# Sustainable Irrigation in the Developing World

Senior Integrated Project (SIP) – Applied Physics

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# Acknowledgements

There are a handful of people to thank when considering this project. Each of these mentioned individuals has influence over the project's success. Thank you to Father Evarist Thadei Mngulu for serving as my project mentor and housing and feeding me during the project's duration. Thank you, Dr. Askew for seeing the initial potential in this SIP topic and supporting me as my advisor through the end. Thank you to Kalamazoo College for providing project funding and remaining my representative institution. Thank you to the anonymous donors who contributed to the GoFundMe fundraiser and thank you to my Tanzanian friends who made me feel welcomed. A special thank you to Linus, the Pawaga Village plumber for his expertise. Thank you to my father, Darin for your interest in my research and to my mother, Michelle who shared in this global adventure with me.

All the people now benefiting from the irrigation system wish to share their thanks as well.

# Abstract

This SIP analyzes an application of physical theories to the design of a sustainable irrigation system like the one constructed in the village of Pawaga. Unlike most physics SIPs whose subject matter is supported by organized research experiences or internships, this SIP was supported by a volunteer experience. My specific contributions to the project (both on and off location) include surveying the system site, researching and studying fluid mechanics, aiding with the system's design and installation, and project funding.

The individual components that make up the system are as follows: Little Ruaha River (source of water), 3-acre horticultural plot (sink for water), drip-line irrigators, 5000 L reservoir tank, electric pump, solar panels, electrical grid control box, water filter, and connective piping of varying diameters. I was able to develop a physical model using the irrigation system's parameters and other data that pertains to the site. The model will study the flow of fluid through the system. Measurements were taken repeatedly throughout the project's schedule. Specifically, I measured distances, diameters, flow rates, and air pressure. With these measurements I calculated hydrostatic and hydrodynamic pressure, measured the angle of the slope that separates the tank and river, and modeled the water moving from elevated source to sink.

The irrigation project is an overall success. This project is an ongoing one as I depart from the project site. Since my departure updates on the project and communication with the student's SIP mentor has been maintained. As the system exists now there are 3-acres of irrigated soil. Since its construction, the system has yielded one successful season of crops. This SIP has presented a dripline irrigation system that successfully functions at a scale above that of a home garden and argues that its design may be implemented as a solution for regions of the world that are challenged with regards to agriculture.

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# Introduction

The East African Rift Valley (EARV) is a linear lowland surrounded by mountainous highland formed from the movement of tectonic plates.[1] It cuts north to south from Ethiopia to Mozambique and lies just west of the Indian Ocean coast.[2] The elevation along the valley ranges from 750 – 2500 meters.[3] Tanzania is one of many countries that lie along the EARV, which makes it an arid and rocky ecosystem. The region experiences frequent droughts, but water is generally available year-round from lakes and rivers. While Tanzania is one of the most developed countries in East Africa, outside of its capital and urban centers the remainder of the country is composed of villages and vast wilderness. Organizations like schools and religious groups provide community support that the otherwise isolated populations would be without (**Figure 1**).

**Figure 1: Pawaga Youth –** adolescents of Pawaga village will visit The Mission daily for school, worship, play, or other activities.

[1] https://en.wikipedia.org/wiki/Rift_valley
[2] https://en.wikipedia.org/wiki/East_African_Rift
[3] https://en-us.topographic-map.com/maps/s5xd/Africa/

As a result of water scarcity, national authorities impose a tax to control the natural resource. Current irrigation practices of the region include watering by hand or the use of ditches. Although energy efficient, these methods are restrictive and wasteful, respectively. In addition, other environmental threats like wildlife and climate change demand more sustainable and conservative methods.

Volunteer organizations like the World Wide Opportunities on Organic Farms (WWOOF) offer experiences in the study and implementation of agricultural practices to tackle the above-mentioned challenges in Tanzania. The organization has a local chapter headed by Father Evarist Thadei Mngulu of the Consolata Missionaries. The mission compound and its outposts in the region act as sites for community engagement, including religious, pharmaceutical, education, and food storage services. Improvements that have been made to the mission since Father Evarist's arrival consist of installing solar panels, preparation of a horticultural field, and plumbing for access to water for direct use. Another focus has been establishing an irrigation system for the horticultural field. Completion of the irrigation system would help combat the malnutrition experienced by the children of Pawaga, encourage regular school attendance, and educate the village in water conservation and sustainable agriculture. The project's technical goal is the installation of an irrigation system that is both sustainable and conservative within the rift valley. Previous attempts to implement said system failed, leading Father Evarist to seek professional aid and volunteers. It is through this volunteer opportunity that the SIP found its subject. After discussing the relevant physics of an irrigation system, a proposed design and plan is put in place.

This SIP analyzes an application of physical theories to the design of a sustainable irrigation system like the one constructed in the village of Pawaga. The project begins with studying the relevant physics, which includes fluid dynamics, hydrostatic and hydrodynamic pressures, and the concept of gravity-driven water flow. Next, the concepts are applied to the design and installation of the new irrigation system. With the system in place, diagnostic tests of the system are run, and measurements of pressure and flow rate are taken. Results and concluding analysis are presented, followed by a discussion of potential future improvements to the system. Finally, an argument promoting the use of sustainable irrigation systems in agricultural sectors of both the developed and developing world will be presented.

