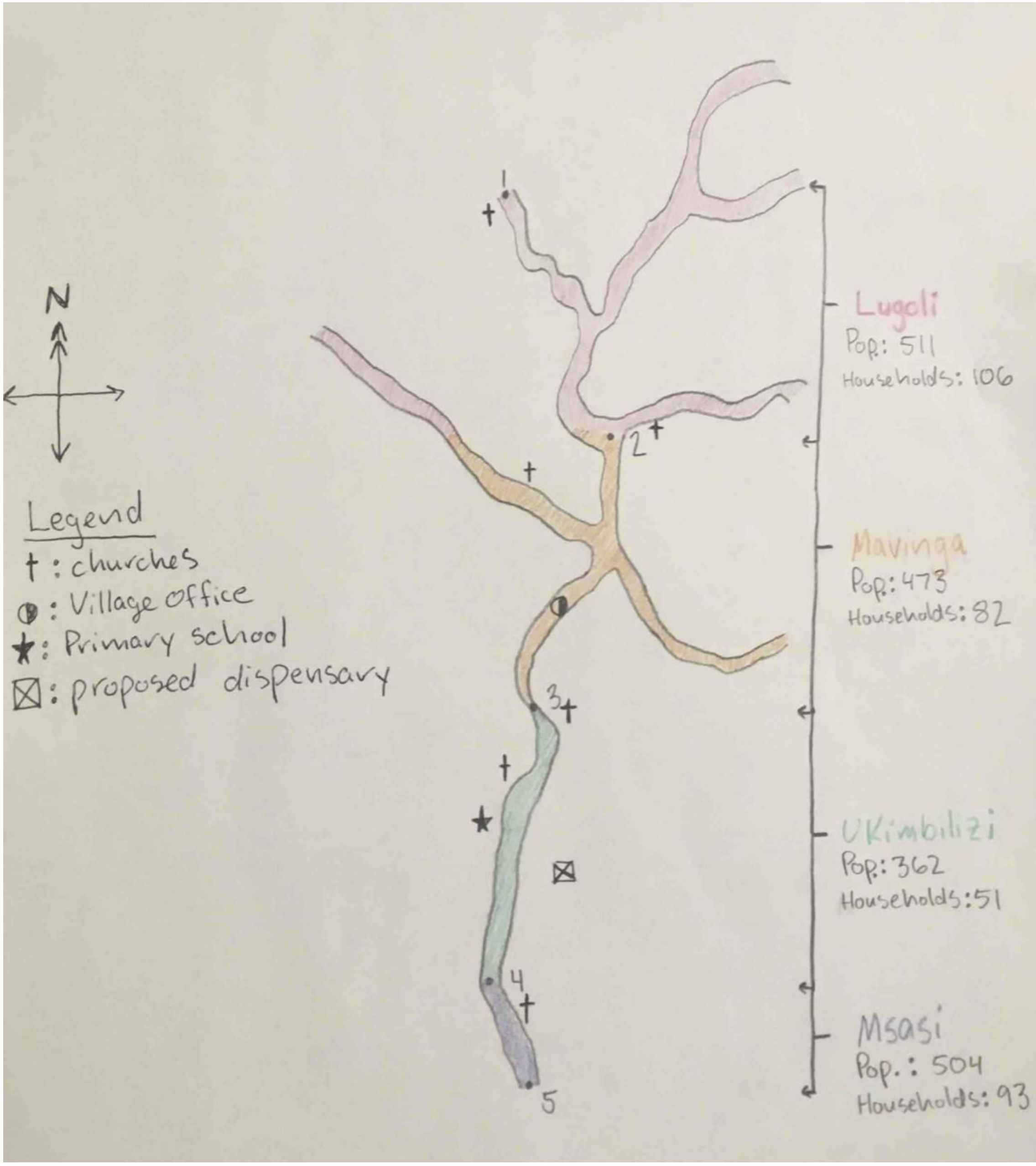

Figure 2: Idunda Map with Sub-Villages and Populations

Several significant locations are scattered throughout the village limits of Idunda. A primary school, shown by a star in Figure 2, is a major location of importance. The primary school had 491 students when we visited on January 11th, 2019, but the enrollment for the school year is expected to reach approximately 550 students. Eight staff members, including teachers and the headmaster, live on the school grounds. Currently, the school uses water for drinking, cleaning, and watering the plants in the courtyard. The school does not currently cook for students; however, a new government initiative may change this in the future, subsequently increasing water use.

The village does not currently have a medical dispensary but is in the process of building one. The old medical dispensary was closed because the facility was not up to code. The new facility is planned to be operational by 2021 and will be located adjacent to the old dispensary. This location of importance can be seen in Figure 2, marked by an “x”. The medical dispensary in Idunda will be funded by the Lutheran Church and staffed by the government.

The village also has six churches, of both Lutheran and Protestant denominations, scattered throughout the village. Church locations are visible as crosses on Figure 2. Lutheran is the dominant denomination of Idunda, with approximately 1,400 people in the village belonging to the Lutheran congregation.

The Village Office, shown as a half circle on Figure 2, is located at the highest elevation point in Idunda. The Village Office contains a committee meeting room as well as a jail cell. The Village Office is a noteworthy location because the proposed water distribution system pumps water up to this location, subsequently utilizing the elevation head to distribute water to other locations around the village.

Several locations within sub-villages received nicknames to make identification easier when discussing the proposed design. A strip of stores on the north end of the village in the sub-village of Mavinga, colored orange in Figure 2, became known as “Rosedale”. A densely populated section of Msasi, colored in purple in Figure 2, received the nickname “Mall of America”. The nicknames carry throughout the design but are always associated with their respective sub-village names.

3.2 | Current Water Sources

The demand for a water system in Idunda is high because the village does not currently have any pumps or water distribution systems. Several years ago, an attempt was made to dig a borehole with a mud rotary machine, but the presence of rock proved the attempt unsuccessful. Currently, villagers gather water from surface sources. The water sources are significantly lower in elevation than the main village road. Reaching the sources requires slippery descents over treacherous terrain. To add, water quality tests performed on the surface sources proved that the water is unfit for consumption due to the presence of coliform and E. coli bacteria (World Health Organization, 1997).

Idunda villagers understand the need for easier access to clean water and initiated the conversation regarding the implementation of a water distribution system in their village. After listening to a program on Radio Furaha, the village pastor reached out to St. Paul Partners indicating Idunda’s interest in a water distribution system. St. Paul Partners set up a field visit and analyzed the conditions of the site. Following that, St. Paul Partners organized for a team of University of Minnesota engineering students to visit the village to create a preliminary design for a water distribution system. Per St. Paul Partner’s request, Idunda formed a water committee to facilitate the initiative. The committee does not currently have any funds or tasks but is ready to act once directed.

Three main surface sources are utilized on the Southern end of the village: Mukaravadanda, Kalengakelu, and Mdetema. Mdetema is made up of three different gathering points: Mdetema A, B, and C. Figure 3 shows the location of the current water sources in relation to some of the important village landmarks.

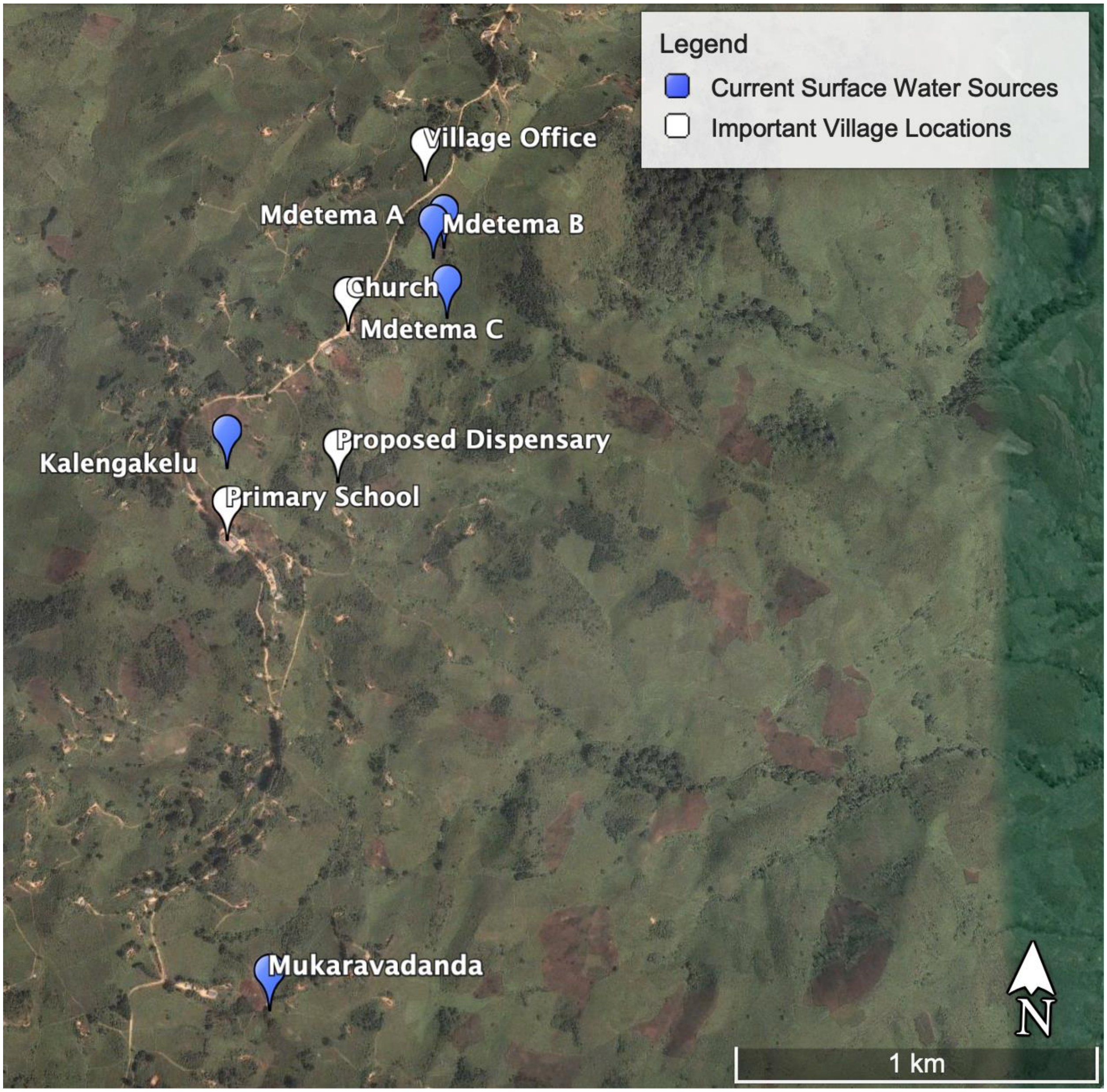

Figure 3: Map of the current water sources in Idunda with important landmarks for reference.

Mukaravadanda is a surface water source in the Southern portion of the village near the Lutheran Preaching Point in Msasi. The source is a small pond that transitions into a stream. The stream is fed by a mountain spring. The source is adjacent to corn fields and serves roughly 10 households. The water is visibly clear, but many bugs can be seen on the surface of the water.

A water quality field test indicated the presence of both coliform and E. coli in the water. Further water quality analysis can be found in Section 3.3.

Figure 4: Mukaravadanda water source. The coordinates for Mukaravadanda are -8.13611° S, 36.0893° E.

Kalengakelu is a surface water source located in the valley adjacent to the primary school. This source serves the primary school students, as well as more than 10 households in the surrounding area. The source begins as a small stagnant pool with a grey color and with many bugs and tadpoles. The pool then transitions into a stream. The source is plentiful throughout the year. Kalengakelu is the location of the failed mud rotary drilling attempt. In English, Kalengakelu means “White Water”. Water quality tests indicated the presence of both coliform and E. coli bacteria. Relative to the other sources tested, Kalengakelu contained the most bacterial contamination. Further water quality analysis can be seen in Section 3.3.

Figure 5: Kalengakelu water source. The coordinates for Kalnegakelu are -8.12483° S, 36.0878° E.

Mdetema is a surface water source in the valley to the east of the Village Office. Mdetema A and B are collection pools for water seeping out of the mountainside. The two pools are physically separated but have similar appearances. The sources are stagnant, but clear. Bugs and tadpoles swim in the pools. Although the sources supposedly never dry out, both had small yields based on visual observation at the time of the field visit, which took place during the rainy season.

Figure 6: Mdetema A water source. The coordinates for Mdetema A are -8.120125° S, 36.0922° E.

Figure 7: Mdetema B water source. The coordinates for Mdetema B are -8.11993° S, 36.0924° E.

Mdetema C is a surface water source approximately 100 vertical meters into the valley to the east of the Village Office, near Mdetema A and B. Water collects underground, seeps to the surface at Mdetema A and B, returns underground, and finds the surface for good at Mdetema C. Thus, Mdetema C is the point at which Mdetema exits the mountainside and becomes a surface stream. At the source, water flows over a rock, forming a one-foot waterfall. The water appeared visibly clear in the stream, however, when collected in a bottle, slight turbidity was detected. According to villagers, the flow rate of the stream varies throughout the year, but never runs dry. In the dry season, the stream is a trickle, but in the rainy season, water can reach up to a person's knees. An estimate of the stream flow in January was measured. As shown in Figure 8, the stream flow divided into two sections; log flow and rock flow. To estimate the flow rate, a plastic water bottle was cut, and the time needed to fill the container was recorded for each section of the stream. The ratio of water flowing over the log versus the rock was determined. The amount of time to fill the entire 1.5-liter bottle with the log section of the stream was recorded for multiple trials. The estimated flow for the whole stream was found to be roughly 59,000 L/day. For accuracy, the flow rate of the stream should be measured at various times of the year to determine the variance of the source. Water quality tests proved the presence of coliform bacteria and the absence of E. coli in the Mdetema C stream. See Section 3.3 for further water quality analysis.

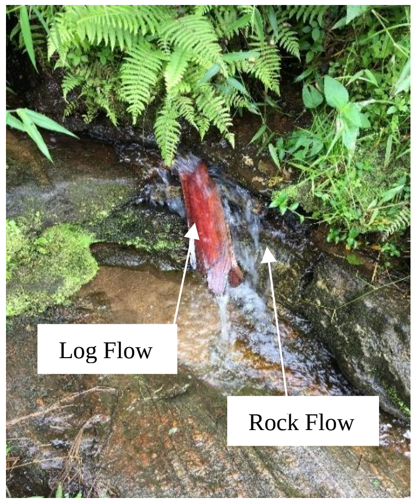

Figure 8: Mdetema C water source. The coordinates for Mdetema C are -8.12142° S, 36.0925° E.

3.3 | Water Quality Testing

Water quality tests determining the presence or absence of coliform and E. coli bacteria were performed on four of the five water sources. Test results are shown in Table 2. Colilert and Petrifilm tests were used; both determining the presence or absence of coliform and E. coli bacteria. The Colilert test consists of a vial, nutrients, and ten mL of water. The test utilizes nutrient indicators that produce color or fluoresce when metabolized by certain bacteria (IDEXX Laboratories, 2017). After a 24-hour incubation period, yellow water indicates the presence of coliform and fluorescence under light indicates the presence of E. coli. The Petrifilm test involves a field agar, Violet Red Bile nutrients, triphenyl tetrazolium chloride (TCC) indicator, and BCIG indicator. Coliform bacteria react with the indicators and turn red. E. coli react with BCIG and are identified as blue colonies with gas bubbles (3M, 2017). After inoculating the agar medium with one mL of water, the sample is incubated for 24 hours. Following the incubation time, the number of colony forming units (CFUs) are counted, differentiating between coliform and E. coli bacteria.

