SANTA CLARA UNIVERSITY

Department of Civil, Environmental, and Sustainable Engineering

I HEREBY RECOMMEND THAT THE SENIOR DESIGN PROJECT REPORT PREPARED UNDER MY SUPERVISION BY

Peter Koros, Richard Matthews, & Ciara Murphy

ENTITLED

Groundwater Irrigation System for Sustainable Agriculture

BE ACCEPTED IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

BACHELOR OF SCIENCE
IN
CIVIL ENGINEERING

Thesis Advisor — Date: 6/12/19

Thesis Advisor — Date

Acting Department Chair — Date: 6.13.2019

Groundwater Irrigation System for Sustainable Agriculture

By

Peter Koros, Richard Matthews, Ciara Murphy

SENIOR DESIGN PROJECT REPORT

Submitted to
the Department of Civil, Environmental, and Sustainable Engineering

of

SANTA CLARA UNIVERSITY

in partial fulfillment of the requirements
for the degree of
Bachelor of Science in Civil Engineering

Santa Clara, California

Spring 2019

Groundwater Irrigation System for Sustainable Agriculture

Peter Koros, Richard Matthews, Ciara Murphy

Department of Civil, Environmental, and Sustainable Engineering

Santa Clara University, Spring 2019

Acknowledgements

We would like to thank BRAID Africa and its president, Rachel Dickins, for the opportunity to work on this project and for all the help offered to us along the way. Thank you to the community in Janzon Town for welcoming us and for implementing our pilot project. We could not have done it without all of you.

Thank you to our advisors: Dr. Edwin Maurer for all of his technical guidance and assistance and to Dr. Laura Doyle for her support.

Thank you to the Santa Clara University School of Engineering and Xilinx for their generous contributions to our project, without which our project implementation would never have happened.

Thank you to the Frugal Innovation Hub, especially Allan Báez Morales, for the continued support since the start of our project. We would like to thank him for facilitating countless meetings and for all the logistical support as we planned our travel.

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Abstract

The aim of this project was to develop a prototype that may be a model to help relieve food insecurity in rural Liberia. This was accomplished by designing a groundwater extraction, recharge, and irrigation system to facilitate year-long crop-growth. The project was in partnership with BRAID Africa and a community in Zwedru, located in east Liberia, near the border of Côte D'Ivoire. During 2010 and 2011, a civil war broke out in Côte D'Ivoire and led to the citizens of the country taking refuge in Liberia (Leaf 2015). Many refugees have decided to stay in Liberia and are struggling to maintain food security as most subsist on rice with not even enough to sell. Currently, villagers in Zwedru only grow the rice in swamps during the rainy season and, with climate change, the rainy season is becoming increasingly unreliable (USAID 2012).

The irrigation system that was designed for this project has allowed villagers to grow certain crops, such as cassava, okra, chard, and squash, during the dry season which will help alleviate food insecurity with the goal of providing a source of income for the farmers. This project was designed for a one hectare (2.47 acres) plot, which can be scaled up or down depending on land area and available resources.

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Introduction

Project Description

The aim of this project was to develop a prototype that may be a model to help relieve food insecurity in rural Liberia. This was accomplished by designing a groundwater extraction, recharge, and irrigation system in order to facilitate year-long crop-growth. The project is in partnership with BRAID Africa and a community in Zwedru, located in east Liberia, near the border of Côte D'Ivoire. During 2010 and 2011, civil war broke out in Côte D'Ivoire and led to the citizens of the country taking refuge in Liberia. Many refugees have decided to stay in Liberia and are struggling to maintain food security as most subsist on rice with not even enough to sell. Currently, villagers in Zwedru only grow the rice in swamps during the rainy season and, with climate change, the rainy season is becoming increasingly unreliable.

BRAID Africa is a non-profit organization dedicated to integrating Ivorian war refugees into "cohesive and self-sustaining communities" (BRAID Africa). Their mission is threefold: first, provide healthcare services to those suffering from physical and psychological trauma from the war; second, provide funding to establish schools for children; third, provide the seed capital in order to establish self-sustaining farming cooperatives. The communities BRAID Africa works with are now on the third phase of their mission; economic empowerment.

Motivated to aid in the healing of war-trauma survivors as they rebuild their lives and communities in Liberia, the team aimed to responsibly design and build a replicable, sustainable irrigation system that will allow communities to kickstart their agricultural economies. This was done by obtaining an understanding of the culture and keeping in sight those practices and design components that can be realistically integrated into the daily life of the community.

This irrigation system will allow villagers to grow crops such as cassava, okra, chard, and squash during the dry season which will help alleviate food insecurity with the additional goal of providing a source of income for the farmers, aiding in generating sustainable and reliable income vital to rebuilding their communities.

Figure 1: *Location of Janzon Town community in relation to the continent of Africa.*

Project Location

The field where the project was implemented was just outside of Janzon Town, a village approximately 13 miles northeast of Zwedru. Janzon Town is located in Grand Gedeh County, of which Zwedru is the capital, and is the second largest county in Liberia. This location was chosen by BRAID Africa due to the cooperation of the village chief and the community's determination to have the project succeed. From the BRAID Africa office in Zwedru, it is approximately a 90 minute drive to the field which allows for easy confirmation of the project's progress.

Demonstrated Need For Project

In order to achieve success in the last phase of BRAID Africa's threefold mission, communities in Grand Gedeh County needed a sustainable, replicable farming system that can provide them access to agriculture year round. To move past sustenance farming and into an economically successful agriculture operation, it is imperative that the community be able to irrigate crops during the dry season.

Scope of Work

Designed a groundwater irrigation system using a solar powered submersible pump, solar panels, irrigation lines, and sprinklers for a one hectare plot of land. The goal for this system was for it to be affordable and replicable in order to allow other communities to implement their own version.

Design Criteria and Standards

The purpose of this project was to provide water for crops on a 1 hectare (2.47 acres) field. The crops chosen by BRAID Africa and the design team were cassava, rice, okra, squash, chard, and pumpkin. The field was divided into six 50 x 33.3 meter (m) plots to organize the crops. The water requirements for these crops determined the amount of water that had to be provided. One of the goals of the project was replicability, and the project had to be affordable so that neighboring communities could implement the same design.

To establish an accurate understanding of the crop water requirements, the team used a program called CROPWAT. This program is a tool developed by the UN's Food and Agriculture Organization that calculates crop water requirements and irrigation requirements based on global soil, climate, and crop data. After using CROPWAT to analyze the planned crops, squash was determined to be the greatest water consumer (FAO, 2009). The flowrate was conservatively designed to meet that water requirement, which meant delivering 303 millimeters (mm) over the area every 10 days. Since the system operated on solar power, the team designed for six hours of good sunlight to power the pump. The water requirement of 303 mm every ten days was converted into a flow rate of 14.1 liters per second (l/s) by multiplying the water requirement by the area of one hectare and completing unit conversions. These calculations can be seen in Appendix A, Page A-1. This flow rate is extremely high, so the team decided to irrigate one-fifth of the field each day with a rotating system. The final flow rate was calculated to be 2.82 l/s. This works out to 60,600 liters per day.

Analysis of Alternatives

Description of Alternatives - Water Source

Alternative #1 - Rainwater Catchment

The problem posed to the design team was providing water for an agricultural project in a location that experiences rain for half of the year, from late March to October, as can be seen in Figure 2 from World Weather Online (WWO, 2018). One idea for a solution was designing a rainwater catchment system to catch water during the rainy season and store it in tanks to use throughout the dry season. Zwedru, Liberia experiences extreme seasonal variation in rainfall. There are approximately 80 inches of rainfall a year, with the majority of that falling between May and November (WWO, 2018).

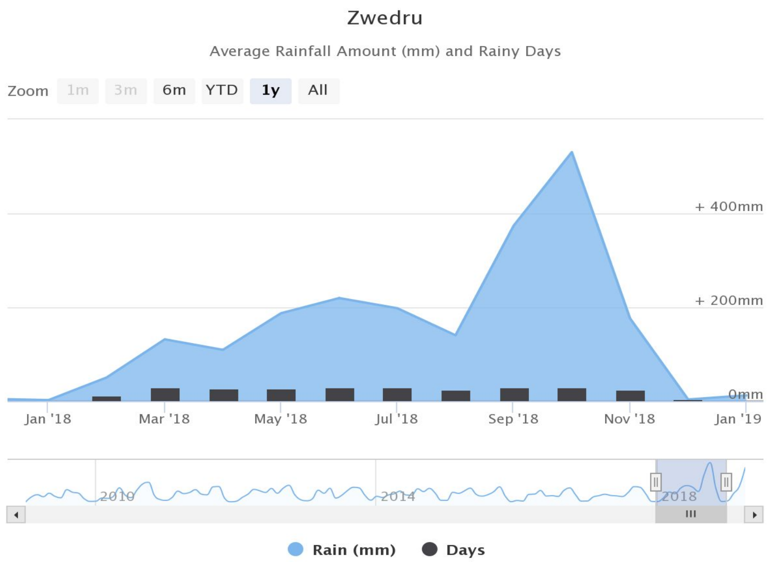

Figure 2: *The average rainfall in mm for each month of 2018. Reprinted from Zwedru Monthly Climate Averages, by World Weather Online, 2018.*

The design team researched several options for the catchment system, including rain saucers and catchment gutters. These options were abandoned when the team calculated the amount of water that would need to be captured and stored. From the CROPWAT data, the design team determined they would need to capture over 14 million gallons of rainwater during the wet season to irrigate the land during the dry season (FAO, 2009). It was not realistic to store this much water.