Examples of the water tests are shown in Figures 9 and 10. Kalengakelu, the source used by the school, had the highest coliform and E. coli counts. Mdetema C, the most promising source, had the lowest bacterial counts.

Table 2: The Coliform and E. coli test results for four of the surface water sources.

Source Name	Sample ID	Colilert Test	Petrifilm Coliform Count (CFU)	Petrifilm E.coli Count (CFU)
Mukaravadanda	1A	Yellow; Not Fluorescent	102	0
	1B	Yellow; Not Fluorescent	47	1
Kalengakelu	2A	Yellow; Not Fluorescent	~940	1
	2B	Yellow; Not Fluorescent	~1200	8
Mdetema A	3A	Yellow; Not Fluorescent	80	1
	3B	Yellow; Not Fluorescent	87	0
Mdetema C	4A	Yellow; Not Fluorescent	32	0
	4B	Yellow; Not Fluorescent	36	0

Figure 9: Example of a Colilert Test positive for Coliform bacteria. This is a test result from Mukaravadanda.

Figure 10: Example of a Petrifilm Test with both E. coli (blue CFU) and Coliform (red CFU) present. This is a test result from Mukaravadanda.

3.4 | Determining the Design Source

Due to the rough condition of the roads leading to Idunda, it is not possible to bring drilling equipment to the village. Thus, a borehole is not a viable option to serve as a design source for a water distribution system. The decision to utilize surface water as a design source was made based on three parameters: relative bacterial contamination, volume, and location. Comparing the water quality results in Table 2, Mdetema C clearly contains the fewest coliform bacterial counts in relation to the other sources. To add, the source indicated no presence of E. coli. Mdetema C proved to be the least contaminated surface water source in the Idunda village. The flow rate of the Mdetema C stream, roughly 59,000 L/day, is enough to supply the village population with water. Further analysis of the water demand can be found in Section 4.0. Mdetema C sits at the highest elevation relative to the other sources. Because of its proximity to the Village Office, the source can be pumped to the highest point in the village, subsequently utilizing the elevational head to distribute water to other points in the village. The water quality, flow rate, and location of Mdetema C were the deciding factors in choosing the stream as the source for the proposed water distribution system design.

3.5 | Village Needs, Priorities, and Involvement

The village needs and priorities were predominantly determined by meeting with the village executive committee and the water committee. The water committee was formed when the village learned of the pending visit from University of Minnesota students and St. Paul Partners. The committee had not taken on any responsibilities but was able to provide valuable insight to the current water situation. It was immediately made clear that access to safer water was a high priority for the villagers, and they had a strong need for a distribution system. Although the committee did not report problems with water-borne illness, it was hard to confirm since there is presently no medical dispensary and thus no medical records. However, based on standards set by the World Health Organization, the water is unfit for drinking because of the presence of coliform and E. coli bacteria, as described in Section 3.3 (World Health Organization, 1997).

The highest priority identified by the water committee was to provide water access to the primary school. If water is available at the school, it will impact many households because most families have kids in the school. To add, children represent the future of the village and their health is paramount for a successful society. The primary school students currently obtain water from Kalengakelu, the source with the most contamination relative to the other sources tested, confirming that the school should be a high priority.

The water committee stated that the proposed medical dispensary was the second priority. To adequately treat illness within the community, the dispensary requires access to safe water. Servicing the proposed dispensary with water also serves the entire village because any sick community member can visit the dispensary for treatment.

The six village churches are the third priority for water service, as identified by the water committee. Idunda is a faith-based community and many villagers attend church on a regular basis.

Servicing the churches with water is a way to place a distribution point in a central location and thus reach a large fraction of the population.

Village involvement in the project was discussed with the water committee to initiate a conversation about system sustainability. To have an ongoing and sustainable water system, the village needs to take ownership of the project. St. Paul Partners staff will work directly with Idunda villagers to build management capacity prior to any planned project implementation. During the implementation phase, the committee agreed to provide a workforce to dig the trenches needed for the pipe network. Once the project is completed and the project enters long-term management, it is crucial that the village water committee taxes water use. The collected funds must be used responsibly to ensure that the system can be properly maintained. The water committee did not have a plan of how money would be collected but will decide upon a taxation procedure once the project is verified to move forward. The committee must also open a bank account for water finances. Being that the water committee is a new establishment, roles must be created (e.g., chairperson, treasurer, local custodians of distribution points, etc.) to ensure that people are held accountable.

The proposed water distribution system requires several other measures of investment from the community. To ensure that the quality of the Mdetema water source does not decrease, the watershed should be designated as protected and kept free of houses, crops, and livestock. Because the proposed distribution system utilizes a surface source, a sedimentation basin is necessary. The tank must be cleaned intermittently to clear build-up. To add, the surface source is not inherently free from bacterial contamination. Consistent water treatment is highly encouraged to provide villagers with the safest water possible. The proposed design requires the implementation of solar panels, necessitating a security guard. Ultimately, the village will be responsible for the operation and maintenance of the system.

4.0 | Design Criteria

The Ministry of Water and Irrigation provided a set of guidelines regarding water system design in Tanzania that was used as guidance (Ministry of Water and Irrigation, 2009). The guidelines are provided in Appendix A for reference. A summary of how the guidelines were applied is described below.

1. *The design period should be for a minimum of 10 years, and the population data should be approximated at a rate of 2.7% per year* (the average national population growth). This translates to a 31% population growth (1.027^{10}). A 2.7% growth rate was used for the design because it is the average national growth rate in Tanzania, although this is likely an overestimation for Idunda. See Table 3 for the projected populations of each sub-village in Idunda in 2029.
2. *Water demand should be based on 25 L/person/day. For schools, design for 10 L/student/day. The dispensary also has a demand of 10 L/student/day.* Table 3 shows the breakdown of the demand by sub-village, school, and dispensary for the current and future demand. As previously mentioned, the approximate flowrate from source Mdetema C was 59,200 L/day, which would meet the current and future demand for water. However, the demand in Table 3 is the demand based only on the raw demand calculated from populations but does not account for the 20% water loss guideline, described later in this section in guideline 10. The demand calculations accounting for the water loss are tabulated in Appendix C. Also, as previously mentioned, the flowrate from Mdetema C should be rechecked near the end of the dry season to ensure that there is enough water yield throughout the year to supply the village. The 59,200 L/day estimate may not be reliable year-round.

Table 3: Current and future water demand for Idunda based on populations.

		2019			2029 (with 2.7% Annual Growth Rate)		
Location		**Population**	**Demand Per Capita (L/person/day)**	**Total Demand (L/day)**	**Population**	**Demand Per Capita (L/person/day)**	**Total Demand (L/day)**
Lugoli		Not Accounted for in Phase I			Not Accounted for in Phase I		
Mavinga		473	25	12,000	620	25	16,000
Ukimbilizi		362	25	9,100	475	25	12,000
Msasi		504	25	13,000	661	25	17,000
Primary School	**Students**	550	10	5,500	721	10	7,200
	Staff	8	25	200	11	25	280
Proposed Medical Dispensary		15	10	150	20	10	200
			Total Demand (L/day)	**39,000**		**Total Demand (L/day)**	**52,000**

3. *The system should be designed to accommodate 2.5 times the average rate of demand.* Hourly water demand is bimodal, with the largest peak in the morning, followed by a lull around noon, and a second peak in the late afternoon. To calculate the necessary flow for each pipe to meet the peak demand, the daily flow was divided by 12 hours and multiplied by 2.5. The pipes were designed to meet the peak hourly demand of each distribution point.
4. *The system should have a minimum water storage capacity equal to 50% of total daily demand.* The design for the system incorporates three 10,000 liter tanks, one 5,000 liter tanks, and one 1,000 liter tank. This provides a total storage capacity of 36,000 liters, which is significantly more than 50% of the total daily demand. This additional capacity was deemed necessary because the system will only be operational when solar power is available (about 8 hours a day), but the water source must collect water over a 24 hour period in order to meet the total daily demand. Therefore, there must be enough storage to collect all the water overnight at the source so that it can be pumped to the ridgeline in the morning when solar power is available. Storing solar energy in batteries is an option to extend the pumping period and reduce the amount of storage needed, but due to the difficulty of battery disposal, the option was negated.
5. *The minimum capacity of each spigot should be 10 L/min.* Each distribution point (DP) should be designed as a "T" having 2 spigots, and each DP should be able to provide 20 L/min. After the velocities of the pipe were determined for the chosen diameters (see Table 4 in Section 5.1.4), the worst-case scenario, when all the valves on the gravity main are opened, was tested

and the flow for each distribution point was determined. When the peak hourly demands were met for each distribution point, the maximum time taken to fill a 20 L bucket was found to be about 50 seconds.

6. *The maximum working pressure for a pipe should be approximately 80% of rating.* For example, if a pipe is rated at PN8 (max. pressure = 8 bar or 116 psig), it should not be used in environments where the pressure exceeds 0.8x116 psig, or 93 psig. The maximum pressure of each pipe occurred at the lowest elevation. After the maximum pressure ratings were determined for each pipe, the 20% safety factor was added to ensure an adequate pipe rating so that the working pressure of the pipe is approximate 80% of the rating, as recommended in the guidelines. A minimum pipe rating of PN 6 was used for all pipes to ensure that the pipe wall thickness is adequate.
7. *One DP can serve a maximum of 250 people. Maximum walking distance to a DP is 400 m.* Several DPs will serve more than 250 people in Phase I. This includes the DP Mavinga, DP Primary School, and DP Msasi. The central and southern portions of the village will be within 400 m of a distribution point with the implementation of Phase I. The northern sub village of Lugoli will not be served in Phase I, so about 30% of the village population will not have close access to a distribution point with Phase I. The goal is to supply water to the rest of the village with a Phase II design.
8. *The velocity of water in a pipe should typically be in the range of 0.5 – 1.5 m/sec.* Slower than 0.5 m/sec usually means your pipe is too large; larger may lead to water hammer or excessive pressure loss. Water hammer occurs when the flowrate of fluid in a pipe changes rapidly causing very high pressures in the pipe, which may result in burst pipes or leakage at joints. The velocity of water in each of the pipes was tested under various valve settings. The velocities in all the main pipes meet this design criteria. The velocities in the pipes to the distribution points are often slightly higher than the recommended range but because the distances that the water travels in those pipes is very short (e.g. 20 meters), this is not a concern. The villagers will also be able to adjust the valves to ensure that water does not aggressively spray out of the taps.
9. *Lines should be buried a minimum of 1 meter*. Sunlight degrades HDPE and farming practices can damage pipes laid near the surface. When the system is constructed, the villagers will be providing the labor for digging the pipe trenches. It will be emphasized that the pipes must be buried at least 1 meter deep to prevent the pipes from being hit or burned on the farming fields.
10. *Design for a total water loss of 20-25% to account for leaks, valves left open, etc*. The design for Idunda accounted for a water loss of 20%. The demand calculations accounting for the water loss is found in Appendix C. The water source will not provide enough water to serve the Phase I demand in 10 years when accounting for this water loss. However, so long as the system is maintained properly, the water losses are not anticipated to be this large. Combined with the aggressive estimates for population growth, we predict that our design demand is significantly higher than the real demand.

11. *All minor losses should be modeled at 5% of major losses. Treat valves separately.* The major frictional head loss was multiplied by 1.05 to account for the minor losses in the system. Valves at the distribution points were assumed to have a K_v value of 10 when the valve was completely open.
12. *Add 15% to pipe costs for fittings. Add 20% to supply costs (pipe/tank/concrete) for shipping.* In the estimated budget, 15% of the pipe costs was added for fittings. An additional 25% of the supply cost was added for shipping, which is higher than the recommended 20%. The increased shipping costs were associated with an assumption that the difficult road conditions leading to Idunda would add to the shipping costs.

5.0 | Proposed Design

The proposed water distribution system design has two phases. Phase I will service approximately 70% of the village of Idunda with access to safer water. Phase I covers the Southern and Central portion of the village. Phase II will provide the remaining villagers with access to safer water and will be located on the northern end of the village. The proposed design presented in the subsequent sections contains an engineered system for Phase I and potential solutions for Phase II.

5.1 | Phase I

5.1.1 | Overview

The proposed design for Phase I provides water to about 70% of the villagers in Idunda. It consists of a rising main bringing water from the source up to the ridgeline, a gravity fed distribution system extending to the north and south along the ridgeline, servicing the primary school and the sub-village of Mavinga, and a gravity-fed distribution system running through the valley and servicing the proposed dispensary and the sub-village of Msasi. Figure 11 shows a map of the proposed Phase I distribution system.

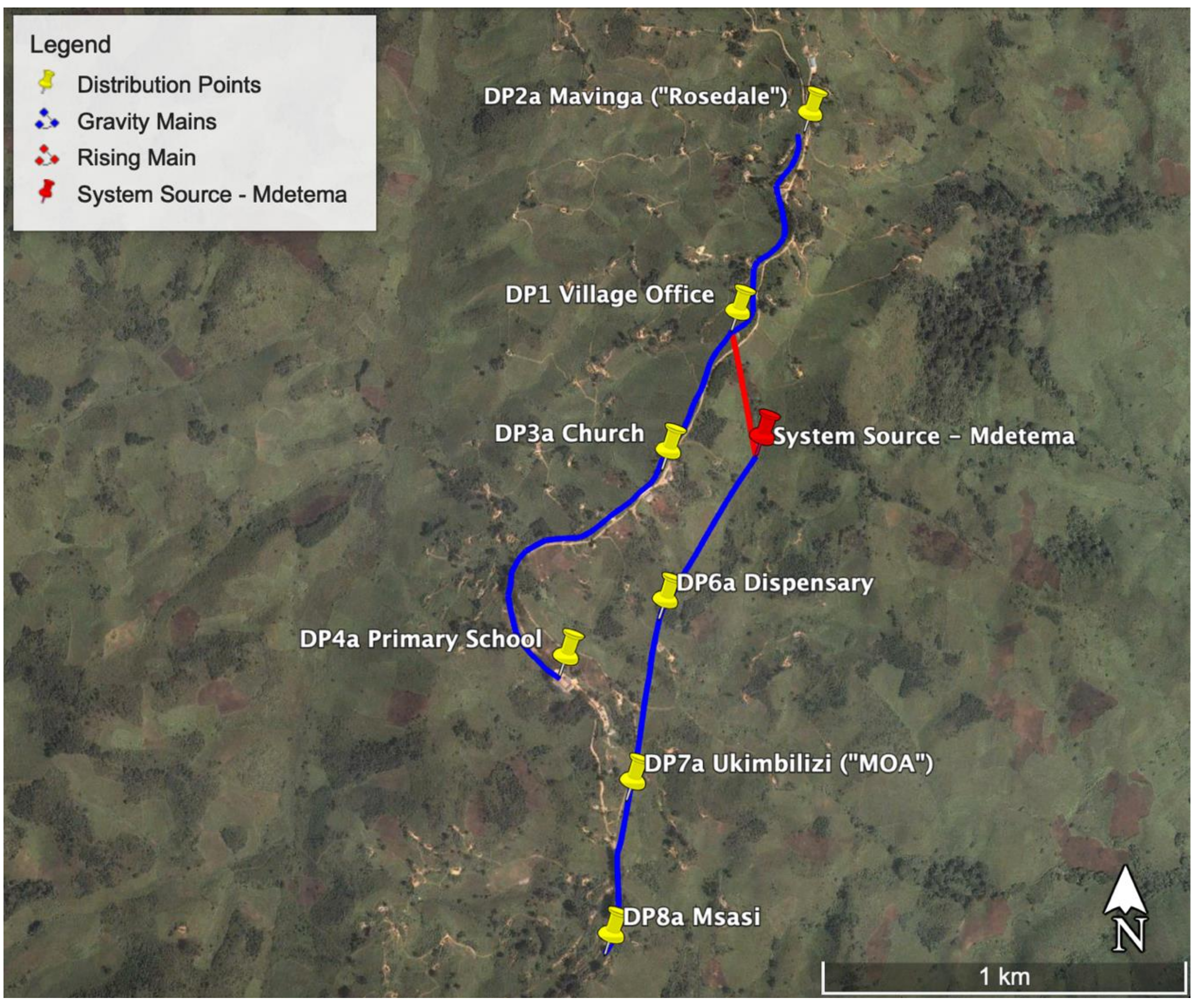

Figure 11: Overview of the proposed Phase I water distribution system servicing Idunda.