Alternative #2 - Creek Diversion

During design talks with BRAID Africa, it was discovered that another village near Zwedru, named Gboloken, placed their agricultural fields on either side of a creek that flows year round. The village built dikes out of sandbags on the banks of the creek. When it was time for a section of a field to be watered, the people would move the sandbags and allow part of the creek to flow into the fields. At this point, the exact location of the field for this project had not yet been determined, so this was evaluated as an option if the field could be located near a creek. It was later abandoned altogether, however, when BRAID Africa received feedback from the people of Gboloken who stated that this system was often hard to control, inefficient, and required intense physical labor.

Alternative #3 - Well

The next alternative considered was the implementation of a well and using groundwater to irrigate the field. There are hand pump wells dug in Janzon Town that are reliable and produce water consistently, so the team was confident that the well would provide enough water if it was dug deep enough. The well design was eventually chosen as the water source, as it would be the most practical and affordable option.

Description of Alternatives - Water Distribution

Alternative #1 - Drip Irrigation

The original design for the water system was drip irrigation. As seen in Figure 3, the original plan had the mainline travel horizontally across the high edge of the field near the well with drip irrigation lines running down the entire length of the 100 x 100 m field, spaced 1.5 m apart. Since drip lines can only run up to 60 m, this layout was infeasible. As seen in Figure 4, the design was altered to have the horizontal main line across the top with six main lines running down the field. Half of them would only run 50 m and the other half would run the full 100 m. Each main line would have 64 drip irrigation lines attached to it to provide water for each designated 50 m x 33 ⅓ m section. In spite of the revised design, there were still two problems with drip irrigation. The first problem was the potential for the lines to clog as water flows through the lines. The water would most likely carry some residual of soil with it without a filter on the pump, which can easily clog the small irrigation outlets of the dripline. The other problem was that drip irrigation lines could not be located in Liberia and would be very expensive to transport to the site. Part of the project was replicability, so it was necessary to change the design to ensure the materials for the project were both affordable and available.

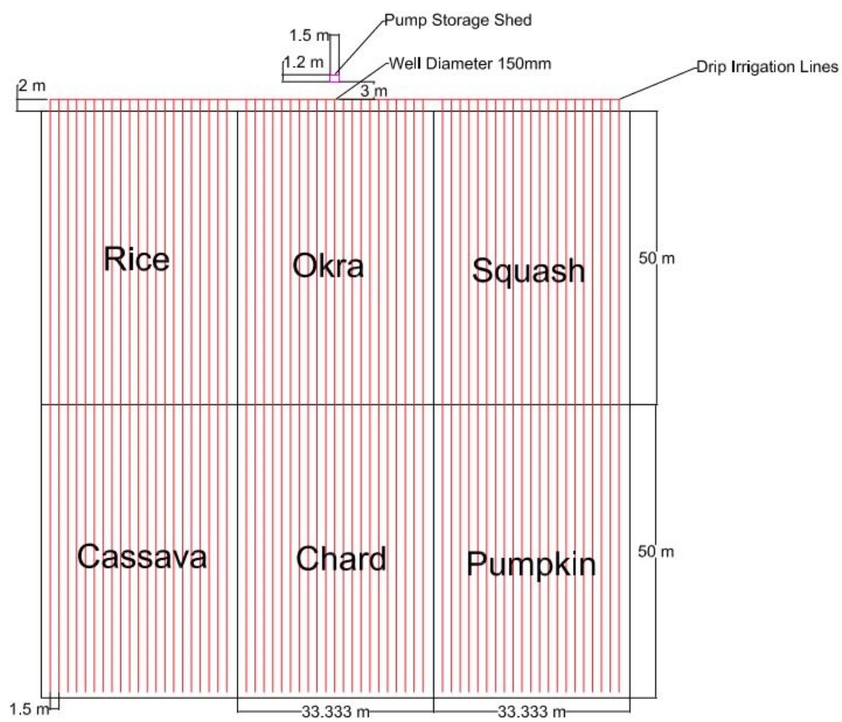

Figure 3*: Initial drip irrigation map layout of the 100 meter by 100 meter field.*

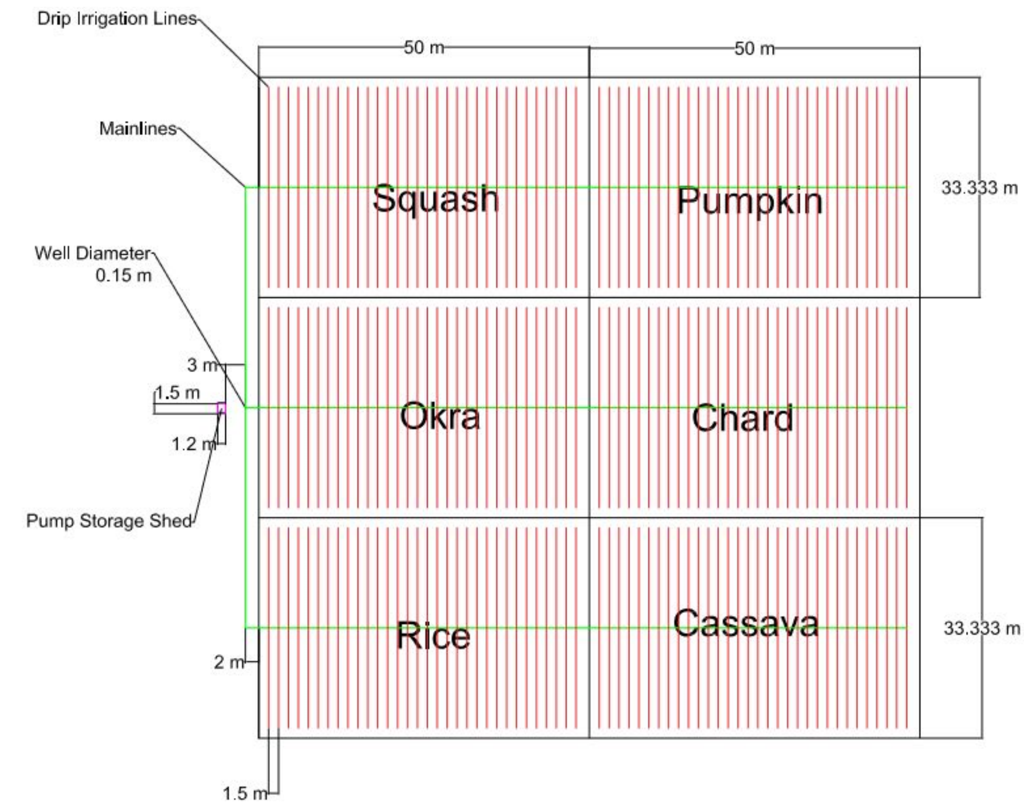

Figure 4: *Altered drip irrigation map layout of the 100 meter by 100 meter field.*

Alternative #2 - Handheld Gun Sprinkler

Another alternative evaluated was the implementation of a handheld gun sprinkler. Even though this system would be the least expensive and easiest to set up for the community, it would be the most basic design and involve many hours of physical labor. The only requirement of this system would be to ensure that the hose line could reach any part of the 100 m x 100 m plot to water all the plants.

Alternative #3 - Sprinkler System

A sprinkler system was another potential solution. Even though water is lost due to evaporation in sprinkler systems, a working system is the most important goal. Traveling with sprinklers and purchasing the necessary tubing in Liberia would be much more manageable and affordable than doing so with drip irrigation materials. As seen in Figure 5, the original proposed sprinkler system has six mainlines traveling the length of the field. Each sprinkler head had a conservative spray radius of 10 m. The sprinklers were placed 21.6 m apart on each line to ensure that all parts of the field would be watered. The sprinkler system that was implemented in Janzon Town (Figure 6) had six mainlines traveling the length of the field and each sprinkler had a maximum radius of 12.8 m at 35 pounds per square inch (psi). This system uses fewer sprinklers and less mainline which reduces the cost of the system, increases simplicity and replicability, and takes full advantage of the sprinkler capacity to completely water the field.

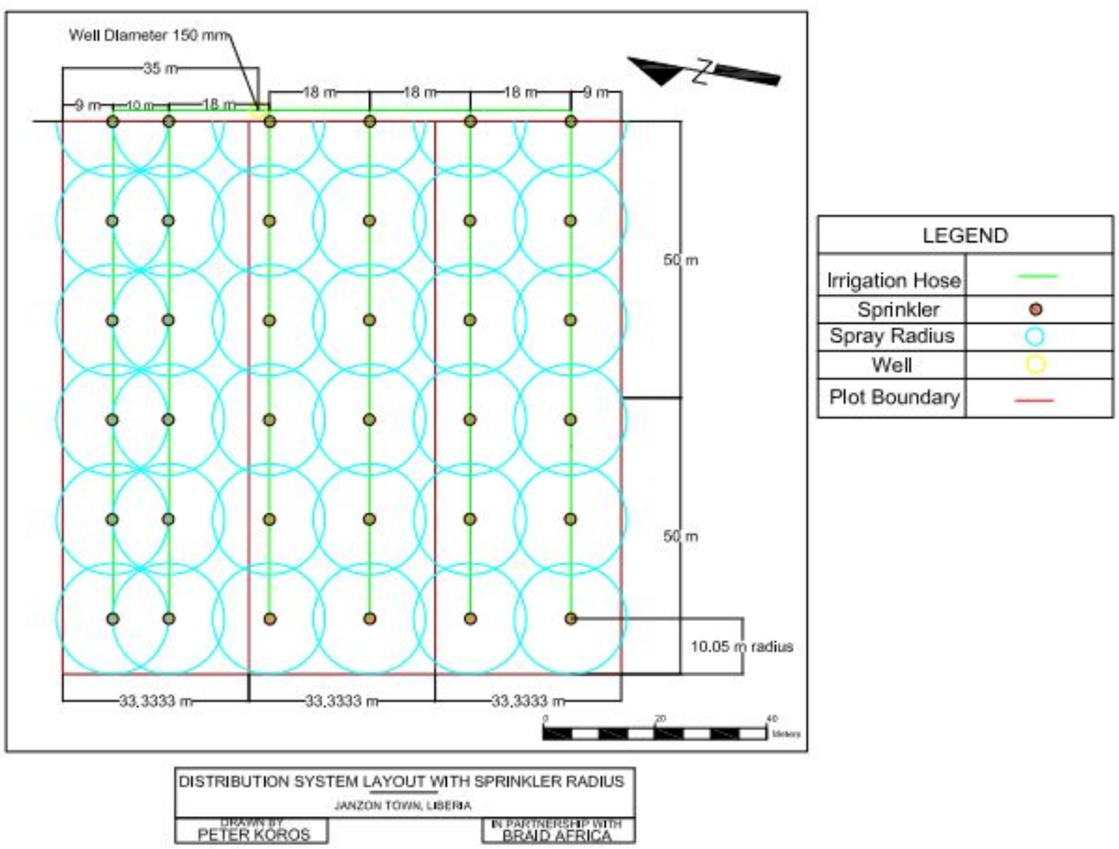

Figure 5*: Initial sprinkler map layout of the 100 meter by 100 meter field as well as the sprinkler radii.*

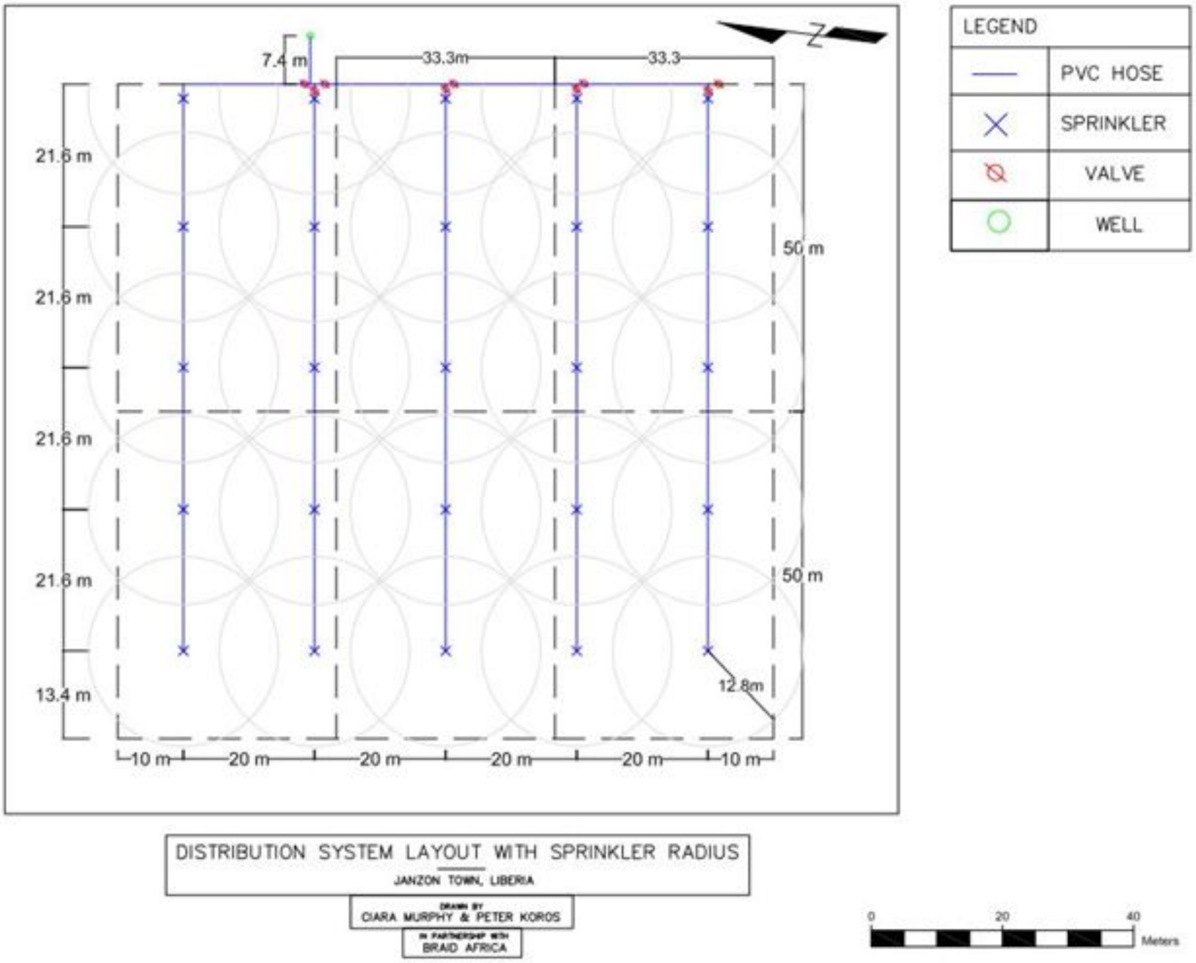

Figure 6: *Updated sprinkler map layout of the 100 m by 100 m field with sprinkler radii.*

Description of Alternatives - Pressure Options

Alternative #1 - Elevated Storage Tank

From the beginning of the design process, the team struggled to provide an adequate flow rate for effective irrigation of the field. One of the solutions to this problem was to have an elevated storage tank near the field. This idea would allow gravity to provide the necessary pressure. First, a digital elevation model (DEM) was used to check the area for any elevated land near the field. The team also reached out to BRAID Africa employees in Liberia to get a survey of the field, and both sources provided informed the team that the land was flat. An alternative to water tanks in flat terrain is a water tower to provide the necessary height and pressure for the desired flow rate. The tower would have to be approximately 75 feet tall to provide the necessary pressure for the sprinklers, on account of the fact that every 2.31 feet of elevation provides one pound per square inch of pressure. The labor skill, labor cost, and material cost were considered limitations when discussing building the water tower, as well as the cost and size of the tank. After much research and discussion, this solution was discarded due to the multitude of monetary and safety issues while constructing the tower.

Alternative #2 - Booster Pump

A second alternative was to provide a booster pump to supplement a submersible pump in a well. The booster pump would add pressure to the flow to run the sprinklers at their maximum potential. Originally, the team considered connecting the booster pump at the well opening so it could pump water directly out of the well. This idea was discarded quickly, as the pumps would be pumping at different flow rates because the booster pump would not be compatible with the submersible pump. Incompatible pumps can have operational problems. To provide a buffer between the pumps, the design team considered placing a tank in between them. This idea would ensure that the submersible pump could refill the tank while the tank could pump water out at a faster rate. The tank and booster pump would both exceed the budget. There was also difficulty finding a large enough (40,000 liter) tank to hold the necessary water.

Comparison of Alternatives

For the water source, the team decided to use a well and a solar powered submersible pump as this system would be practical to construct and affordable to implement compared to both the rainwater catchment and the creek diversion systems. For water distribution, the sprinkler system was chosen to deliver the water. Even though water would be lost due to evaporation in sprinkler systems, a working system was the most important goal. Aside from the sprinkler system being more affordable, water pressure and clogging would not be an issue in a sprinkler system like it would be for a drip irrigation system, and the sprinkler system is significantly more efficient than the handheld sprinkler gun. For pressure options, the team considered both an elevated water tank as well as a booster pump. The team moved away from these options as an industry advisor assured that the submersible pump had the necessary power to pressurize the system on its own. This assurance was confirmed by modeling the system on WaterCAD.