Table 4 contains a summary of the pipe runs and the corresponding diameters, lengths, and pressure ratings. Each number represents a point in the system and the numbers with an “a” are the distribution point locations. Pipe information is elaborated on in Section 5.1.3 and Section 5.1.4. Elevation profiles are also included for each pipe in Appendix E.

Table 4: Pipe Sizes, Lengths, and Pressure Ratings

Pipe #	Diameter [mm]	Length [m]	Pressure Rating
1-2	40	623	PN 6
2-2a	25.4	20	PN 6
1-3	40	395	PN 6
3-3a	25.4	20	PN 6
3-4	40	807	PN 12.5
4-4a	25.4	20	PN 6
5-1	40	317	PN 12.5
5-6	50	479	PN 6
6-6a	25.4	20	PN 6
6-7	50	458	PN 6
7-7a	25.4	20	PN 6
7-8	50	382	PN 8
8-8a	25.4	20	PN 6

Figure 12 displays a map of the piping network for the system. This map gives details for each pipe including the length, diameter, and pressure grades.

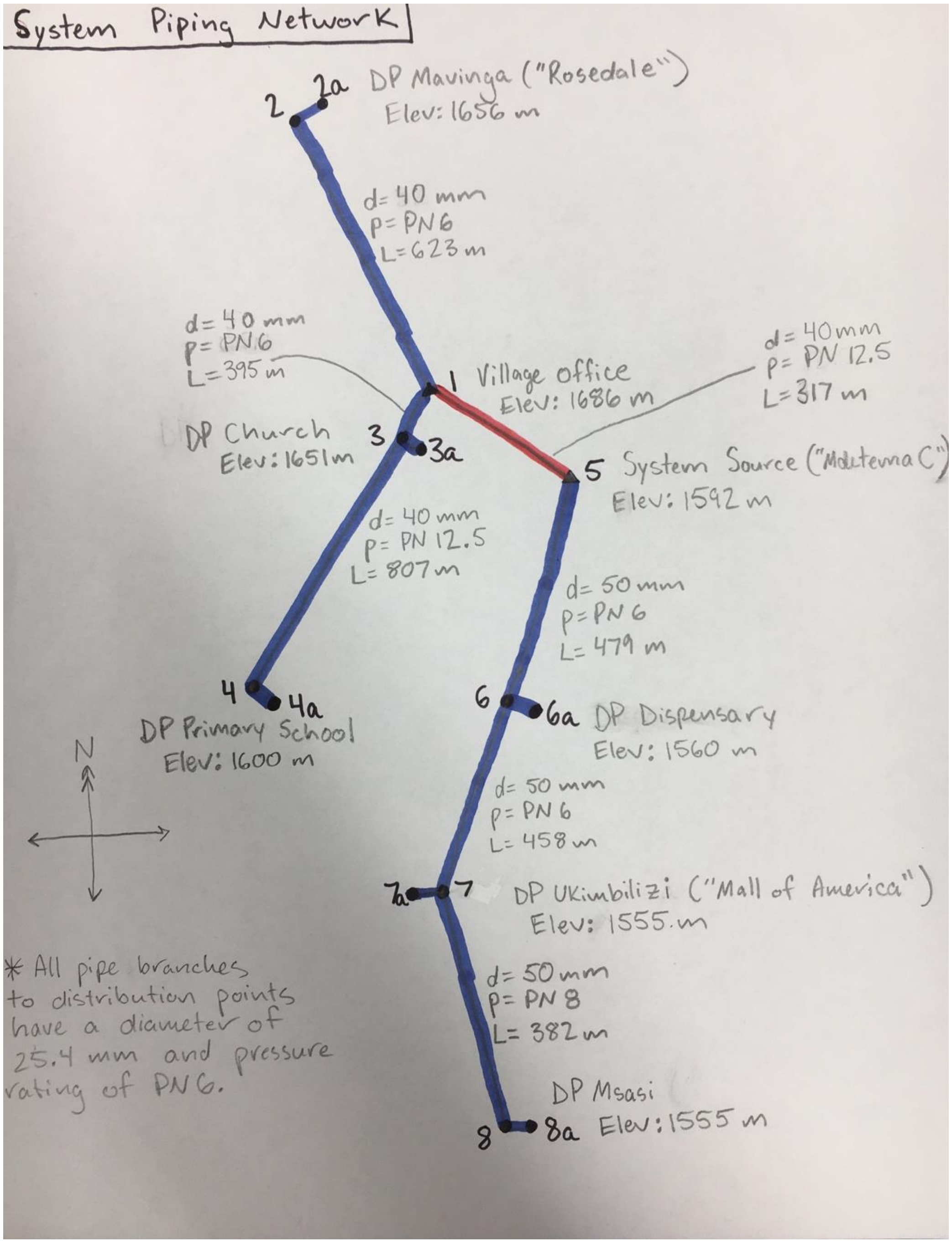

Figure 12: Map illustrating all distribution points, pipe sizes, pressure grades, lengths, and elevations.

5.1.2 | Water Source

After analyzing the cleanliness and location of each source, Mdetema C was selected for the Phase I design. Mdetema C had the lowest coliform count in addition to the lowest E. coli count. The source is located near the highest point in the village and had a higher elevation than most of the other sources that were visited.

The water from the source is planned to be collected using a concrete settling basin, as shown in Figure 13. The settling basin will serve to settle out particles and debris that may enter the water source. An area of the ground will be dug out under the spot where the source comes out from the mountainside to allow the water to fall into the basin. A gravity-fed pipe will lead from the basin to storage tanks, called SIM tanks, which will be located slightly downhill from the source. A detailed design for the settling basin is included in Appendix D.

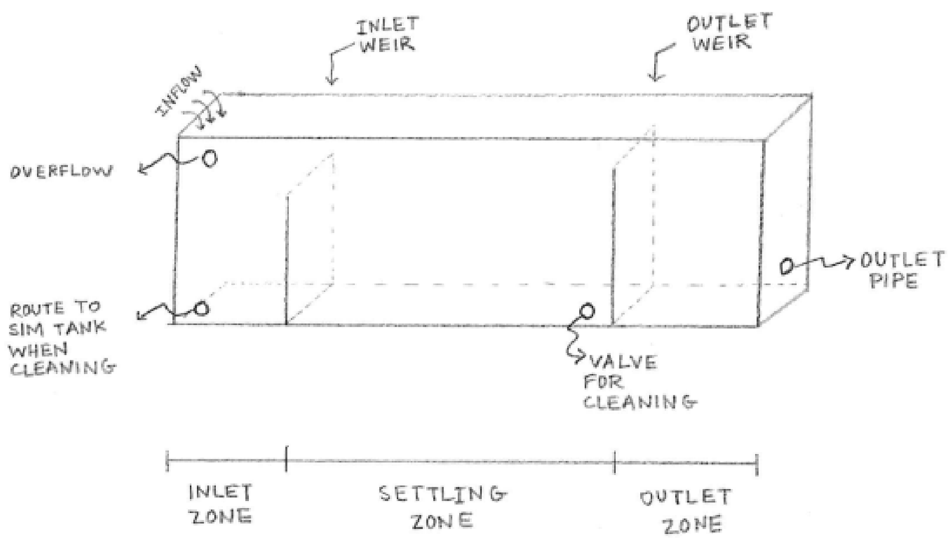

Figure 13: Proposed Sedimentation Basin

Ideally, a borehole would act as the system water source instead of a surface source. Due to rocky terrain, transporting a drill rig to Idunda is nearly impossible. Alternatively, a pit could be dug in the earth to act as a reservoir for water collection. Because subsurface data was not obtained, excavation options were negated.

5.1.3 | Rising Main

To serve the distribution points along the ridge, DP 1, 2a, 3a, and 4a, water from the system source will have to be pumped to the Village Office. The Village Office is the highest point of the village and is the proposed location of two SIM tanks. The elevation difference is 94 meters with a distance of 343 meters between the source and the Village Office. Since Idunda is off the grid, villager leaders do not anticipate getting electricity anytime in the near future. Therefore, multiple poles will be erected with the ability to hold eight solar panels required to power a three horsepower pump at the source. The size of the pump was determined assuming an overall pump efficiency of 50% (equations and calculations can be found in Appendix C). The solar powered pump will operate for roughly eight hours each day, during which time, it will pump approximately 34,700 L/day. According to the NASA's Prediction of Worldwide Energy Resources database, the average daily kW-hr/m^2 of sunlight through a year is 9.5 (NASA, 2018). Based on this data, eight pump operating hours is a conservative value, but it will ensure that the water supplied will be enough throughout the year. Figure 14, shown below, is the graph of the daily kW-hr/m^2 over each day in 2018 at the system source. To meet the required flow demand, the HDPE pipe extending from the source to the Village Office must be 40 mm in diameter. The HDPE pipe is specified to have a pressure rating of PN 12.5. Although a 20 mm pipe would be equally as effective (it would require an identical pump size and pressure rating), based on the pipe demands for other portions of the system, it was determined to be more cost effective to purchase additional 40 mm pipe rather than a different size pipe for the relatively short distance. A full list of the pipe sizes used and their respective prices can be found in Section 7.

Figure 14: A graph and histogram of the kW-hr/m^2 for each day of 2018.

5.1.4 | Gravity Mains

Water transported up the hill in the rising main will be stored in one 10,000-liter SIM tank and one 5,000-liter SIM tank (15,000 liters of total storage) situated at the Village Office. This water will principally serve residents of Mavinga, as well as the primary school. From the SIM tanks, water will be distributed both to the north and south, following the local ridgeline, as shown in Figure 11. Pipe details can be found in Table 4. To the north, a 40 mm pipe will run from the

Village Office (location 1) to a series of shops along the road approximately 623 m away (location 2a). Location 2a is in Mavinga and is also referred to as Rosedale. The gravity main has a rating of PN 6. Over the 623 m line, 30 m of elevation is lost. To the south, a gravity main services the Lutheran preaching point as well as the primary school. A 40 mm pipe runs from the Village Office (location 1) to the Lutheran preaching point (location 3a), covering 395 m and dropping 35 m in elevation. The pipe has a pressure rating of PN 6. The gravity main continues from the church (location 3a) to the primary school (location 4a) with a diameter of 40 mm. The pipe run spans 807 m and drops 51 m in elevation. The pipe has a pressure rating of PN 12.5. Although a 32 mm pipe would be sufficient for the transmission pipe in the gravity main from the Village Office to the Primary School, a 40 mm pipe was selected in order to reduce the number of different sized pipes in the system.

To service the southernmost reaches of Idunda, a gravity main extends directly from the source to Msasi preaching point. Along the way, the gravity main distributes water to the proposed dispensary and a densely populated area in Ukimbilizi, referred to as Mall of America. A 50 mm pipe runs from the source (location 5) to the proposed dispensary (location 6a). Running 479 m and dropping 32 m in elevation, the pipe has a pressure rating of PN 6. The 50 mm gravity main continues from the dispensary (location 6a) to Ukimbilizi ("Mall of America") (location 7a). The pipe covers 458 m, drops 5 m of elevation, and has a pressure rating of PN 6. From Ukimibilizi ("Mall of America") (location 7a), a 50 mm pipe runs for 382 m to Msasi preaching point (location 8a). The pipeline decreases and subsequently rises to end at the same elevation as the distribution point at Ukimibilizi ("Mall of America") preaching point. The pressure rating of the line is PN 8. At each distribution point location, a 25.4 mm pipe branches off the main gravity line to service the spigot. These lines run for 20 m and have a pressure rating of PN 6.

The pressures and the velocities in the pipes were found using Bernoulli's equation and the conservation of flow. An Excel code was used, which is included in Appendix B, and Appendix C contains all equations that were inputted into the Excel code. The peak hour demands for each distribution point were determined (included in Appendix C) and each pipe was chosen to accommodate these demands. K_v values were adjusted to simulate the most likely operation conditions, while maintaining enough flow to each distribution point to meet the peak hour demand and meet the guideline that each distribution point should produce at least 20 L/min. The velocities in each pipe under the likely operation conditions and the maximum pressure in each pipe, which will occur when all valves are shut, are tabulated in Table 5. More details can be found in Appendix B and C.

Table 5: Likely Operating Velocities and Maximum Pressures

Pipe #	Velocity [m/s]	Maximum Pressure [bar]
1-2	0.993	2.94
2-2a	2.462	NA
1-3	1.487	3.43
3-3a	1.922	NA
3-4	0.712	8.44
4-4a	1.767	NA
5-1	1.205	9.25
5-6	1.085	3.14
6-6a	0.798	NA
6-7	0.879	3.63
7-7a	1.052	NA
7-8	0.608	4.91
8-8a	2.355	NA

5.1.5 | Storage Tanks

To use the surface water source, water will be collected at the source and stored in two 10,000-liter SIM tanks. Because the design requires the full yield of the constantly running source of water to meet the water demand, but the water can only be pumped for a portion of the day, a large amount of storage capacity is necessary to supply the gravity mains on the ridge. The storage capacity at the source needs to be about two-thirds of the demand on the ridgeline, such that water can be collected overnight and is available for pumping in the morning. Although batteries were considered to store solar power and reduce the number of SIM tanks needed, other concerns arose with the use of batteries. Solar batteries are expensive and would be difficult to replace and dispose of in a village such as Idunda. The pipe leading from the settling basin at the source to the base of the SIM tanks will fill the two SIM tanks. The SIM tanks will be connected to each other with a small pipe near the bottom of the tanks; this will ensure that all the tanks fill evenly due to the hydrostatic pressures.

In addition to the SIM tanks at the source, one 10,000-liter and one 5,000-liter SIM tank will be placed at the Village Office and a 1,000-liter SIM tank will be placed at the proposed dispensary. The two SIM tanks at the Village Office will help accommodate the daytime variations in demand so that the flow at the distribution points is not completely dependent on the pumping capacity. Water storage at the Village Office will allow people on the ridgeline to obtain water in the early morning or at night even when the solar powered pump is not able to run. The 1,000-liter SIM tank at the proposed dispensary will serve as a back-up water supply if the system temporarily breaks. The SIM tank should provide enough water to the proposed dispensary to continue treating patients for about five days after the system breaks or is shut off.