Description of Final Solution & Logic Behind Decision

System Description

The final design was completed after alternative design discussions and final preparations in Santa Clara. The system began with the solar powered submersible pump located 37 feet (ft.) down the 42 ft. deep well. The pump was connected to a discharge pipe, power cord, and safety cord, as seen in Figure 7.

Figure 7: *The pump connected to the blue discharge pipe, the yellow safety cord, and the black power cord.*

The power cord was connected directly to the pump control box placed inside a shed constructed seven ft. from the well. The pump control box was connected in series to four 24-volt (V) solar panels installed on top of the shed, as well as a lightning arrester and grounding rod buried three ft. deep located two ft. outside the shed, and a DC breaker connected to the wall next to the control box. The discharge pipe was connected to a PVC reducer directly above the well. The PVC adaptor was attached to a one-inch distribution hose that travels 10 ft. to the edge of the field. This hose connects to a second hose that runs along the top of the field, as can be seen in Figure 6. The one hectare field was to be divided into six 33.3 x 50 m plots, with the intention of each plot hosting a different crop. This spacing allowed for complete overlap of the sprinkler radius, which was 12.8 m, so that no part of the field would be left unwatered. The sprinklers were installed at the top of each line, and then every 21.6 m., indicated by the x's visible in

Figure 6. There are valves throughout the system, as seen in Figure 6, that control the flow of water so only one fifth of the field is watered each day.

Water Requirements

The final design utilized four solar panels to power the pump. To calculate the necessary flowrate for the crops, the team conservatively assumed six hours of pump operation each day. The team converted the water requirement of 303 mm every 10 days into a flowrate of 14.1 l/s. Since this is an extremely high flowrate, the team decided to implement a rotating system of irrigation that would water one fifth of the field each day. The re-calculated flowrate was 2.82 l/s. These calculations can be found in Appendix A, page A-1.

Well

The designed well was based on United States Geological Survey (USGS) and Schumacher Centre for Technology and Development recommendations and data, and information received from BRAID Africa regarding five wells in Janzon Town that had been constructed approximately 20 years earlier by the United Nations International Children's Emergency Fund (UNICEF). These five wells were all between 100-200 ft. deep, and the townspeople reported to BRAID Africa that two of the wells provided sufficient water consistently throughout the dry season. The Schumacher Centre for Technology and Development report *Developing Groundwater* recommended a six-inch diameter well for wells in rural areas (MacDonald, *et al*., 2005). Thus, the well design demanded a well that was 100-120 ft. deep, and six inches in diameter. From six inches above ground to 20 ft. below ground there should be either steel or

PVC casing to protect the well from contaminated surface water. From 20 ft. below ground to 100-120 ft. below ground there would be screening with holes that were 0.1 - 0.4 square ft. in size to allow water to flow into the well (MacDonald, *et al*., 2005). There would also be a concrete apron and concrete cap to protect the well casing and borehole. The designed well, along with the calculated aquifer characteristics, can be found in Appendix B. The aquifer characteristics were meant to tell the design team whether or not the constructed well could provide the necessary water each day. The Theis Drawdown Method was used to determine how far the water dropped each day. This method revealed the drawdown would be 15.8 ft. after six hours of pumping at 2.82 l/s each day (the design rate). It also showed that the next 18 hours would be enough to recharge the well to its original level each day. These values were approximate from the soil characteristics that were estimated from USGS averages (Heath, 2004) since no precise soil analysis could be performed by the contractors in Liberia. Affordability prevented the design team from recommending a deeper well. According to calculations, this well could provide the necessary water, depending on the exact soil characteristics surrounding the well. Local resources and time constraints, however, prevented this design from being implemented. BRAID Africa had an affordable well contractor, trained by Oxfam International, that would construct the well using a hand-powered drill. This type of drilling prevented the contractor from breaking through a rock layer 42 ft. below the ground surface. The drill this contractor used was four inches in diameter, resulting in a much smaller well than designed.


Figure 8: *Well contractors hand drilling the constructed well near Janzon Town.*

The constructed well was completed on February 20, 2019. The contractor provided a well log, as seen in Appendix B, page B-2, detailing the soil types down the well, the depth of the well (46 ft.), and the depth to water (22 ft.). When the design team arrived in Janzon Town, one of the first steps was to check the well and determine the accuracy of the well log. Using a metal bracket attached to a string, it was determined the well was actually only 42 ft. deep and the water was 24 ft. down. The constructed well's small diameter limited the amount of immediately available water in the well.

Pump

In order to purchase the correct pump for this system, the design team had to determine the total dynamic head. Total dynamic head is the addition of static lift and friction losses. Based on the well log received from the well contractor, the static lift was 24 ft. The total calculated friction loss, seen in Appendix A, page A-2, was 14 ft. The total dynamic head, therefore, was 37.8 ft. The pump needed to be able to operate with this total dynamic head and provide at least 35 psi of pressure for the sprinklers to function properly. After internal discussions and a meeting with a design group from University of Michigan who also completed a water project in Liberia, the design team began searching for pumps options with SunPumps, a pump supplier from Phoenix, Arizona. Based on the hydraulic requirements calculated, the team decided on the SCS 45-70-120 model (SunPumps, 2019). This pump had a power range of 75-120 volts. The pump was sized to fit in a well with a minimum diameter of four inches. In this system, the pump had to provide a flow rate of 2.82 l/s in order to provide the crops with the water needed to grow. The water demand was determined using CROPWAT. The pump system curve seen in Appendix C shows the pump is capable of operating at the calculated flow rate and total dynamic head. The curve also shows that if the system was placed in a deeper well, the pump could still operate within its range. The pump system purchased from SunPumps came with a 1.5 horsepower pump, the system control box, a 50 ft. power cord, a 50 ft. safety cord, and the 50 ft. drop hose. In order to attempt to provide the necessary water, the pump was placed 37 ft. down in the well.

Shed

A shed was constructed for several reasons. The solar panels that powered the pump had to be mounted in some way. Also, the pump controls and wiring had to be sheltered from rain and general exposure. Finally, the system needed security. The solar panels were connected to the roof, then latched down with steel bars. The shed had a lock that kept the controls and wiring out of sight and reach.

Figure 9: *The constructed shed with its door open, pump controls inside, and solar panels on the roof.*

The shed was built out of tree trunks that had been cut down while clearing the field, wood planks from the town, and scrap metal for the walls. The shed was designed and built by BRAID Africa contractors. It had a six ft. by six ft. concrete floor and foundation, was built seven ft. from the well, and was approximately 10 ft. tall. The exact location of the shed was decided by the contractors with the hopes that it would be close enough to the well to provide security for materials without interfering with work near the well. The pump power cord was covered with a PVC pipe cut in half longways for protection between the well and the shed.

Solar Panels

The SCS 45-70-120 model pump purchased from SunPumps was designed to run on 75-120 volts. Four 24 volt solar panels were purchased in Monrovia to provide this power. These panels were five ft. x three ft. This panel size and voltage was the best option available in Monrovia. The panels were connected in series to the pump system control box. The panels were connected in series in order to additively provide the system with a nominal voltage of 96 volts. In the relatively likely event of a lightning strike on the panels or the metal roof of the shed, a lightning arrestor was purchased to ensure the system was not destroyed due to a lightning strike. Additionally, a lightning rod and DC breaker were purchased to ground the entire system and protect the pump from power surges.

Sprinklers & Irrigation Lines

The sprinklers were purchased at a Home Depot in Santa Clara. The sprinklers design specifications stated that they sprayed 360 degrees and had a radius of 12 m at 40 psi of water pressure. The radius of the sprinklers drove the iterative hydraulic design process; the radius determined the spacing of the lines, which determined how many sprinklers were needed, which determined the pressure losses. Twenty-five sprinklers were placed throughout the field, shown in Figure 6. They were placed in series 21.6 m apart along each of the five irrigation lines traveling down the length of the field. The spacing of the five lines and the sprinklers was based on the 12 m radius of the sprinklers. As seen in Figure 6, the goal was to come as close as possible to ensuring that no space on the field was out of reach of the sprinklers.

Design Phase Obstacles

The largest obstacle was operating as a satellite design team and relying on others for gathering the necessary information. This type of communication made it very difficult to get accurate descriptions of the field and surrounding area, the soil characteristics, aquifer characteristics, and materials and resources available in Liberia. Traveling to Liberia to survey the project site would have been impractical with the project's funding constraints, so the project had to be designed through descriptions during video meetings, text updates through WhatsApp, email, photos, and ArcGIS for geologic data.

Construction of System

Obtaining and Purchasing Materials

For the final design utilized over $8,000 worth of materials. This $8,000 included the submersible pump system, solar panels, irrigation lines, sprinklers, hose fittings, shed materials, and well materials. The pump, hose fittings, and sprinklers were all purchased in the United States (US), while the remainder of the materials were purchased at a variety of shops in Monrovia and Zwedru. Once in Liberia, it was determined that similar versions of all the materials purchased in the US could have been purchased in Liberia, at a much lower price.