5.1.6 | Distribution Points

The Phase I system will include seven distribution points: four along the ridge and three in the valley and southern portion of the village. Table 6 shows the locations and elevations of the proposed distribution points and the critical location of Phase I. Figure 11 provides a map of the proposed water supply system and shows the location of each distribution point.

Table 6: Phase I design points of interest.

Point Number	Description	Latitude	Longitude	Elevation (m) (± 10 m)
1	DP Village Office	8.11852° S	36.0919° E	1686
2a	DP Mavinga ("Rosedale")	8.11361° S	36.0938° E	1656
3a	DP Church	8.12171° S	36.0903° E	1651
4a	DP Primary School	8.12643° S	36.0879° E	1600
5	Mdetema Water Source	8.12142° S	36.0925° E	1592
6a	DP Dispensary	8.12511° S	36.0903° E	1560
7a	DP Ukimbilizi ("Mall of America")	8.12910° S	36.0894° E	1555
8a	DP Msasi Preaching Point	8.13244° S	36.08861° E	1555

In the Phase I design, there are three gravity mains. On the ridge line, there are a total of four distribution points among two separate gravity mains. DP1 Village Office is the highest point of the village so the water will be pumped from the Mdetema water source to the Village Office. DP2a Mavinga ("Rosedale") will serve the northern portion of the village, sub-villages Lugoli and Mavinga. There are a few small stores, several households, and a Lutheran Preaching Point at DP2a. DP3a is to the south of the Village Office and serves the main Lutheran Church in the village. DP4a will be located in the courtyard of the primary school to provide cleaner drinking water to the students, which was the highest village priority.

In the valley, there are three additional distribution points on another gravity main. DP6a Dispensary will supply the dispensary and potentially serve a few households around the dispensary as well. DP7a Ukimbilizi ("Mall of America") serves a significant number of households and several shops in the vicinity. Lastly, DP8a is near the Msasi Preaching Point, which is the busiest church in the village and at the southern end of the village.

To ensure meeting the Tanzanian design guideline that "no villager should travel more than 400 meters for water" was met, Google Earth was used to create 400 meter radii circles around each distribution point, as shown in Figure 15. The northern portion of Idunda is not served by Phase I of the design for multiple reasons. The highest village priorities were located in the central and southern portions of the village. The surface source selected also does not have enough yield to supply the entire village population in 10 years, and there is a large distance and elevation drop between the system water source and the northern portion of the village. A proposed design for Phase II, discussed in section 5.2, addresses this portion of the village.

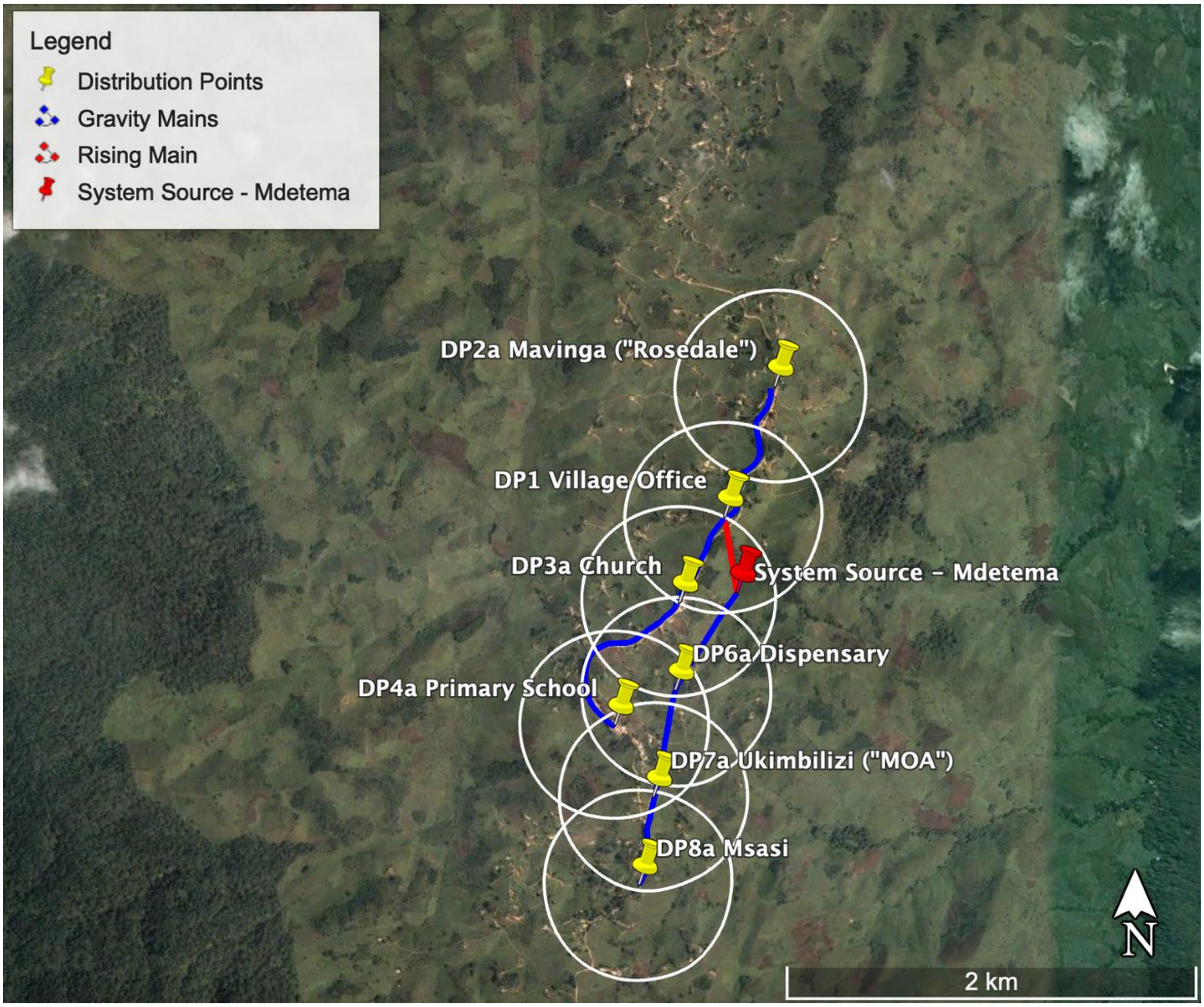

Figure 15: Proposed Phase I System with 400 Meter Radii around Distribution Points

5.2 | Phase II

Several options exist to completely service the village of Idunda with a water distribution system. The portion of the village not served in Phase I is the sub-village of Lugoli. The different areas that Phase I and Phase II would serve are highlighted in Figure 16. The first option to serve Lugoli is to find a surface source in the northern portion of the village. An independent gravity-fed system would be implemented using a source closer to Lugoli. Two or three distribution points would likely be placed near the population density of Lugoli to serve the remaining 30% of the population not served by Phase I.

As a second option, a mud rotary drill could be used to attempt to establish a well in the valley situated at the northern entrance to the village. The well would provide clean groundwater to the village residents in Lugoli. It is believed that a drilling attempt at this location would be more likely to work than the attempt on the south end of the village because less rock may be present in the sub-surface at the lower elevation. It is also believed that a mud rotary drill would have an easier time reaching the village as compared to an air hammer drill. The implementation of Phase II is important because a significant percentage of the village population lives in the area. Because information on the north end of the village is uncertain, design calculations for Phase II were not conducted.

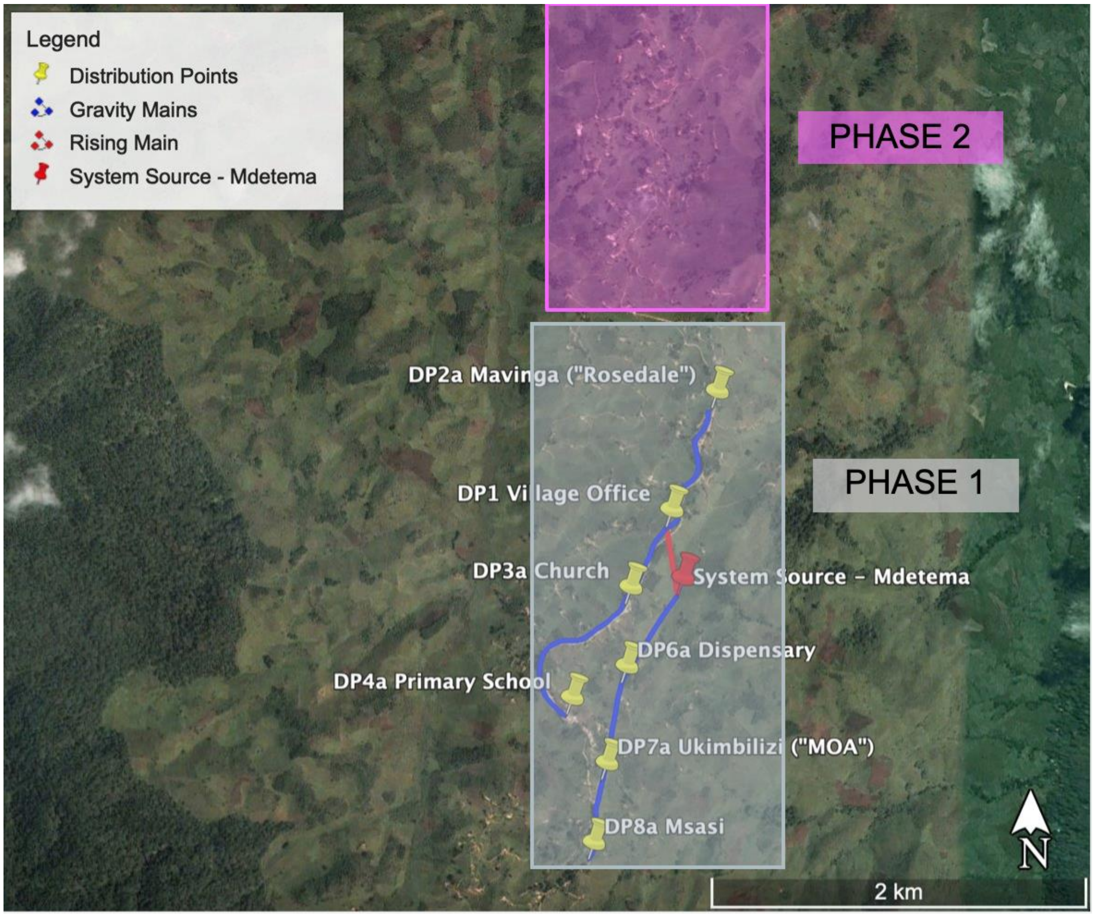

Figure 16: Area Served in Proposed Phase II

6.0 | Social Impacts of Design

6.1 | Health and Safety

Currently, villagers must travel considerable distances and navigate drastic elevation changes to gather water. A mix of soil and weather conditions make steep trails unsafe for descent and ascent. During the rainy season, the clay soil becomes slick and difficult to maintain solid footing. Traversing the terrain while carrying a 20-liter bucket filled with water is treacherous. The implementation of a water distribution system will create safer conditions for gathering the essential resource.

Not only does water collection present a physical safety hazard, but the current sources tested positive for coliform and E. coli bacteria. Both bacteria types are indicators of contamination, which could be pathogenic and lead to waterborne illnesses. Although the water source is a surface spring source and therefore not immune to impurities, the closed water distribution system will assist in keeping the water safe from the origin. The bacteria count entering the system in the incoming water flow will theoretically be the same or less than the bacteria exiting the system. If the system is closed to the air, animals, plants, and organic matter cannot enter the system beyond the origin point, reducing bacteria's food source and limiting growth and reproduction within the system. The settling basin will serve to screen out large debris, such as leaves, and to settle particles. In addition, regular or periodic water treatment at the storage tanks, such as the addition of disinfection tablets, remains an option in the proposed system. Although this would increase operating costs, it could also significantly improve water safety. Since the overall operating costs of the solar powered system are relatively low, the water committee can decide if they want to pursue other treatment options once the system is operational.

Because Idunda does not currently have a functioning dispensary, health care records are not available for the village population. In numbers, it is not clear how many villagers suffer from water-borne sicknesses each year. However, the consensus within the village is that people do not get sick from drinking the water. Although the villagers did not express a large problem with water-borne illnesses, they understand the importance of clean water and fear that water-borne illnesses may plague villagers in the future if the water quality decreases. A water distribution system will provide safer water than most villagers currently have access to and if villagers agree, chlorine tablets can be used to disinfect the water. Disinfection could significantly improve the water quality by decreasing the number of bacteria in the water, as discussed above. The ease of access and cleanliness of water will be improved with the implementation of a water distribution system, positively impacting many lives.

6.2 | Working to End the Poverty Cycle

Currently, villagers must dedicate a large portion of their day to gathering water. Both distance of dwellings from the water source and water demand impact the amount of time villagers must spend collecting water each day. A water distribution system would place distribution points within 400 meters of many households, drastically reducing the distance that must be traveled to obtain water. The risks involved with accessing water will also dramatically decrease because distribution points will be on the ridgeline and near the road. If villagers can reduce the amount of time they spend collecting water each day, they can focus on other tasks, such as education and work. Students can advance out of poverty by educating themselves to obtain better paying jobs. Farmers in the village can focus more energy on their fields, produce greater yield, and thus make more profit.

Health is another important component of the poverty cycle. A water distribution system would decrease the risk of water-borne illnesses. If the villagers are ill less often, they can keep up with school and work. Overall, a water distribution system has many benefits to a village and gives the inhabitants opportunities to escape poverty.

6.3 | Environmental Impacts

One of the key concerns for the proposed design is the impact on the existing water source. Because it is planned to use a natural spring surface source, there is a possibility that access to water may be reduced for people further downstream. The full capacity of the stream is required to supply the village, which would eliminate access to stream water below the collection point. The pastor assured the design team that there were no households in the valley below the source that use the stream as the water source. Furthermore, the gravity line to the dispensary passes near the area, which would be downstream. Should there be people found to use the source downstream, this issue should be addressed prior to implementing the system.

6.4 | Operating Costs and Maintenance

After construction of the system, the villagers will be responsible for the operating costs of the system. The water committee agreed to create a bank account to deposit water collection fees, although the fee collection process was still uncertain. Because the system will be solar powered, the costs of running the system will be low. However, villagers will be responsible for maintenance costs including fixing leaky valves, cleaning the tanks and settling basin, and providing security of the system. Should disinfection water treatment be implemented after the system is operational, the operating costs will increase. The water committee will need to decide if they will treat the water, however they should be strongly advised to do so. If they elect to treat the water, they will need to determine the frequency of treatment and how to price the water accordingly to account for the additional operating costs.

The water committee will also be crucial to ensure that funds are saved for when components of the system will need to be replaced. Solar panels have an average life expectancy of 30 years. Overtime, external factors such as weather will degrade the panels and reduce the energy production capabilities of the panels (Aggarwal, 2016). The supply pipes are under constant pressure and thus have an average lifespan of 50 years (Essentra, 2015). Plumbing components such as the spigots have a life expectancy of 15 years (Mallery, 2013). Polyethylene storage tanks require replacement after an average of 20 years, depending on external factors and if treatment options are used within the tank (Assmann Corporation of America, 2015). The system pump has a life expectancy of 10 years and greatly depends upon the amount of sediment in the water (A1

Well Drilling, 2017). Factoring all the components of the system together returns an average system life expectancy of 25 years. Funds must be allocated appropriately to account for necessary replacements to keep the system operational and extend the lifespan.