Well Construction

The placement of the well was difficult to establish. The challenge was to determine which location would have the highest water elevation. The design team had received information from BRAID Africa that there was a swamp near the field that never dried up at any point during the dry season. This fact indicated that there should be a shallow water table. The well construction had to occur before the design team arrived, and BRAID Africa's contractor completed the project in just a few days. The first two wells that were dug were abandoned because the well contractor did not think they would supply much water due to the soil type. The third attempt revealed the desired soil type and was completed. The well log that was filled out by the contractor stated that the well was four inches in diameter, 46 ft. deep, and the water level was 22 ft. below the ground surface.

Shed Construction and Solar Panel Installation

Shed construction began before the design team's arrival. The concrete floor was poured the week before arrival. Construction of the structure of the shed began during the first day of the design team's time in the area. Wood from trees cut down in the field, wood planks from town, and scrap sheet metal were used for the framing, walls, and roof of the shed. Although the design of the shed was completed by BRAID Africa contractors, the design team added suggestions, such as an angled roof, to allow the solar panels to sit at an angle that faced the sun. The solar panels arrived from Monrovia on the second day and were immediately brought from the trucks to the shed and mounted on the roof by the community. The design team had done the necessary research to ensure the panels were wired correctly and connected to the pump control box, however, BRAID Africa had an extremely capable electrician. As soon as the panels were mounted, this electrician completed the wiring in under 30 minutes. Each panel was generating up to 30 volts throughout the day, which was well above their nominal voltage. As aforementioned, the power range of the pump system was 75-120 volts, so four panels generating up to 30 volts was within the range of the system. The additional electrical materials meant to protect the electrical components were installed in the shed, while the lightning rod was secured in a hole just outside the shed that was three ft. deep.

Pump Installation

The solar powered submersible pump system that was purchased from SunPumps included a 50 ft. power cord to attach to approximately three ft. of power cord that was directly connected to the pump. The first step in installation was to connect these cords. This connection had to be a waterproof connection given that it would be underwater in the well. Using two types of tape, plastic tubing, and silicone, the design team ensured that the submerged connection was waterproof and safe from shorting out the system. The power cord was then wired into the control box, as seen in Figure 10. Next, the design team had to determine how deep to install the pump. The goal was to have as much water above the pump as possible, while also preventing dirt from the bottom of the well from being churned up and clogging the pump systems. After discussing this with local well contractor, the decision was made to place the pump 37 ft. down. The discharge hose was cut to 37.5 ft. to allow the hose and clamp to extend out of the well. This clamping was done to prevent the hose from creasing over the edge of the well, restricting the flow of water. Next, the pump was placed in the well. This was a tight fit, given that the minimum diameter for a well this pump could fit in was four inches and the well casing was four inch PVC piping. Nevertheless, the pump fit and functioned properly. A safety cord was also attached to the pump, further preventing the possibility of the pump falling down the well. On the second day in Janzon Town, the design team tested the pump system. The system ran for one minute and water poured out the top of the well. This one minute test drained over 80% of the well. Installation continued with the understanding that a deeper well would likely have to be constructed for the system to work long term. The flexibility of the design allowed for all system components to be transplanted into a new well once a deeper one was constructed, which was thoroughly explained to BRAID Africa and the Janzon Town community.

Figure 10: *The wiring that connected the solar panels and pump, and the controls of the pump's flow rate.*

Discharge Pipe Assembly

The discharge pipe that came with the pump had a two inch diameter, while the irrigation lines were one inch in diameter. This necessitated a reducer that could connect the two inch and one inch pipes securely. This reducer introduced additional head losses in the system, which were calculated on site using Bernoulli's energy equation to be 1.5 m. This increased the total friction headloss in the system to 5.2 m. When the team arrived on site, it became apparent that the field was on an approximately 1% slope, estimated as a one meter elevation change across 100 m of distance. This change in elevation brought the total friction head loss to 4.2 m.

Sprinkler and Valve Installation

The team spent one day laying out all the mainline, cutting it, and then placing it throughout the field as displayed in the layout plans. As seen in Figure 11, the sprinklers were attached to the mainline by attaching a male adapter with a hose clamp to the hose just before the impact sprinkler and attaching a female adapter with a hose clamp to the hose just after the impact sprinkler. As seen in Figure 12, the valves were attached to the hose by attaching a male adapter just before and just after the valve because the valves had female connections on both sides. The team used the layed out mainline to ensure the sprinklers were an appropriate distance away from one another while running down the field, as well as used a string to ensure the distance from sprinkler from row to row was accurate. During the third day on the site, the design team tested the system again, this time with the pump connected to a test line with two sprinklers and a flow control valve. The well had recovered enough from the day before to allow this short test that let the team observe the sprinklers in action. This test showed that the sprinkler-to-adaptor connections leaked. Using rubber rings that came with the sprinklers and teflon tape, the leaks were corrected. The two tests provided a secure proof of concept.

Figure 11: *The connection of the sprinklers to the mainline using male and female adapters.*

Figure 12: *The connection of valves to the hose at a T-joint using male adapters. Valves can be seen on all three sides of the T-joint.*

Construction Phase Obstacles

The largest obstacle in terms of construction and implementation was adjusting the design to the realities of the resources, materials, and measurements in Liberia. The primary difference was the well. The well log reported a well that was 46 ft. deep and a water surface that was 22 ft. from the ground surface. In reality, the well was 42 ft. deep and the water surface was 24 ft. from the ground surface. This reality required the design team initially to adjust the pump elevation, and finally to recommend a new well. The deeper water level changed the pump placement because it changed the amount of water that would be above the pump. Ideally, the pump would have been located further from the bottom of the well, but the deeper water level necessitated the pump be deeper. After the tests described in the Results section, it was determined that a deeper and wider well should be constructed in order to provide the required amount of water to the field.

Cost Breakdown

Materials

The materials that were necessary for the system to function properly are displayed below in Table 1. The adapters, pump, valves, sprinklers, and hose clamps were bought in the US, while the surge protector, DC breaker, lightning rod, hose, and shed materials were purchased in Liberia. Some of these materials were bought in the US because it was unclear if those materials would be available in Liberia. The same model of pump was found for sale in Liberia that only cost $800 compared to over $3,000 in the US. The same solar panels that were purchased in Liberia were later found at another store for nearly $100 cheaper per unit. In Table 2, the costs of the pump and the solar panels were adjusted to make the project more affordable moving forward. According to the Comprehensive Assessment of the Agriculture Sector, written by the Republic of Liberia's Ministry of Agriculture, communities with lowland farms use 11% of the harvest for personal consumption in the community while the other 89% are used for sales (Republic of Liberia Ministry of Agriculture, 2007). The average income per crop per harvest was determined for each one sixth of a hectare plot. As seen in Table 3, the team determined the number of harvests per year for each crop and that the total income per year would be nearly $1500. For the system implemented, it would take roughly six years to pay off the system, and for the adjusted material cost system, it would take roughly four years to pay off the system, as seen in Table 4.

Table 1: *Initial material costs for materials bought in the United States as well as in Liberia.*

Material Cost	
Adapters	$202.04
Pump	$3,148.20
Solar Panels	$1,800.00
Well	$1,500.00
Surge Protector & DC Breaker	$180.00
Valves	$38.50
Lightning Rod	$45.00
Sprinklers	$399.40
Hose Clamps	$88.00
Hose	$1,015.00
Shed Materials	$106.50
Total	**$8,522.64**

Table 2: *Adjusted material costs for materials bought in the United States as well as in Liberia.*

Adjusted Material Cost	
Adapters	$202.04
Pump	$800.00
Solar Panels	$1,400.00
Well	$1,500.00
Surge Protector & DC Breaker	$180.00
Valves	$38.50
Lightning Rod	$45.00
Sprinklers	$399.40
Hose Clamps	$88.00
Hose	$1,015.00
Shed Materials	$106.50
Total	**$5,774.44**

Table 3: *Income from crop yield per year based on the Liberian Ministry of Agriculture's Comprehensive Assessment of the Agriculture Sector.*

Income from Crop Yield per Year			
Vegetables	Income per Harvest	# of Harvests	Total Income
Rice	$21.41	2	$42.82
Okra	$136.13	2	$272.26
Pumpkin	$136.13	1	$272.26
Cassava	$39.50	2	$79.00
Squash	$136.13	2	$272.26
Chard	$136.13	4	$544.52
Total			**$1,483.12**

Table 4: *Years it takes to pay off both the current system as well as the adjusted system*

	Crop Yield Total	Crop Yield Income per Year	Price/Income	Years to Payoff System
Material Price Current System	$8,522.64	$1,483.12	5.7	6
Material Price Adjusted System	$5,774.44	$1,483.12	3.9	4

Transportation

The team flew to Liberia on March 16, 2019. The tickets for the international flights cost $7,286.97 for the three students. Once in Liberia, the team would need a rental car and driver as driving in Liberia can be dangerous for foreigners due to lack of traffic law enforcement. The cost of the rental car and driver for the total eight day trip was $1,127.50. The team also needed to fly in a charter flight from Monrovia to Zwedru as it would take 18 hours to drive that distance compared to a 45 minute flight. The charter flight cost $2,448.31 for one way, so it came out to a total of $4,896.62 for the three students.