7.0 | Budget

In designing the water distribution system for Idunda, all aspects of the project were examined and priced to get an estimated cost. Table 7 contains the estimated budget for Phase I of the Idunda water distribution system.

Table 7: Phase I Proposed Design Estimated Budget

PHASE 1				
Item	**Description**	**Qty.**	**Price**	**Amount**
Polytank (10,000 L)	10,000 L	3	$ 1,072.53	$ 3,217.58
Polytank (5,000 L)	5,000 L	1	$ 366.67	$ 366.67
Polytank (1,000 L)	1,000 L	1	$ 70.23	$ 70.23
Tank foundations/fittings	Includes concrete and rebar	5	$ 550.00	$ 2,750.00
System pump	3 hp	1	$ 2,700.00	$ 2,700.00
Distribution points		7	$ 175.00	$ 1,225.00
Subtotal				**$10,329.47**
Solar				
Solar panels		8	$ 298.76	$ 2,390.10
Solar poles		2	$ 50.00	$ 100.00
Protection	Fencing for livestock	1	$ 250.00	$ 250.00
Wiring		1	$ 500.00	$ 500.00
Subtotal				**$ 3,240.10**
Piping				
Pipe (25.4 mm, PN 6) 150 MTRS		1	$ 51.88	$ 51.88
Pipe (50 mm, PN 6) 150 MTRS		7	$ 232.68	$ 1,628.73
Pipe (40 mm, PN 12.5) 150 MTRS		8	$ 294.17	$ 2,353.35
Pipe (50 mm, PN 8) 150 MTRS		3	$ 312.55	$ 937.65
Pipe fittings	15% of piping cost	1	15%	$ 801.42
Subtotal				**$ 6,144.21**
Settling Tank				
Concrete (cement bags + aggregate)		288	$ 6.80	$ 1,957.82
Reinforcing steel bar #3 (meters)		141	$ 2.75	$ 387.75
Subtotal				**$ 2,345.57**
Labor				
Piping/Trenches		2550	$ 2.00	$ 5,100.00
Plumbing (Fundi)		1	$ 500.00	$ 500.00
Catch basin		1	$ 300.00	$ 300.00
Village in-kind contribution	Village offered labor for piping/trenching	1	$ (5,100.00)	$ (5,100.00)
Subtotal				**$ 800.00**
Expected Annual Costs	Maintenance (cleaning, repairs, chlorination)			**$ 500.00**
Supplies shipping			25%	**$ 5,514.84**
Contingency (10%)			$ 5,001.87	**$ 5,001.87**
TOTAL				**$33,376.07**

The values used for the items contained in Table 7 were compiled using recommendations of costs from village leaders, costs found in pricing sheets from Tanzanian companies, previous reports pricing, and estimations based on known costs. The estimated cost is $33,376.07 for the implementation of Phase I. An assumption was made using previous report pricing that inflation increasing these prices by 10%. Another assumption is that all Tanzanian prices can be converted from TSH to USD using a conversion rate of 2343 TSH/USD. The individual pricings and total cost are subject to change based on changes in design and updates with more accurate pricings. To account for potential problems and unforeseen obstacles, a 10% contingency has been added to the overall cost.

One important aspect of the estimated budget is the shipping cost for the goods. The location of Idunda offers particular challenges when traveling; therefore, a 25% rate was used to calculate shipping costs. The Idunda Water Committee pledged to provide the labor for trenches and pipe laying, which is reflected in the labor portion of the budget. Other items within the cost estimate include the piping system, pumping components, storage tanks, material costs for tank foundations and settling tank, and other miscellaneous items. A yearly maintenance cost was estimated and includes cleaning of the settling tank and solar panels, pipe and system repairs, potential chlorination of the water, security, and additional operating costs. Since the exact specifications for Phase II are not known at this point, a Phase II budget was not included.

8.0 | Conclusion

As an isolated village in rural Tanzania, Idunda does not have modern conveniences such as electricity and easy access to water. Despite this, the villagers understand the importance of water. They want to see their society advance and understand that basic needs must be met for progression to occur. After initiating the conversation about implementing a water distribution system in the village, Idunda villagers welcomed St. Paul Partners representatives and University of Minnesota students to gather data and develop a design for a water distribution system.

In order to improve the well-being of the villagers, a preliminary design for a water distribution system was developed using the Tanzanian Design Guidelines. The proposed system for the village of Idunda involves a surface source, a rising main transporting water from the valley to the ridgeline, and gravity mains distributing water north and south along the ridgeline as well as through the valley to the south of the water source. Other important components of the system include solar panels, a pump, SIM storage tanks, spigots, and a settling basin. In total, taking into account in-kind contributions, the system is expected to cost approximately $33,000. For Phase II, it is planned to construct a completely separate water system near the village entrance to serve the sub-village of Lugoli. This system will utilize either another surface source or a mud roatry drilled borehole, which is likely to be more feasible at the lower elevation.

Idunda villagers were doubtful that they would be considered for a water distribution system. The villagers understand the issue of water safety and feel a great need for accessible water in their community, and they are hopeful that the project will proceed. The village leaders have organized a water committee that is ready for the next steps of this project.

9.0 | References

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Appendix A: Tanzanian Design Guidelines

Below is the given list of guidelines used in the design (Ministry of Water and Irrigation, 2009).

- The design period should be for a minimum of 10 years. Population data should be approximated at a rate of 2.7% per year (the average national population growth). This translates to a 31% population growth ($[1.027]^{10}$).
- Water demand should be based on 25 liters/person/day. For schools, design for 10 liters per student per day.
- The system should be designed to accommodate 2.5 times the average rate of demand. Hourly water demand is bimodal, with the largest peak in the morning, followed by a lull around noon, and a second peak in the late afternoon.
- The system should have a minimum water storage capacity equal to 50% of the average daily demand.
- The minimum capacity of each spigot should be 10 liters/min. Each distribution point (DP) should be designed as a T having 2 spigots, and each DP should be able to provide 20 liters/min.
- Approximate pipe surface roughness: PVC and HDPE 0.01 mm; galvanized steel 0.15 mm (relative roughness epsilon/d is roughness divided by internal pipe diameter).
- The maximum working pressure for a pipe should be approximately 80% of rating. For example, if a pipe is rated at PN8 (max. pressure=8 bar/116 psig), it shouldn't be used in environments where the pressure exceeds 0.8x116 psig, or 93 psig.
- Design for a total water loss of 20-25% to account for leaks, valves left open, etc.
- Washout valves and air bleed valves may be required for undulating pipe layouts, low points and high points, respectively.
- Isolation valves need to be used at all branches and at 3 km intervals on straight sections.
- One DP can serve a maximum of 250 people. Maximum walking distance to a DP is 400 m.
- The velocity of water in a pipe should typically be in the range of 0.5 – 1.5 m/sec. Slower than 0.5 m/sec usually means you pipe is too large, larger may lead to water hammer.
- Lines should be buried a minimum of 1 meter. Sunlight degrades HDPE and farming practices can damage pipes laid near the surface.
- All minor losses should be modeled at 5% of major losses. Treat valves separately
- Add 15% to pipe costs for fittings. Add 20% to supply costs (pipe/tank/concrete) for shipping

Appendix B: Excel Code

To determine the pipes needed for each segment of the Phase I design, an Excel code was used. The Solver tool was utilized to solve multiple equations simultaneously. The pressure and velocity in each pipe were solved for when a pipe diameter was inputted. Bernoulli's equation and the continuity of flow equations were used, detailed in Appendix C. Each valve was assigned a K_v value, ranging from 10 to infinity, signifying a completely open and closed valve, respectively. The system was modeled with a variety of combinations for when valves are opened and closed. The worst-case scenario, when all the valves are open at the same time, was tested to ensure that each distribution point would be able to output water in this scenario. A variety of scenarios were tested to ensure that the velocities in the pipe met the guidelines and that the flow output was sufficient.

A likely operating condition is modeled for each gravity main below in Tables B1, B2, and B3. K_v values were adjusted so that peak hour demands were met at each distribution point and so each spigot can produce 10 L/min. Although this model does not assume all valves are completely open, it should still ensure that each distribution point has sufficient water to meet the demand.

The following variables and abbreviations were used in the code:

- P = Gage pressure [Pa]
- z = Elevation [m]
- v = Average Velocity in Pipe [m/s]
- L = Length of the Pipe[m]
- d = Internal Diameter of the Pipe [m]
- f = Friction Factor []
- p = Water Density [kg/m^3]
- g = Gravitational Acceleration [m/s^2]
- kv = Loss coefficient for a valve []
- Q = Volumetric Flow Rate of Water [L/hour]

Table B1: Gravity Main Village Office to Mavinga Code

	A	B	C
1			
2	**Gravity Main 1 - Village Office to Mavinga**		
3			
4	**Variable**	**Value**	**Units**
5	P2	92913.9	[Pa]
6	z1	1686	[m]
7	z2	1656	[m]
8	v12	0.993	[m/s]
9	v22a	2.462	[m/s]
10	L12	623	[m]
11	L22a	20	[m]
12	d12	0.04	[m]
13	d22a	0.0254	[m]
14	f	0.025	[]
15	p	1000	[kg/m^3]
16	g	9.81	[m/s^2]
17	kv, 2a	10	[]
18			
19	Bern. 1→ 2	3.80307E-08	
20	Bern. 2→ 2a	-3.95632E-08	
21	Flow 1	2.81893E-18	
22			
23	Q12	4,490.18	[L/hour]
24	Q22a	5,717.07	[L/hour]
25	Time 20 L, 2a	12.59	[sec]
26			

Cell B19 = (B8^2/(2*B16)*B14*B10/B12*1.05)+(B5/(B15*B16))+B7-B6
Cell B20 = ((B9^2/(2*B16))*(B14*B11/B13*1.05+B17))-(B5/(B15*B16))
Cell B21 = B9*B13^2-B8*B12^2
Cell B23 = PI()*0.25*B8*B12^2*1000*3600
Cell B24 = B9*B13^2*1000*3600
Cell B25 = 20/(B24/60)*60

Table B2: Gravity Main Village Office to Primary School

	E	F	G
1			
2	**Gravity Main 2 - Village Office to School**		
3			
4	**Variable**	**Value**	**Units**
5	P3	56628.9	[Pa]
6	P4	422523.4	[Pa]
7	z1	1686	[m]
8	z3	1651	[m]
9	z4	1600	[m]
10	v13	1.487	[m/s]
11	v33a	1.922	[m/s]
12	v34	0.712	[m/s]
13	v44a	1.767	[m/s]
14	L13	395	[m]
15	L34	807	[m]
16	L33a	20	[m]
17	L44a	20	[m]
18	d13	0.04	[m]
19	d33a	0.0254	[m]
20	d34	0.04	[m]
21	d44a	0.0254	[m]
22	f	0.025	[]
23	p	1000	[kg/m^3]
24	g	9.81	[m/s^2]
25	kv,3a	10	[]
26	kv,4a	250	[]
27			
28	Bern. 1→ 3	-5.66911E-09	
29	Bern. 3→ 3a	-1.43192E-08	
30	Bern. 3→4	-9.75815E-08	
31	Bern. 4→ 4a	3.06738E-07	
32	Flow 1	0	
33	Flow 2	0	
34			
35	Q13	6,728.59	[L/hour]
36	Q33a	3,505.44	[L/hour]
37	Q34	3,223.15	[L/hour]
38	Q44a	3,223.15	[L/hour]
39	Time 20 L, 3a	20.54	[sec]
40	Time 20 L, 4a	22.34	[sec]

Cell F28 = (F10^2/(2*F24)*F22*F14/F18*1.05)+(F5/(F23*F24))+F8-F7
Cell F29 = (F11^2/(2*F24))*(F22*F16/F19*1.05+F25)-(F5/(F23*F24))
Cell F30 = (F12^2/(2*F24)*F22*F15/F20*1.05)+((F6-F5)/(F23*F24))+F9-F8
Cell F31 = -(F13^2/(2*F24))*(F22*F17/F21*1.05+F26)+(F6/(F23*F24))
Cell F32 = F12*F20^2+F11*F19^2-F10*F18^2
Cell F33 = F13*F21^2-F12*F20^2
Cell F35 = PI()*0.25*F10*F18^2*1000*3600
Cell F36 = PI()*0.25*F11*F19^2*1000*3600
Cell F37 = PI()*0.25*F12*F20^2*1000*3600
Cell F38 = PI()*0.25*F13*F21^2*1000*3600
Cell F39 = 20/(F36/60)*60
Cell F40 = 20/(F38/60)*60

Table B3: Gravity Main Water Source to Msasi

	I	J	K
2	**Gravity Main 3 - Source to Msasi**		
3			
4	Variable	Value	Units
5	P6	165888.0	[Pa]
6	P7	122039.0	[Pa]
7	P8	85015.8	[Pa]
8	z5	1592	[m]
9	z6	1560	[m]
10	z7	1555	[m]
11	z8	1555	[m]
12	v56	1.085	[m/s]
13	v66a	0.798	[m/s]
14	v67	0.879	[m/s]
15	v77a	1.052	[m/s]
16	v78	0.608	[m/s]
17	v88a	2.355	[m/s]
18	L56	479	[m]
19	L66a	20	[m]
20	L67	458	[m]
21	L77a	20	[m]
22	L78	382	[m]
23	L88a	20	[m]
24	d56	0.05	[m]
25	d66a	0.0254	[m]
26	d67	0.05	[m]
27	d77a	0.0254	[m]
28	d78	0.05	[m]
29	d88a	0.0254	[m]
30	f	0.025	[]
31	p	1000	[kg/m^3]
32	g	9.81	[m/s^2]
33	kv, 6a	500	[]
34	Kv, 7a	200	[]
35	kv, 8a	10	[]
36			
37	Bern. 5→ 6	-4.00428E-07	
38	Bern. 5→ 5a	-2.83159E-05	
39	Bern. 6→ 7	-9.77111E-08	
40	Bern. 7→ 7a	-1.2836E-07	
41	Bern. 7→ 8	-3.89412E-08	
42	Bern. 8→ 8a	-8.94202E-08	
43	Flow 1	2.0383E-17	
44	Flow 2	-6.93889E-18	
45	Flow 3	0	
46			
47	Q56	7,669.69	[L/hour]
48	Q66a	1,456.13	[L/hour]
49	Q67	6,213.56	[L/hour]
50	Q77a	1,918.46	[L/hour]
51	Q78	4,295.10	[L/hour]
52	Q88a	4,295.10	[L/hour]
53	Time 20 L, 6a	49.45	[sec]
54	Time 20 L, 7a	37.53	[sec]
55	Time 20 L, 8a	16.76	[sec]

Cell J37 = (J12^2/(2*J32)*J30*J18/J24*1.05)+(J5/(J31*J32))+J9-J8
Cell J38 = (J13^2/(2*J32))*(J30*J19/J25*1.05+J33)-(J5/(J31*J32))
Cell J39 = (J14^2/(2*J32)*J30*J20/J26*1.05)+((J6-J5)/(J31*J32))+J10-J9
Cell J40 = (J15^2/(2*J32))*(J30*J21/J27*1.05+J34)-(J6/(J31*J32))
Cell J41 = (J16^2/(2*J32)*J30*J22/J28*1.05)+((J7-J6)/(J31*J32))+J11-J10
Cell J42 = (J17^2/(2*J32))*(J30*J23/J29*1.05+J35)-(J7/(J31*J32))
Cell J43 = J13*J25^2+J14*J26^2-J12*J24^2
Cell J44 = J15*J27^2+J16*J28^2-J14*J26^2
Cell J45 = J16*J28^2-J17*J29^2
Cell J47 = PI()*0.25*J12*J24^2*1000*3600
Cell J48 = PI()*0.25*J13*J25^2*1000*3600
Cell J49 = PI()*0.25*J14*J26^2*1000*3600
Cell J50 = PI()*0.25*J15*J27^2*1000*3600
Cell J51 = PI()*0.25*J16*J28^2*1000*3600
Cell J52 = PI()*0.25*J17*J29^2*1000*3600
Cell J53 = 20/(J48/60)*60
Cell J54 = 20/(J50/60)*60
Cell J55 = 20/(J52/60)*60

Appendix C: Sample Calculations

Water Demand in Each Pipe:

The water demand calculations, split up for each pipe and accounting for a 20% water loss due to leaks in the system, are found in Table C1. The water demand for each pipe was based on the populations near the distribution points of the pipe. Pipe 1, which runs from the Village Office to Mavinga, will serve the entire population of the Mavinga sub-village. Pipe 2, which runs from the Village Office to the primary school, will serve the demand for the primary school (students and staff) and half the demand for the sub-village of Ukimbilizi. Pipe 3, which runs from the water source to the Msasi distribution point, will meet the demand of the other half of the sub-village of Ukimbilizi, the entire sub-village of Msasi, and the demand of the proposed dispensary.