Lodging

The team spent a total of three days in Monrovia and five days in Janzon Town. In Monrovia, the team stayed at the Bella Casa Hotel for all three nights which came out to a total of $570. In Janzon Town, the team stayed at the Ma-Queenyonnah Hotel for five nights which came out to a total of $320. The total cost of housing was $890.

Labor

For well construction, BRAID Africa knew of a subcontractor they had worked with before who had been trained to dig wells by Oxfam. The subcontractor charged $1,500 for the construction of the well. BRAID Africa paid some of the community members in Janzon Town to clear and level the field of trees, other foliage, and termite mounds.

Total Project Cost

As seen in Appendix D-6, the total cost of the project, including material costs, food, labor, housing, and transportation, came out to $19,768.13. The budget is extremely large for a senior design project, but most of the expenses came from travel and transportation. As seen in Table 4, the system itself could be replicated for $5,774.44, discluding labor. If the project is to be replicated moving forward, having a contact in Liberia to implement the system and having someone ship the materials not available in Liberia from the US would greatly reduce costs of the project.

Ethics of Solution

Ethical Justification of the Project

While in Liberia, the design team came to terms with several ethical dilemmas, some of which were expected and some of which were not. While working on the design in the months leading up to their departure, one of the main obstacles was fundraising. The design team determined they needed to raise approximately $23,000 (estimated January 2019) in order to pay for the different elements of the design and for travel to and from Zwedru. This was far more than the original budget of $14,000 (estimated October 2018). This sum of money brought up the ethical dilemma of whether or not it was appropriate or necessary for the design team to travel to Liberia to install this project. Of the $23,000, over $11,000 was for the team's travel expenses. If the team was able to raise $23,000, would it be ethical to spend $11,000 to travel to a developing country and give them a $12,000 irrigation system, when instead they could simply give the community $23,000? The design team took a utilitarian approach to the ethics of this problem, understanding that what would provide the most good to the most amount of people was a successful implementation of the project and a chance for the design engineers to troubleshoot and learn by doing.

Many of the decisions and dilemmas encountered by the team required careful consideration of privileges and the lenses through which they were biased to view things. In the design and implementation processes, the team tried to maintain awareness of the white savior industrial complex and how it has potential to play out in well-intentioned projects such as this. This complex is when a white person from outside a community comes in to provide relief or help, but instead their actions turn out to be self-serving, showing little regard for the community in need. It also assumes the community in question cannot help themselves. The design team felt comfortable with the second aspect due to the fact that BRAID Africa, headquartered in Zwedru, came to the University looking for engineering help on this project.

Acknowledging this fact, the design team also considered the justice approach when trying to decide how best to spend their time and money. The justice approach asks which course of action treats people equally. In some ways, if the team travelled to Liberia, they would not be treating the people of Zwedru equally, as they would never spend large sums of money to travel to Texas and then implement a groundwater irrigation system. In this case they would logically give the Texas community the money raised and send the system and trust they would be able to either install it themselves or hire someone to do it. The team met extremely capable people in Zwedru and Janzon Town, some of whom had extensive water project experience after working with various Non-Governmental Organizations (NGO's) that had worked in Liberia before. Traveling would allow the team to ensure the design was installed how they knew it needed to be, however. If a problem were to arise, they would be putting all the responsibility of the system into the hands of a community that may not have the ability to fix it. The design team therefore travelled to Liberia as a group because they wanted to take full responsibility for any issues or failures in the system, as well as have the opportunity to learn how to improve and simplify the design for future reference. If materials were mishandled, the team wanted that to be their fault and not the fault of a community member who may never have worked with that material before. The project was a large, international team effort, but the responsibility of a successful design and implementation should be with the design team.

The ethics of money and money allocation in this project came up in more ways than one. Establishing a budget of $23,000 for a humanitarian project has some issues associated with it. The design team was trying to make this a replicable agricultural project, however the upfront cost of the project would be extremely prohibitive to most communities attempting to replicate it, let alone a refugee community in Liberia. Without the cost of travel, the project still cost about

$8,000 in materials and labor. This was not a feasibly replicable project. Thus, the team was forced to consider the ethics of deploying such a project. In following with Santa Clara's Engineering Handbook, the team considered what is fair and just. Obviously, at the time they were faced with these issues of feasibility, it would have been unethical to back out of the project just because it did not seem that it could be sustainable. The design team had the means to pay for this project, the community expected them to provide a design, and the community would benefit from the implementation of this project, regardless of how replicable it was. The ethical dialogue now revolved around the team's responsibility to share the design. The design team has kept working on simplifying the design and cost so that it can be feasibly scaled.

Another difficult issue encountered was the dilemma of water. One fear was that the system would draw massive amounts of water from the ground everyday. It was difficult to determine a solid estimate of the drawdown of the water in the well because the team was not at the site in person during the design process, the site lacked adequate equipment to determine the soil content, and communication with the team in Liberia proved to be very difficult. It was challenging to confidently estimate the depth of the groundwater, the hydrologic conductivity of the soil, and the recharge rate of the well due to these circumstances. Without having solid figures on this information, the team risked extracting water from the aquifer extremely quickly and not providing the aquifer enough time to naturally and properly recharge. Over-extraction can cause the surrounding surface water such as lakes and rivers to be dried out along with wells in the neighboring communities.

This project faced several ethical dilemmas during design and implementation. After the initial meetings with BRAID Africa, the design team felt an ethical responsibility to take on this project and make it successful. The community in Janzon Town was in need of assistance, and thanks to BRAID Africa's initiative, they have now received that help. Had this project not been taken on, the community in Janzon Town would likely be stuck using subsistence farming for at least the next year. This method was not a sustainable way for their community to grow and prosper, so this project had to happen as soon as possible. On account of this project and all the teamwork that occurred, the system has fortunately been successfully operating for weeks now.

Conclusion

Some of the next steps needed to make this project truly replicable and sustainable would be a deeper search for alternate materials and models to reduce the overall cost of the project. As can be seen in Table 4, re-sourcing all the materials to Liberia reduces the return rate from six years to four years. Since the team left Liberia, a new well has been dug that is deeper and wider and the community has been able to operate the system successfully. Okra was recently harvested from the site.

The project was successful in establishing a groundwater irrigation system that could sustain crop-life and be operated and maintained by members of the community. The project in its current design, however, is not replicable. The team anticipated purchasing more materials in Liberia than the US and assumed materials would be less expensive in Liberia. While this is true, the team was not able to access these materials during the design phase and did not design for the readily available materials in Liberia. The cost of the implemented project is prohibitive, however the team hopes that through further investigations this project can be replicated sustainably.

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Appendix A

MAX IRRIGATION: 303.1 mm/10d — CROPWAT

= 30.3 mm/d

IRRIGATE FOR 120 DAYS — CROPWAT

$30.31 \frac{mm}{d} (120d) = 3,637.2 mm = 3.637 m = 11.93 ft$

1 HECTARE = $107,639 ft^2$

$11.93 ft (107639 ft^2) = 1,284,133.3 ft^3$

└ WATER DEMAND OVER WHOLE SEASON

$1,284,133 ft^3 / 120d = 10,701.1 ft^3/d$

TO ONLY PUMP 6 hrs/d

$Q = V/t = \frac{10701.1 ft^3}{6 hrs} = 1783.5 ft^3/hr = 14.1 l/s = Q$

$$P+\frac{V_1^2}{2g}=P+\frac{V_2^2}{2g}$$

$V_1 \rightarrow$ 2" diameter

$V_2 \rightarrow$ 1" diameter

$$\frac{1.39^2}{2(9.81)}+P=P+\frac{2.82^2}{2(9.81)} \Rightarrow \frac{1.93}{19.62}+P=P+\frac{7.95}{19.62}$$

$$0.0984+P=P+0.4052$$

$$\Sigma P=0.31\,m$$

$$\frac{1.39^2}{2(9.81)}+P=P+\frac{5.57^2}{2(9.81)} \Rightarrow \frac{1.93}{19.62}+P_1=P_2+\frac{31.03}{19.62}$$

$$0.0984+P_1=P_2+1.5813 \qquad \Sigma P=1.5\,m$$

Sprinkler reduction

$$P_1+\frac{V_1^2}{2g}=P_2+\frac{V_2^2}{2g}$$

$V_1 \rightarrow$ 1" diameter

$V_2 \rightarrow$ ½" diameter

$$P_1+\frac{5.57^2}{19.62}=P_2+\frac{22.28^2}{19.62}$$

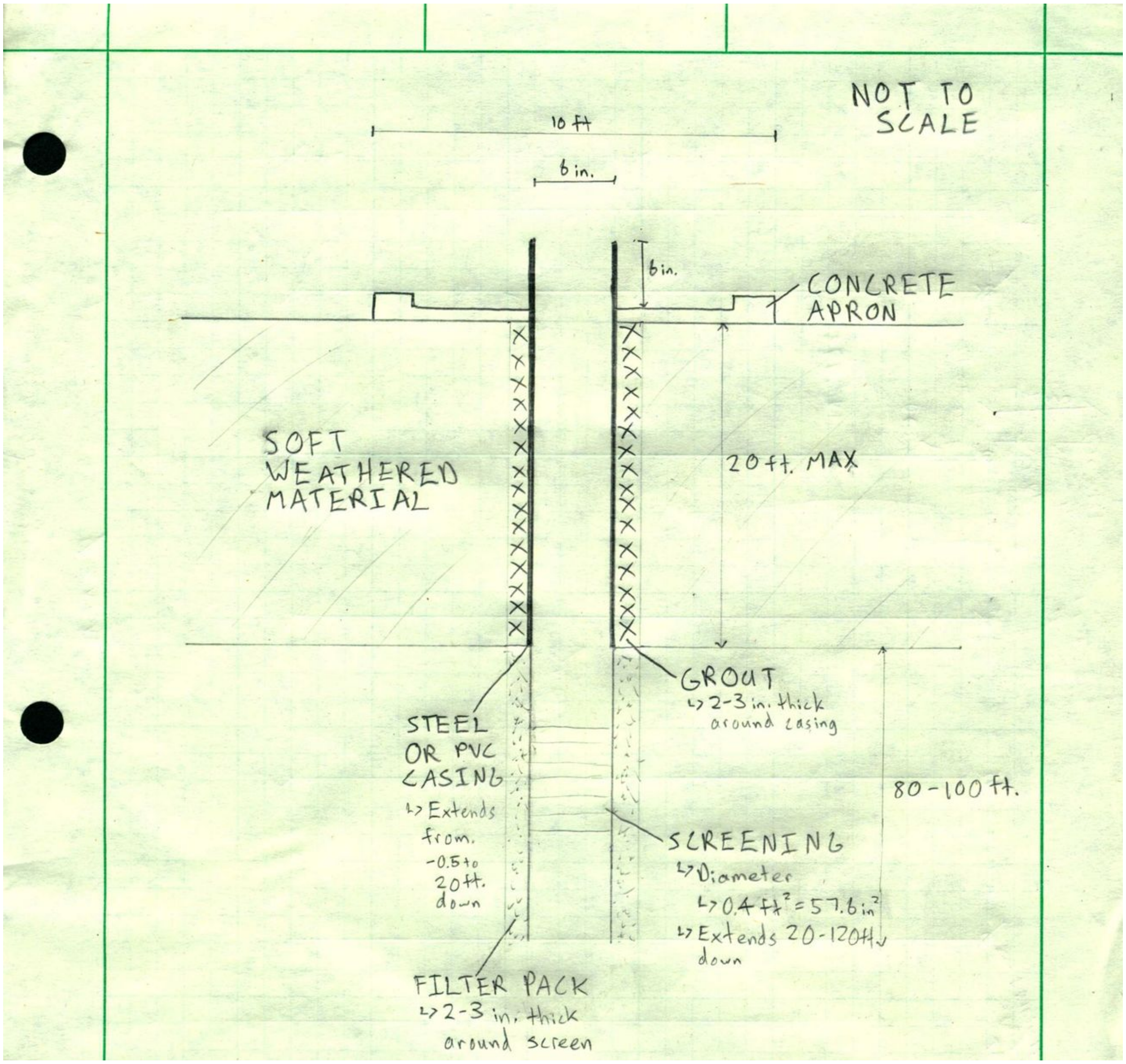
$V_1 = 5.57$ m/s

$V_2 = 22.28$ m/s

$$P_1+1.5813=P_2+25.3006$$

$$\Sigma P=23.72\,m$$

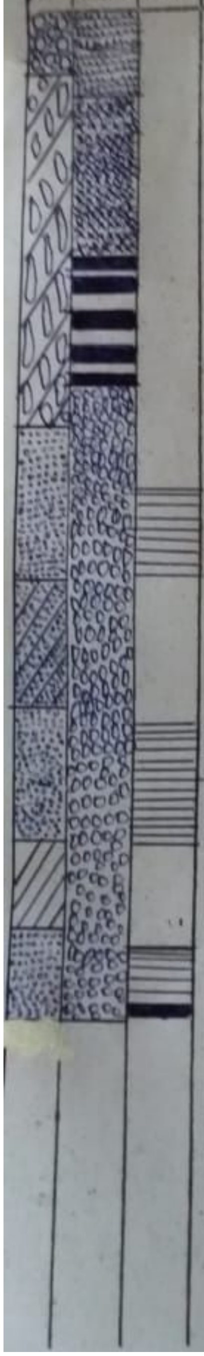
Appendix B


NOT TO SCALE
10 ft
6 in.
6 in.
CONCRETE APRON
SOFT WEATHERED MATERIAL
20 ft. MAX
GROUT
↳ 2-3 in. thick around casing
STEEL OR PVC CASING
↳ Extends from -0.5 to 20 ft. down
80-100 ft.
SCREENING
↳ Diameter
↳ 0.4 ft² = 57.6 in²
↳ Extends 20-120 ft. down
FILTER PACK
↳ 2-3 in. thick around screen

Name: Jacob   Site Name: Agriculture   Start Date: 10/02/2019

Latitude: ______   Population: ______   Partner Org: God Provide Water

Altitude: ______   Longitude: ______   Village Contact Info: ______

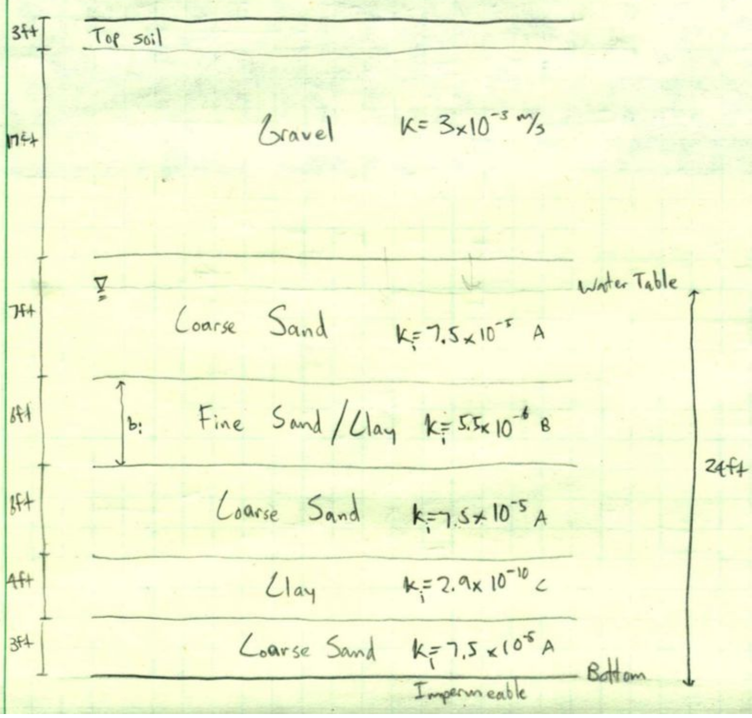


Depth (ft)	Soil Type	Fine/Course	Hard/Soft	Color	Time	Date	Notes
0	Top Soil	Course	Hard	Brown	09:15	10/02/19	we start work
1	V	V	V	V			at 09:15 Am and
2	V	V	V	V			the layer was
3	Gravel	Course	Hard	yellow			gravels
4	V	V	V	V			
5	V	V	V	V			
6	V	V	V	V			
7	V	V	V	V			
8	V	V	V	V			
9	V	V	V	V			
10	V	V	V	V			
11	V	V	V	V			
12	V	V	V	V			
13	V	V	V	V			
14	V	V	V	V			
15	V	V	V	V			
16	V	V	V	V			
17	V	V	V	V			
18	V	V	V	V			
19	V	V	V	V			
20	Sand	Course	Soft	brown			
21		V		V			
22	WATER			H2O	02:14	13/02/19	we heat water
23	V	V	V	V			at 22 feet and
24	V	V	V	V			layer was sand
25	V	V	V	V			permable layer
26	Sand	V	V	V			
27	Clay Sand	Fine	Hard	yellow			
28	V	V	V	V			
29	V	V	V	V			
30	V	V	V	V			
31	V	V	V	V			
32	V	V	V	V			
33	Sand	Course	Soft	brown			
34	V	V	V	V			
35	V	V	V	V			
36	V	V	V	V			
37	V	V	V	V			
38	Sand	V	V	V			
39	Clay	Fine	Hard	yellow			
40	V	V	V	V			
41	V	V	V	V			
42	V	V	V	V			
43	Sand	course	Hard	brown			
44	V	V	V	V			
45	V	V	V	V			
46	V	V	V	V			
47					03:19	15/02/19	we stop at
48							46 feet at
49							03:19 and the
50							layer was
51							[illegible] impermable
52							layer
53							
54							
55							
56							
57							
58							
59							
60							