Table C1: Design Pipe Demands

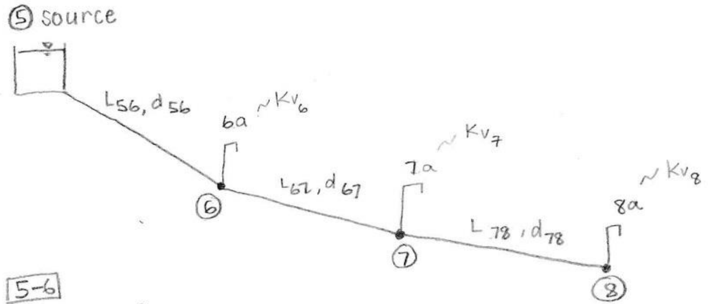
Pipe Number	Pipe Description	2019 Water Demand	2019 Water Demand with 20% Loss	2029 Water Demand	2029 Water Demand with 20% Loss	Peak Hourly Demand
1	Village Office → Mavinga	11,825	14,190	15,500	18,600	3,875
2	Village Office → Primary School	10,225	12,270	13,423	16,107	3,356
3	Water Source → Msasi	17,275	20,730	22,663	27,195	5,666
Rising Main	Water Source → Village Office	22,050	26,460	28,923	34,707	7,231
Total		**39,325**	**47,190**	**51,585**	**61,902**	

The water demand was also calculated for each distribution point based on populations near the given distribution points, as tabulated in Table C2. Although it is not possible to confidently predict exactly how many people will use each distribution point, these estimations were used to determine the peak hourly demand for each distribution point. Although the Village Office will be a distribution point, this was not included in Table C2 since the storage tanks at the Village Office will be tapped as the mechanism of water distribution as opposed to having a spigot.

Table C2: Distribution Point Demands

Pipe Number	Distribution Point	2019 Water Demand	2019 Water Demand with 20% Loss	2029 Water Demand	2029 Water Demand with 20% Loss	Peak Hourly Demand
1	Mavinga	11,825	14,190	15,500	18,600	3,875
2	Church	4,525	5,430	5,938	7,125	1,484
2	School	5,700	6,840	7,485	8,982	1,871
3	Dispensary	150	180	200	240	50
3	Ukimbilizi	4,525	5,430	5,938	7,125	1,484
3	Msasi	12,600	15,120	16,525	19,830	4,131

Pipe Sizing:



Source (Mdetema) (5)
→ dispensary (6)
→ "MOA" (7)
→ Msasi (8)

5-6

$$\frac{P_6 - P_5 \,(\to 0)}{\rho g} + z_6 - z_5 = -\frac{V_{56}^2}{2g}\left[f\,\frac{L_{56}}{d_{56}}\,(1.05)\right]$$

6-6a

$$\frac{P_{6a} \,(\to 0) - P_6}{\rho g} = \frac{-V_{66a}^2}{2g}\left[f\,\frac{L}{d}\,(1.05) + K_{v_6}\right]$$

6-7

$$\frac{P_7 - P_6}{\rho g} + z_7 - z_6 = -\frac{V_{67}^2}{2g}\left[f\,\frac{L_{67}}{d_{67}}\,(1.05)\right]$$

7-7a

$$\frac{P_{7a} \,(\to 0) - P_7}{\rho g} = -\frac{V_{77a}^2}{2g}\left[f\,\frac{L}{d}\,(1.05) + K_{V_7}\right]$$

7-8

$$\frac{P_8 - P_7}{\rho g} + z_8 - z_7 = -\frac{V_{78}^2}{2g}\left[f\,\frac{L_{78}}{d_{78}}\,(1.05)\right]$$

8-8a

$$\frac{P_{8a} \,(\to 0) - P_8}{\rho g} = -\frac{V_{88a}^2}{2g}\left[f\,\frac{L}{d}\,(1.05) + K_{V_8}\right]$$

@6

$$Q_{56} = Q_{66a} + Q_{67}$$

$$\frac{\pi d_{56}^2}{4} V_{56} = \frac{\pi d_{66a}^2}{4} V_{66a} + \frac{\pi d_{67}^2}{4} V_{67}$$

@7

$$Q_{67} = Q_{77a} + Q_{78}$$

$$\frac{\pi d_{67}^2}{4} V_{67} = \frac{\pi d_{77a}^2}{4} V_{77a} + \frac{\pi d_{78}^2}{4} V_{78}$$

@8

$$Q_{78} = Q_{88a}$$

$$\frac{\pi d_{78}^2}{4} V_{78} = \frac{\pi d_{88a}^2}{4} V_{88a}$$

Equations

$$-\frac{V_{56}^2}{2g}\left[f\frac{L_{56}}{d_{56}}(1.05)\right] - \frac{P_6}{\rho g} - z_6 + z_5 = 0$$

$$-\frac{V_{66a}^2}{2g}\left[f\frac{L}{d}(1.05) + K_{v_6}\right] + \frac{P_6}{\rho g} = 0$$

$$-\frac{V_{67}^2}{2g}\left[f\frac{L_{67}}{d_{67}}(1.05)\right] - \left[\frac{P_7 - P_6}{\rho g}\right] - z_7 + z_6 = 0$$

$$-\frac{V_{77a}^2}{2g}\left[f\frac{L}{d}(1.05) + K_{v_7}\right] + \frac{P_7}{\rho g} = 0$$

$$-\frac{V_{78}^2}{2g}\left[f\frac{L_{78}}{d_{78}}(1.05)\right] - \left[\frac{P_8 - P_7}{\rho g}\right] - z_8 + z_7 = 0$$

$$-\frac{V_{88a}^2}{2g}\left[f\frac{L}{d}(1.05) + K_{v_8}\right] + \frac{P_8}{\rho g} = 0$$

$$d_{56}^2 V_{56} - d_{66a}^2 V_{66a} - d_{67}^2 V_{67} = 0$$

$$d_{67}^2 V_{67} - d_{77a}^2 V_{77a} - d_{78}^2 V_{78} = 0$$

$$d_{78}^2 V_{78} - d_{88a}^2 V_{88a} = 0$$

source (5)
→ dispensary (6)
→ "MOA" (7)
→ Msasi (8)

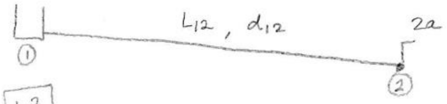
Unknowns

V_{56}
V_{66a}
V_{67}
V_{77a}
V_{78}
V_{88}
P_6
P_7
P_8

$z_5 = 1592$
$z_6 = 1560$
$z_7 = 1542$
$z_8 = 5179\text{ft} = 1579$

$L_{56} = 479$
$L_{67} = 602$
$L_{78} = 506$
$L = 20$

$d_{56} = 0.03$
$d_{67} = 0.02$?
$d_{78} = 0.01$
$d = 0.0245$



Village office ① → Mavinga ② (Rosedale)

1-2

$$\frac{P_2 - \cancel{P_1}^{\,0}}{\rho g} + Z_2 - Z_1 = \frac{-V_{12}^2}{2g}\left[f \ \frac{L_{12}}{d_{12}} \ (1.05)\right]$$

2-2a

$$\frac{\cancel{P_{2a}}^{\,0} - P_2}{\rho g} = \frac{-V_{22a}^2}{2g}\left[f \ \left(\frac{L}{d}\right) 1.05 + K_{V_2}\right]$$

@ 2

$$Q_{12} = Q_{22a}$$

$$\frac{\pi}{4} d_{12}^2 \ V_{12} = \frac{\pi}{4} d^2 \ V_{22a}$$

Equations

$$-\frac{V_{12}^2}{2g}\left[f \ \frac{L_{12}}{d_{12}} \ (1.05)\right] - \frac{P_2}{\rho g} - Z_2 + Z_1 = 0$$

$$-\frac{V_{22a}^2}{2g}\left[f \ \frac{L}{d} \ (1.05) + K_{V_2}\right] + \frac{P_2}{\rho g} = 0$$

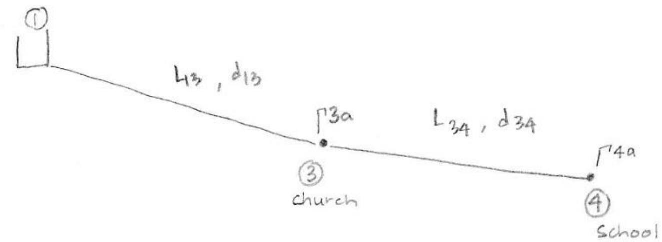
$$d_{12}^2 \ V_{12} - d^2 \ V_{22a} = 0$$

Unknowns

P_2

V_{12}

V_{22a}



Village office ① →
church ③ →
School ④

1-3

$$\frac{P_3 - P_1^{\,0}}{\rho g} + z_3 - z_1 = \frac{-V_{13}^2}{2g}\left[f \frac{L_{13}}{d_{13}} (1.05)\right]$$

3-3a

$$\frac{P_{3a}^{\,0} - P_3}{\rho g} = \frac{-V_{33a}^2}{2g}\left[f\left(\frac{L}{d}\right)_{DP} (1.05) + KV_3\right]$$

3-4

$$\frac{P_4 - P_3}{\rho g} + z_4 - z_3 = -\frac{V_{34}^2}{2g}\left[f \frac{L_{34}}{d_{34}} (1.05)\right]$$

4-4a

$$\frac{P_{4a}^{\,0} - P_4}{\rho g} = -\frac{V_{44a}^2}{2g}\left[f\left(\frac{L}{d}\right)_{DP} (1.05) + KV_4\right]$$

$z_1 = 1686$ m $\quad L_{13} = 395$ m $\quad d_{13} = ?$

$z_3 = 1651$ m $\quad L_{34} = 807$ m $\quad d_{34} = ?$

$z_4 = 1600$ m $\quad L = 20$ m $\quad d = 0.0245$ m

@3

$$Q_{13} = Q_{33a} + Q_{34}$$

$$\frac{\pi d_{13}^2}{4} V_{13} = \frac{\pi d_{33a}^2}{4} V_{33a} + \frac{\pi d_{34}^2}{4} V_{34}$$

@4

$$Q_{34} = Q_{44a}$$

$$\frac{\pi d_{34}^2}{4} V_{34} = \frac{\pi d_{44a}^2}{4} V_{44a}$$

Equations

$$-\frac{V_{13}^2}{2g}\left[f\ \frac{L_{13}}{d_{13}}(1.05)\right] - \frac{P_3}{\rho g} - z_3 + z_1 = 0$$

$$-\frac{V_{33}\,a^2}{2g}\left[f\ \frac{L}{d}\ (1.05) + kv_3\right] + \frac{P_3}{\rho g} = 0$$

$$-\frac{V_{34}^{\ 2}}{2g}\left[f\ \frac{L_{34}}{d_{34}}\ (1.05)\right] - \left[\frac{P_4 - P_3}{\rho g}\right] - z_4 + z_3 = 0$$

$$-\frac{V_{44}\,a^2}{2g}\left[f\ \frac{L}{d}\ (1.05) + kv_4\right] + \frac{P_4}{\rho g} = 0$$

$$d_{13}^{\ 2}\,V_{13} - d_{33a}^{\ 2}\,V_{33a} - d_{34}^{\ 2}\,V_{34} = 0$$

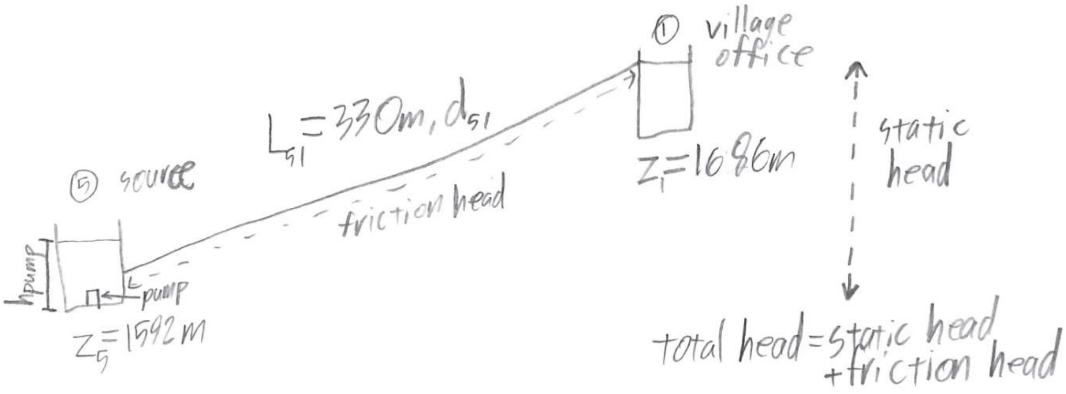
$$d_{34}^{\ 2}\,V_{34} - d_{44a}^{\ 2}\,V_{44a} = 0$$

village office (1)
→ church (3)
→ school (4)

Unknowns

V_{13}
V_{33a}
V_{34}
V_{44a}
P_3
P_4

Pump Sizing:



For this main, $Q = 34{,}700 \frac{L}{day} = 1.20 \frac{L}{s}$ (8-hr operation)

variables

$L_{51} = 330m$

$\Delta Z_{51} = 1686m - 1592m = 94m$

$h_{pump} = 3m$

$\rho = 1000 \frac{kg}{m^3}$

$g = 9.8 \frac{m}{s^2}$

$f = 0.025$

$\eta = 55\%$

d_{51}, V_{51}, ΔP_{51}, $\dot{W}$ } unknowns

Step 1

Find total head with mech. energy balance between pump outlet and village office:

$$\dot{W} = 0 = \rho Q \frac{\Delta P_{51}}{\rho} + \rho Q g \Delta Z_{51} + \frac{\rho Q V_{51}^2}{2}\left(1.05 f \frac{L_{51}}{d_{51}}\right)$$

$$\Rightarrow \Delta P_{51} = -\left[\rho g \Delta Z_{51} + \rho \frac{V_{51}^2}{2}\left(1.05 f \frac{L_{51}}{d_{51}}\right)\right]$$

where: $V_{51} = \frac{Q}{A} = \frac{Q}{\left(\frac{d_{51}^2}{4}\pi\right)}$

Step 2

Find the required pump power required to overcome the total head. For this balance:

$$\Delta P = \Delta P_{51} - \rho g h_{pump}$$

$$\dot{W} = \frac{\dot{W}_{req'd}}{\eta} = \frac{Q[\Delta P_{51} - \rho g h_{pump}]}{\eta} \quad \text{(multiply by } \frac{1\,hp}{750\,W}\text{)}$$

Step 3

Find the optimal d_{51}. As $d_{51} \to \infty$, we find that:

minimum $\begin{cases} \dot{W} = 2.60\ hp \\ P_{max} = 9.21\ bar \text{ (pressure immediately following pump)} \end{cases}$

Using the smallest pipe size, $d_{51} = 20\,mm$, this yields:

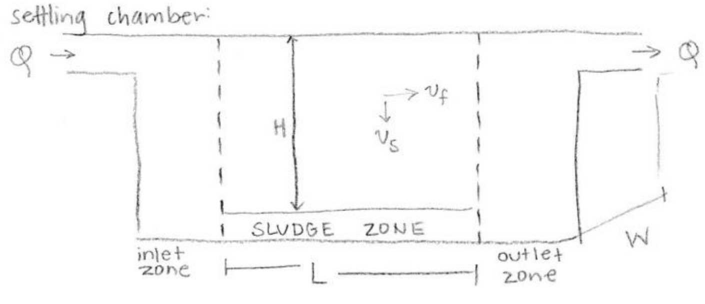
$\dot{W} = 2.61\ hp$ (within 0.37% of minimum)

$P_{max} = 9.24\ bar$ (within 0.36% of minimum)

Appendix D: Settling Basin Design

Rectangular Settling Basin

sizing settling chamber:



IMPORTANT DESIGN NOTES

- sedimentation basin designed for a 3 hour retention time, as specified in the "Utilization and Proper Development of Surface Sources" (St. Paul Partners, UMN PowerPoint).
- Design based on retention time instead of particle settling velocity, as done in the Wasa report. (Why this basin is so much longer)
- Also, per nptel.ac.in Water & Wastewater Engineering, Long rectangular basins commonly have $t = 3$-4hrs, and total length between 30 − 100 m. (very Long)

key parameters

H = depth of settling zone　　　t = retention time

L = length of settling zone

W = width of settling zone

V = volume of settling zone = HLW

Q = volumetric flow rate

v_f = velocity (horizontal component) of flow

v_s = settling velocity of particles

Assumptions

desired outflow $Q = 62{,}000$ L/day　　　* demand in 2029

water Temp = 20°C　　　* avg. stream temp

$\mu = 1.002 \times 10^{-3}$ Ns/m²　　　* dynamic viscosity

~~remove particles $d \geq 0.1$ mm~~　　　* sand: $\rho = 2640$ kg/m³

Retention time = 3 hours　　　* Tanzanian standard

Settling velocity of particles (example)

Stokes Law:

$$v_s = \frac{g(\rho_p - \rho)\, d_p^2}{18\mu}$$

$$= \frac{9.81 \frac{m}{s^2} \left(2640 - 1000 \frac{kg}{m^3}\right) (0.0001\ m)^2}{18\left(1.002 \times 10^{-3}\ \frac{Ns}{m^2}\right)}$$

$$v_s = 0.00892 \text{ m/s}$$

Relationships/Equations

① retention time = $t = \frac{V}{Q}$ * Tanzanian Standard is > 3 hrs

② Length : width $L > 4W$ * Tanzanian Standard

③ Length : depth $L = 15H$ * Davis (2010) Design criteria for rectang. sed. basin

Solving For size

$t = \frac{V}{Q}$ using equation ①

$$Q = 62\,000\ \frac{L}{d} \cdot \frac{0.001}{1}\frac{m^3}{L} \cdot \frac{1\ d}{24\ h} \cdot \frac{1}{3600\ s} = 7.176 \times 10^{-4}\ \frac{m^3}{s}$$

$$t = 3\ hrs \cdot \frac{3600\ s}{1\ hr} = 10800\ s$$

$$10800\ s = \frac{V}{7.176 \times 10^{-4}\ \frac{m^3}{s}}$$

$$V = 7.75\ m^3$$

use equations ② & ③ to solve for the length of the settling zone

$$V = H \cdot L \cdot W$$

$$V = \frac{L}{15} \cdot L \cdot \frac{L}{4}$$

$$V = \frac{L^3}{60} \rightarrow (V \cdot 60)^{1/3} = (L^3)^{1/3}$$

$$L = (V \cdot 60)^{1/3}$$

$$= (7.75\ m^3 \cdot 60)^{1/3}$$

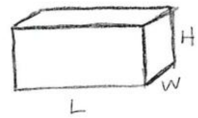
$$L = 7.7473\ m$$

$$W = \frac{7.7473}{4} = 1.9368\ m$$

$$H = \frac{7.7473}{15} = 0.5164\ m$$

Dimensions of settling zone:

Cube of water:



$L = 7.747$ m
$W = 1.937$ m
$H = 0.516$ m

Design of inlet & outlet zones

outlet: 1/3 length of basin
- Place a weir here

* Davis (2010) Design criteria for rectangular sed. basin

inlet: 2m = distance to diffuser wall.
use a baffle in this case

* Davis (2010)

outlet weir determines water level

Flow over a weir: $Q = CWh^{3/2}$ *rectangular

* Mays, Water Resources Engineering (2010)

C = Discharge coefficient = 1.84
W = crest length
Q = discharge
h = depth of flow above elev. of crest

$$7.176 \times 10^{-4} \frac{m^3}{s} = 1.84 (1.937 \text{ m}) (H)^{3/2}$$

$$\left(2.0134 \times 10^{-4} \frac{m^2}{s}\right)^{\frac{2}{3}} = \left(H^{3/2}\right)^{\frac{2}{3}}$$

$$0.0034 \text{ m} = h$$

Weir height = depth of water − head = H − h

weir height = 0.516 − 0.0034
= 0.513 m

Inlet weir: submerged 15% of water level * Tanzanian standard

= 0.15(H) = 0.15(0.516) = 0.0774

inlet weir height = 0.516 − 0.0774 = 0.4386 m

Back to the depth of the basin

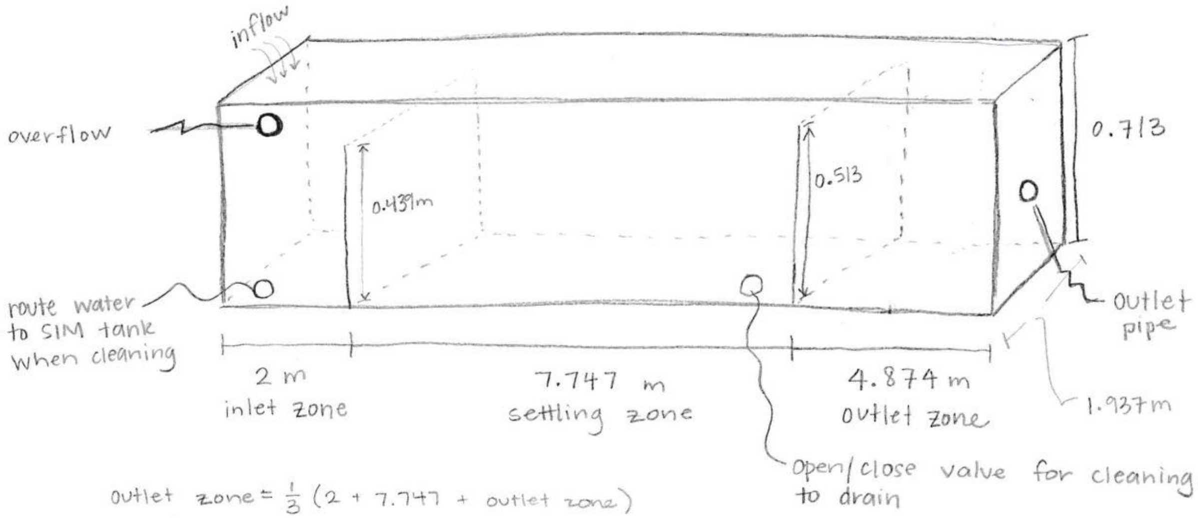
The settling zone = 0.516 m

Build the walls to fit an overflow pipe (0.1 m) above outlet weir

0.513 + 0.1 = 0.613 + 2(0.05) on each side

= 0.713

↑ height of walls



outlet zone $= \frac{1}{3}$ (2 + 7.747 + outlet zone)

$$\phi = \frac{1}{3}(9.747 + \phi)$$

$$\phi = 3.249 + \frac{\phi}{3}$$

$$\phi - \frac{\phi}{3} = 3.249$$

$$\phi\left(1 - \frac{1}{3}\right) = 3.249$$

$$\phi(0.67) = 3.249$$

$$\phi = 4.8735 \text{ m}$$

* outlet pipe must be below outlet weir.

Using Stokes

settling out particles that are:

$$v_s = \frac{H}{t} = \frac{0.516 \text{ m}}{10800 \text{ s}} = 4.77 \times 10^{-5} \text{ m/s}$$

*Assume $\rho = 2640$ (sand)

$$4.77 \times 10^{-5} \frac{m}{s} = \frac{9.81\ (2640 - 1000)\ (d)^2}{18(1.002 \times 10^{-3})}$$

$$d = 7.3 \times 10^{-6} \text{ m} = 0.0073 \text{ mm}$$ approximately in diameter

*very rough estimate!

Final settling / catch Basin INTERIOR Dimensions

Total length = 14.621 m

Total width = 1.937 m

Total height = 0.713 m

inlet weir height = 0.439 m

outlet weir height = 0.513 m

overflow pipe center at 0.539 m → heading directly to SIM tanks

outlet pipe center at 0.2 m

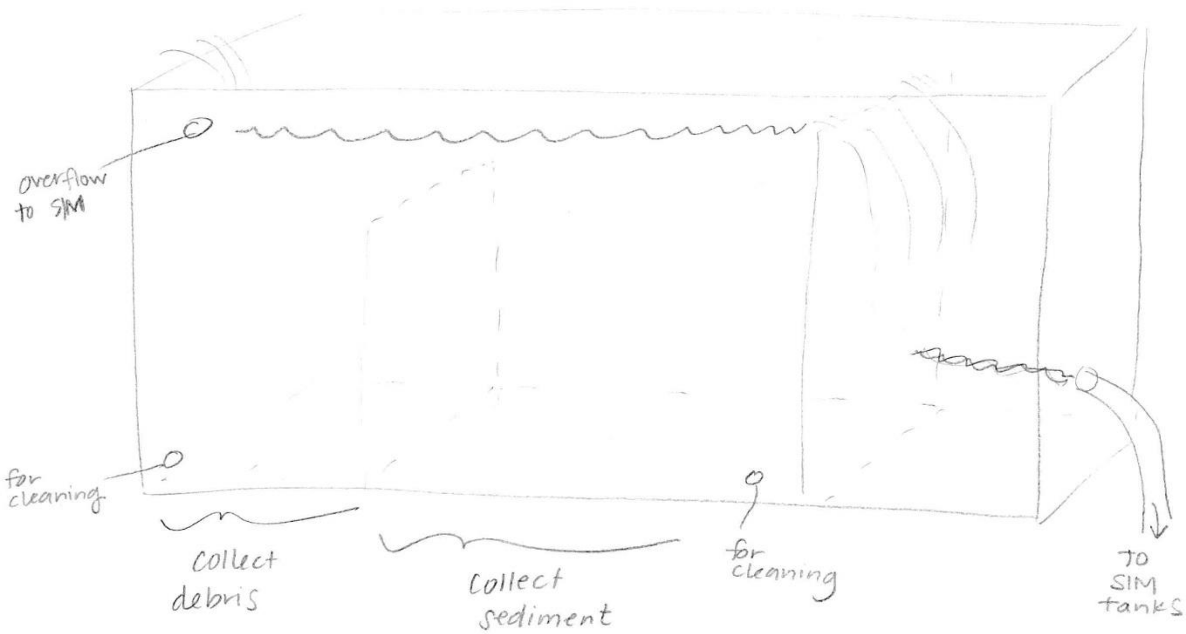


TABLE 10-4
Typical design criteria for horizontal-flow rectangular sedimentation basins

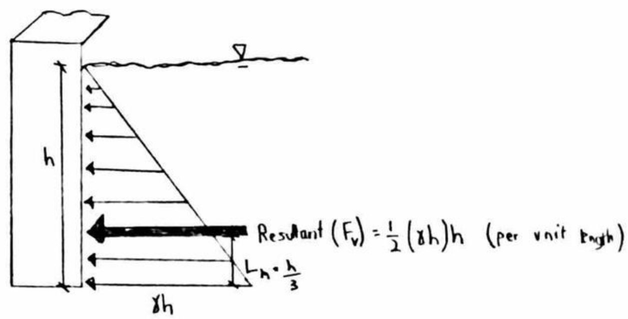
Parameter	Typical range of values	Comment
Inlet zone		
Distance to diffuser wall	2 m	
Diffuser hole diameter	0.10–0.20 m	
Settling zone		
Overflow rate	40–70 $m^3/d \cdot m^2$	See Table 10-2
Side water depth (SWD)	3–5 m	
Length	30 m	Wind constraint
	60 m	Chain-and-flight
	≥80–90 m	Traveling bridge
Width	0.3 m increments	Chain-and-flight
	6 m maximum per train	Chain-and-flight
	24 m maximum = 3 trains per drive	Chain-and-flight
	30 m maximum	Traveling bridge
L:W	4:1 to 6:1	≥6:1 preferred
L:D	15:1	Minimum
Velocity	0.005–0.018 m/s	Horizontal, mean
Reynolds number	< 20,000	
Froude number	$> 10^{-5}$	
Outlet zone		
Launder length	1/3–1/2 length of basin	Evenly spaced
Launder weir loading	140–320 $m^3/d \cdot m$	See Table 10-3
Sludge zone		
Depth	0.6–1 m	Equipment dependent
Slope	1:600	Mechanical cleaning
Sludge collector speed	0.3–0.9 m/min	

Source: AWWA, 1990; Davis and Cornwell, 2008; Kawamura, 2000; MWH, 2005; Willis, 2005.

Figure D1: Rectangular Sedimentation Basin Design Criteria (Davis 2010)

Structural Design of the Settling Basin:

Design for shear:



$$\frac{V_{demand}}{L} \leq \frac{V_{capacity}}{L}$$

Calculate the demand:

$$\frac{V_{demand}}{L} = (LF)(F_v) = (LF)\left(\frac{1}{2}\gamma h\right)(h)$$

where: LF = load factor = 1.4 for fluids

F_v = Resultant force of shear

γ = Unit weight of water = 62.4 lb/ft^3

h = depth of water

$$\frac{V_{demand}}{L} = 1.4\left(62.4\ lb/ft^3\right)\left(\frac{1}{2}\right)(2.34\ ft)^2$$

$$\frac{V_{demand}}{L} = 239.2\ lb/ft$$

Calculate the capacity:

$$\frac{V_{capacity}}{L} = \phi \cdot 2\sqrt{f_c'} \cdot d$$

Where: ϕ = under capacity factor = 0.75

f_c' = compressive strength of concrete = 2500 lb/in^2

d = distance from reinforcement centroid to member face

$$\frac{V_{capacity}}{L} = (0.75)\left(2\sqrt{2500\frac{lb}{in^2}\left(144\ in^2/ft^2\right)}\right)d$$

Solve for d:

$$\frac{V_{demand}}{L} \leq \frac{V_{capacity}}{L}$$

$$239.2\ lb/ft < 900\ d$$

$$d = 0.27\ ft = 3.24\ in.$$

Wall thickness = d + reinforcement bar radius + 3"

* 3 in. is added to provide the required concrete cover to protect the reinforcement.

Calculate the wall thickness after the reinforcement requirements are found.

Design for Moment:

Calculate the demand:

$$\frac{M_{demand}}{L} \leq \frac{M_{capacity}}{L}$$

$$\frac{M_{demand}}{L} = (LF)(F_v)(L_m) = 1.4\left(\tfrac{1}{2}\gamma h^2\right)\left(\tfrac{h}{3}\right)$$

where: LF = load factor = 1.4 for fluids

F_v = Resultant force of shear

L_m = Moment arm

γ = unit weight of water = 62.4 lb/ft³

h = depth of water

$$\frac{M_{demand}}{L} = 1.4\left(\tfrac{1}{2}(62.4\ \text{lb/ft}^3)(2.34\ \text{ft})^2\right)\left(\tfrac{2.34\ \text{ft}}{3}\right)$$

$$\frac{M_{demand}}{L} = 186.6\ \text{lbs}$$

Calculate the capacity:

$$\frac{M_{capacity}}{L} = \phi A_s F_y\left[d - \tfrac{1}{2}a\right] = \phi A_s F_y\left[d - \frac{A_s F_y}{2(0.85 L f_c')}\right]$$

where: ϕ = under capacity factor = 0.75

A_s = Area of steel reinforcement per unit length

F_y = Yield strength of steel = 60,000 psi

d = distance from reinforcement centroid to member face

a = depth of equivalent stress block

L = Unit length of wall (12in/ft)

f_c' = Compressive strength of concrete = 2500 lb/in²

$$\frac{M_{capacity}}{L} = 0.75(60{,}000\ \text{psi})(A_s)\left[3.24\ \text{in.} - \frac{A_s(60{,}000\ \text{psi})}{2(0.85)(12\ \text{in/ft})(2500\ \text{psi})}\right]$$

Solve for A_s:

Set $\frac{M_{capacity}}{L}$ equal to $\frac{M_{demand}}{L}$ and solve the quadratic equation for A_s.

$$A_s = 0.0129\ \text{in}^2/\text{ft}$$

Since the required area of reinforcement is low, the smallest reinforcement bar was deemed sufficient.

Bar size = No. 3

Diameter = 3/8 in.

Bar spacing was determined to be 18 inches (0.45 m), which is the minimum spacing requirement determined from Figure D2.

The vertical reinforcement bars will bend at the base to serve as an anchor.

$$L_a = \left(\frac{F_y}{50 \cdot \sqrt{f_c'}}\right) \cdot d_b$$

Where:

L_a = length of bar after bend

F_y = Yield strength of steel = 60,000 lb/in²

f_c' = compressive strength of concrete = 2500 lb/in²

d_b = diameter of reinforcement bar

$$L_a = \left(\frac{(60{,}000 \text{ psi})}{50 \cdot \sqrt{2500 \text{ psi}}}\right) \cdot (3/8 \text{ in})$$

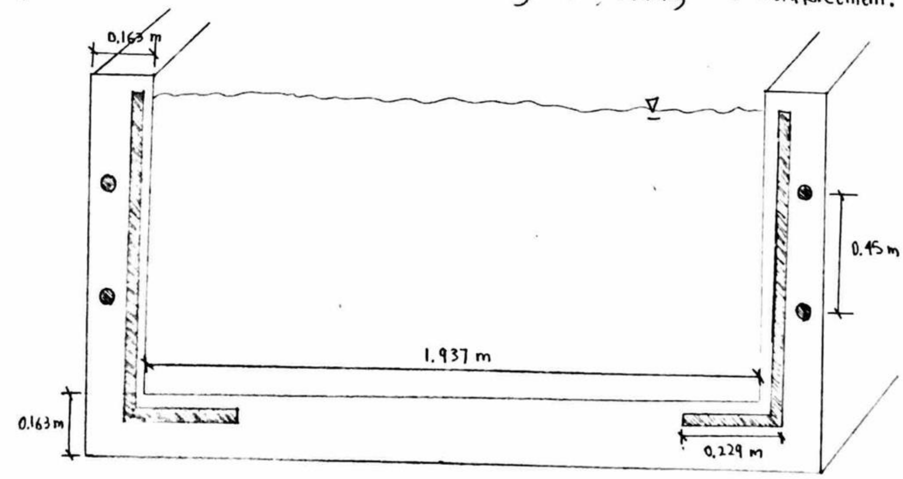
$$L_a = 9 \text{ in.} = 0.229 \text{ m}$$

Since the diameter of the bar is now known, the wall thickness can be computed. A constant thickness was used

$$\text{wall thickness } (t_w) = 3.24 \text{ in} + \frac{3/8 \text{ in}}{2} + 3 \text{ in}$$

$$t_w = 6.43 \text{ in.} = 0.163 \text{ m}$$

The following figure is a cross section of the settling basin showing the reinforcement.



* Not drawn to scale

The number of vertical and horizontal bars were calculated based on the spacing of 0.45 m and the settling basin dimensions.

# of vertical bars required = 76 bars

≈ 72 meters of bars

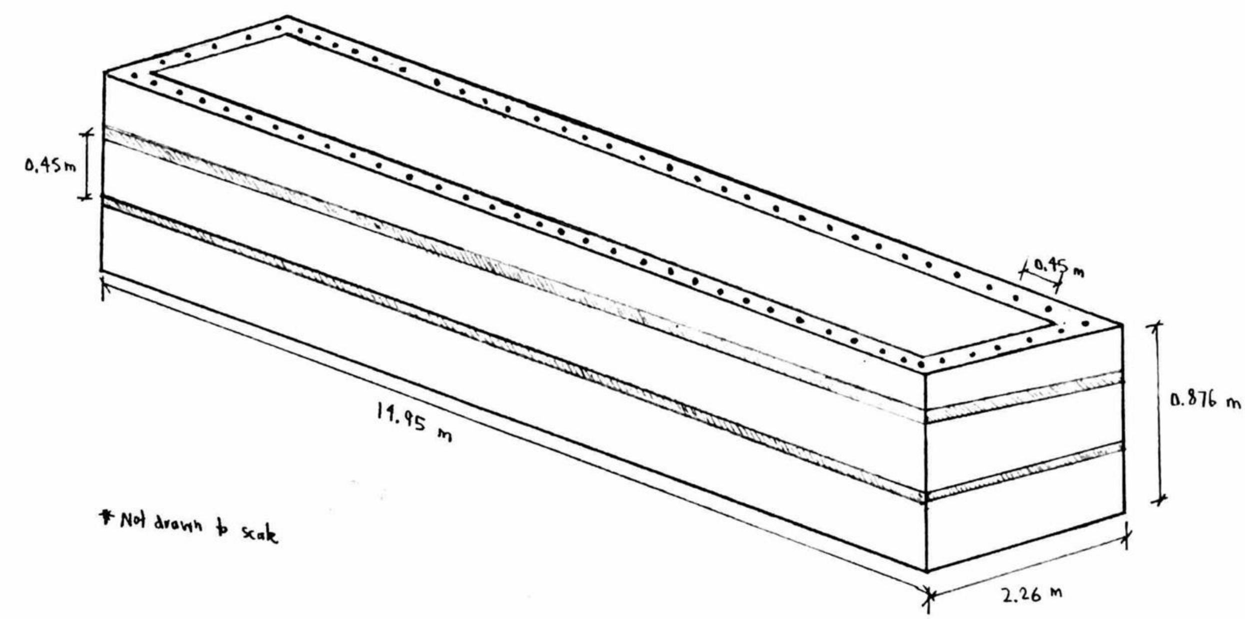
# of horizontal bars required = 8 bars

≈ 69 meters of bars

Total amount of rebar needed = 141 meters

∀ of concrete needed = 9.5 m^3

The figure below shows the concrete and structural design or the settling basin. The dimensions shown are the final outer dimensions for the settling basin.



Areas of Bars in a Section 1 ft wide (in^2/ft) REVISED

Bar Spacing (in.)	No. 3	No. 4	No. 5	No. 6	No. 7
4	0.33	0.60	0.93	1.32	1.80
4.5	0.29	0.53	0.83	1.17	1.60
5	0.26	0.48	0.74	1.06	1.44
5.5	0.24	0.44	0.68	0.96	1.31
6	0.22	0.40	0.62	0.88	1.20
6.5	0.20	0.37	0.57	0.81	1.11
7	0.19	0.34	0.53	0.75	1.03
7.5	0.18	0.32	0.50	0.70	0.96
8	0.17	0.30	0.47	0.66	0.90
8.5	0.16	0.28	0.44	0.62	0.85
9	0.15	0.27	0.41	0.59	0.80
9.5	0.14	0.25	0.39	0.56	0.76
10	0.13	0.24	0.37	0.53	0.72
10.5	0.13	0.23	0.35	0.50	0.69
11	0.12	0.22	0.34	0.48	0.65
11.5	0.11	0.21	0.32	0.46	0.63
12	0.11	0.20	0.31	0.44	0.60
13	0.10	0.18	0.29	0.41	0.55
14	0.09	0.17	0.27	0.38	0.51
15	0.09	0.16	0.25	0.35	0.48
16	0.08	0.15	0.23	0.33	0.45
17	0.08	0.14	0.22	0.31	0.42
18	0.07	0.13	0.21	0.29	0.40

Figure D2: Reinforcement Bar Areas and Spacing

Appendix E: Elevation Profiles

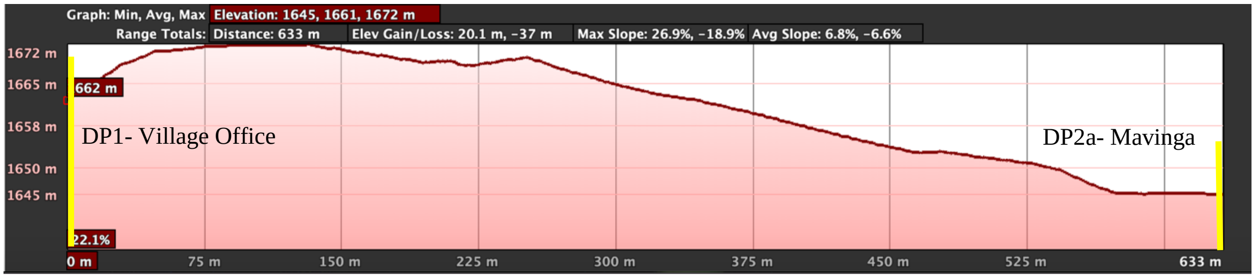


Figure E1: Elevation profile for the gravity main from the Village Office to Mavinga ("Rosedale").

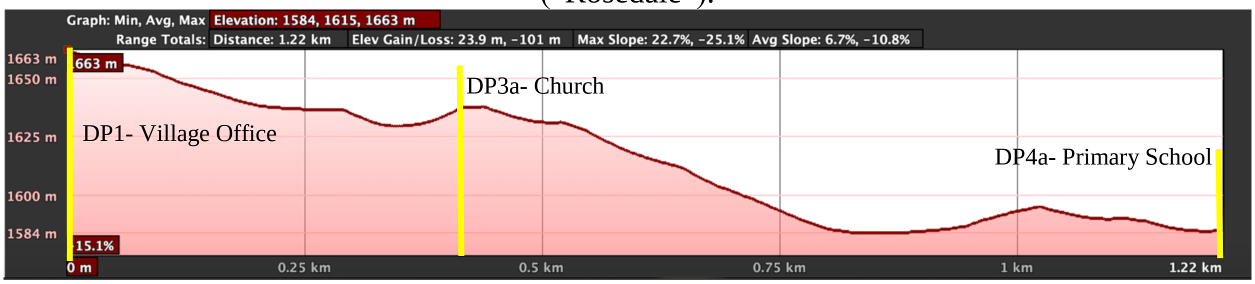


Figure E2: Elevation profile for the gravity main from the Village Office to the Primary School.

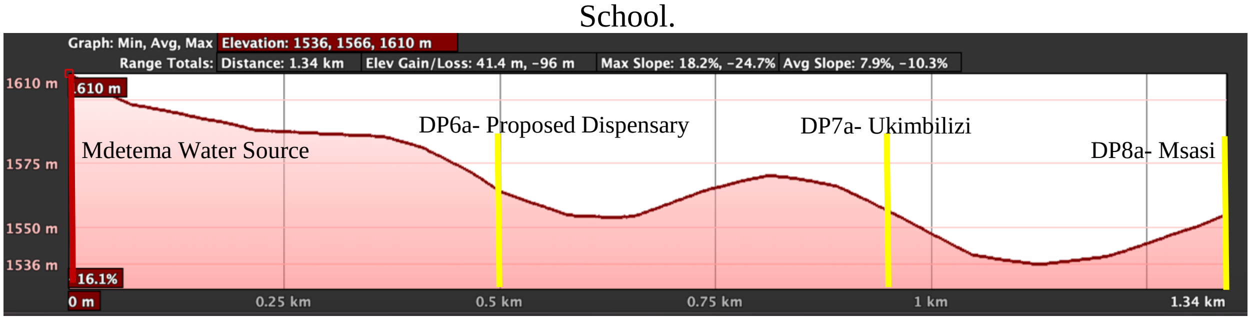


Figure E3: Elevation profile for the gravity main from the Water Source to the Msasi Preaching Point.

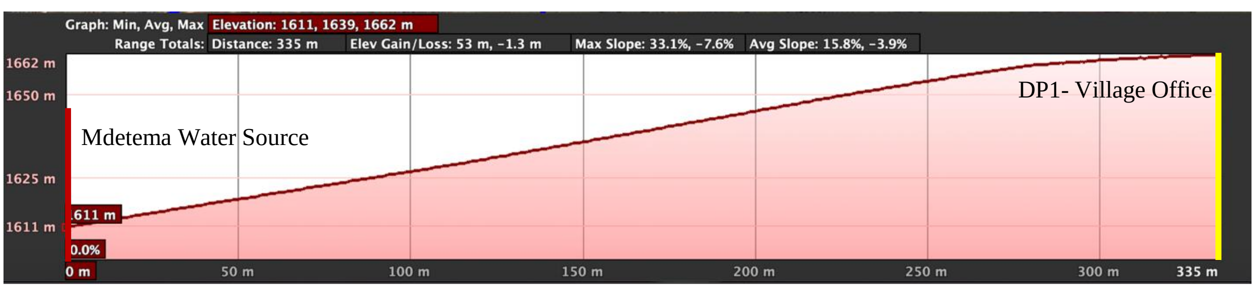


Figure E4: Elevation profile for the pumping pipe from the Water Source to the Village Office.