Aquifer Characteristics

$T = kb$ $\qquad$ $b \approx 17\ ft$ $\qquad$ $dh/dL \approx \frac{22 ft}{229.7 ft} =$

$dh/dL \approx 0.096$



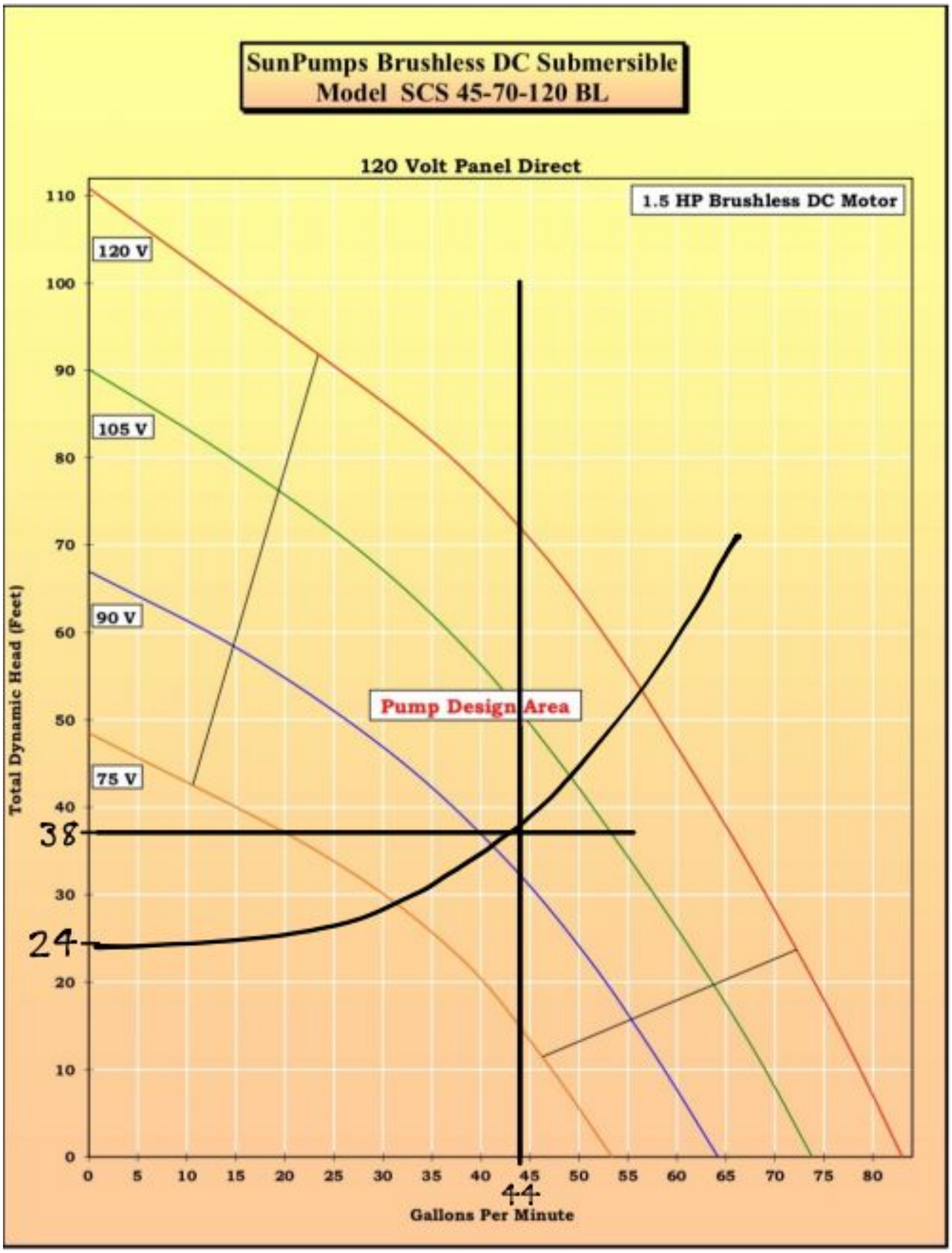
$K_x = \frac{\sum k_i b_i}{\sum b_i}$

$K_x = 12.79\ ft/day$

$T = kb = 306.9\ ft^2/day$

Theis Drawdown	
Aquifer Thickness, b, ft	24
USGS Hydraulic Conductivity, k, ft/day	
Coarse Sand	21
Clayey Sand	1.6
Clay	0.000082
Combined k	13
Transmissivity, ft^2/day	308
USGS Storativity	0.2
Radius Squared, ft	0.14
u-Value	0.000091
W(u)	8.7
Drawdown, ft	**16**

Appendix C


SunPumps Brushless DC Submersible
Model SCS 45-70-120 BL
120 Volt Panel Direct
1.5 HP Brushless DC Motor
120 V
105 V
90 V
75 V
Pump Design Area
Total Dynamic Head (Feet)
Gallons Per Minute
0
5
10
15
20
25
30
35
40
45
50
55
60
65
70
75
80
90
100
110
38
24
44

Appendix D

ORBIT					
Head Model	Price	Radius (ft)	Radius (m)	Flow rate (GPM)	Pressure (psi)
0.5" Zinc Impact Sprinkler	$4.74	20	6.096	2.7	20
		33	10.0584	3.3	30
		36	10.9728	3.8	40
		38	11.5824	4.3	50
		38	11.5824	4.7	60
1/2" Plastic Impact Sprinkler Head	$3.95	24	7.3152	2.3	20
		37	11.2776	2.8	30
		39	11.8872	3.2	40
		42	12.8016	3.6	50
		44	13.4112	3.9	60
Zinc Impact on Aluminum Step Spike - 2 pack	$19.97 ($9.99 for 1 sprinkler)	20	6.096	2.7	20
		33	10.0584	3.3	30
		36	10.9728	3.8	40
		38	11.5824	4.3	50
		38	11.5824	4.7	60
1/2" Brass Impact Head	$10.71	28	8.5344	2.8	20
		38	11.5824	3.4	30
		43	13.1064	4	40
		46	14.0208	4.4	50
		46	14.0208	4.9	60
1/2" Spinning Sprinkler Head	$2.97	16	4.8768	2.5	20
		18	5.4864	2.5	30
		19	5.7912	2.8	40
		19	5.7912	3.2	50
		20	6.096	3.5	60

RAINBIRD					
Head Model	Price	Radius (ft)	Radius (m)	Flow rate (GPM)	Pressure (psi)
		44	13.4112	5.5	30
		47	14.3256	6.5	40
		49	14.9352	7.2	50
35_ADJ-TNT-B (3/4")	$39.99	51	15.5448	7.8	60
		38	11.5824	3.4	25
		39	11.8872	3.8	30
		40	12.192	4.4	40
25-PJDA-C (1/2")	$17.84	41	12.4968	5	50
		35	10.668	2.8	25
		38	11.5824	3.3	35
		40	12.192	3.7	45
P5R (1/2")	$6.29	41	12.4968	4.1	55

	Price	Quantity	Total Price per item
1/2" Plastic Impact Sprinkler Orbit	$3.95	40	$158.00
PVC Tee 3/4"x1/2"	$1.14	32	$36.48
PVC Bushing 3/4"x1/2"	$0.83	8	$6.64
3/4" Male Adapter	$3.12	80	$249.60
Teflon Tape	$0.50	5	$2.50
Hose Clamp	$0.98	80	$78.40
		Total	$531.62

	Price	**Quantity**	**Total**
1/2" Zinc Impact Sprinkler Orbit	$9.99	40	$399.60
3/4" Male Adapter	$3.12	80	$249.60
Hose Clamp	$0.98	80	$78.40
		Total	$727.60

	Price	**Quantity**	**Total**
1/2" Zinc Impact Sprinkler Orbit	$4.49	40	$179.60
3/4" Male Adapter	$3.12	80	$249.60
Hose Clamp	$0.98	80	$78.40
		Total	$507.60

Item	Cost
Bella Casa - C's room	$285.00
Bella Casa - R & P's room	$285.00
Ma-Queenyonnah - R & P's room	$160.00
Ma-Queenyonnah - C's room	$160.00
Lightning Rod - Ma Musu	$45.00
Pipe fittings - Jet Trading	$15.00
Surge Protector & DC Breaker (West Coast Energy)	$180.00
City Builders Purchases	$1,083.25
Food	$153.19
Passport Photo	$16.38
Solar Panels - Union Strong	$1,800.00
Well	$1,500.00
Home Depot - PVC Ball VLV (return)	-$11.55
Home Depot - PVC Ball VLV	$23.09
Home Depot - 3/4" Female Adapters	$130.42
Home Depot - Male Adapter (return)	-$48.54
Home Depot - Male Adapter	$120.16
Staples - Receipt Books	$21.89
BoA - Visa Fees	$840.00
UPS Shipping for Visas	$126.36
Pump	$3,148.20
Flights	$7,286.97
MAF Flight	$2,448.31
Total	**$19,768.13**