## My Part

Unlike most physics SIPs whose subject matter is supported by organized research experiences or internships, this SIP was supported by a volunteer experience. I had a high degree of flexibility regarding the project subject and structure. My mentor and I set clear goals for the project and structured it as phases to occur over a period of 6 weeks. During the weeks of 6/14/21 – 7/23/21 I was in Tanzania and involved in work at the project site. My specific contributions to the project (both on and off location) include surveying the system site, researching and studying fluid mechanics, aiding with the system’s design and installation, and project funding which totaled over $3,000.00.

This project will greatly aid Father Evarist’s mission. Previously, he initiated the above-mentioned improvements to the mission compound and more recently created a proposal for the sustainable irrigation system. Evarist was inspired by his larger vision for the mission and desired to produce excess horticulture crops efficiently and reliably. Emphasis was on watermelon, beans, and corn, sunflower seeds and papaya for human consumption. There are members of the Pawaga community who suffer from malnutrition due to privation, therefore, this excess food would be shared with the greater Pawaga community. A direct benefactor would be the nursery/elementary school that is a part of the mission compound. Regularly providing an afternoon meal to the students acts as incentive for them to attend just as regularly, feeding the student’s and growing the educated community in Pawaga. Another potential for the sustainable irrigation system is the use of it as a tool to educate the community in water and agricultural conservation.

Father Evarist sought professional aid with regards to the irrigation system. He contacted Davis and Shirtliff[4], a professional contractor located in Dar es Salaam, Tanzania. They provided a professional design and quote for a dripline irrigation system that Evarist was envisioning. Evarist was also in regular contact with an engineer that worked for the contractor. I never spoke with this engineer but encouraged Evarist to use him as professional consolation when it came to any major decisions of the future project. The engineer's quote was approximately $16,000.00, an expense that was not available during my participation with the project.

Aided by the inspirational project proposal and professional engineering designs, my mentor and I forged ahead. A new design we developed incorporates aspects of the professional design into an affordable and independent plan. Evarist was confident in our ability to proceed, supported by the infrastructure that was already at the mission and Evarist's own knowledge and resources, we were confident in our ability to proceed.

The new design still has its goals to be sustainable and conservative. Aspects of the design include an elevated source and a system of piping that is separate from the compound's plumbing for direct purposes. Proper functionality of the system will involve filling the elevated reservoir tanks during the day when solar power will be most efficient, fully powering the electric water pump, then using gravity to irrigate the fields in the evening when the sun is low and the land is cooler, mitigating evaporation.

The project design has four phases. The first two phases were carried out at the system site in Tanzania. Phase One includes the surveying the system site, purchasing materials, and constructing 200 meters of tubbing between the pump, elevated reservoir, and the dripline emitters. Phase Two includes testing trials with stabilizing pressure, water flow, varying sources, and providing progress updates to

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[4] Davis and Shirtliff

our consulters. Phase Three is establishing a second electric pump whose soul function would be to move water for irrigation and expanding the system by acreage of dripline along with reservoir capacity. Phase Four is the expansion of the dripline emitters to maximize the acreage of farmable soil.

Previous to this SIP, the current project was not the only irrigation system in use by the mission. Before Evarist became the mission's overseeing priest, the previous residents constructed an irrigation system that was powered by a diesel pump. When the time the agriculture field was first created, an infrastructure existed at the river source, the fields, and directly adjacent to the mission compound which irrigates the kitchen gardens. This system satisfied the need of the compound's plumbing but failed to reliably irrigate the entire acreage because it did not have sufficient pressure to uniformly irrigate the agriculture field and was also a source of pollution to the environment and required the purchase of diesel fuel. These problems would be addressed in the new systems design.

The irrigation processes reliably used by the people of the Rift Valley are ditch irrigation and hand-held watering methods. The ditch irrigation is used for larger scale crop cultivation, like rice patties. Home gardens rely on manual distribution of water. Our design stands apart from previous and current methods by implementing drip-line emitters. The dripline employs narrow tubing to distribute water over a large area at a steady and conservative rate. Most drip-line systems are the size for home gardens, our challenge will be scaling up the same design to multiple acres of area.

## The Physical System Investigated

The drip-line emitters support the conservative design by distributing small amounts of water constantly over a long period of time to the plant. This aspect mitigates water loss due to evaporation and agricultural runoff. The elevated reservoir forms pressure due to gravity. This hydrostatic pressure requires no external power source which follows a sustainable design. Also, having the ability to store water in a reservoir independent of the remaining compounds plumbing supports the goal of establishing an independent irrigation system.

The schematics and images that follow illustrate the composition of the irrigation system. The individual components that make up the system are as follows: Little Ruaha River (source of water), 3-acre horticultural plot (sink for water), drip-line irrigators, 5000 L reservoir tank, electric pump, solar panels, electrical grid control box, water filter, and connective piping of varying diameters. **Figure 2** is an illustration of how water travels through the irrigation system from source to sink.

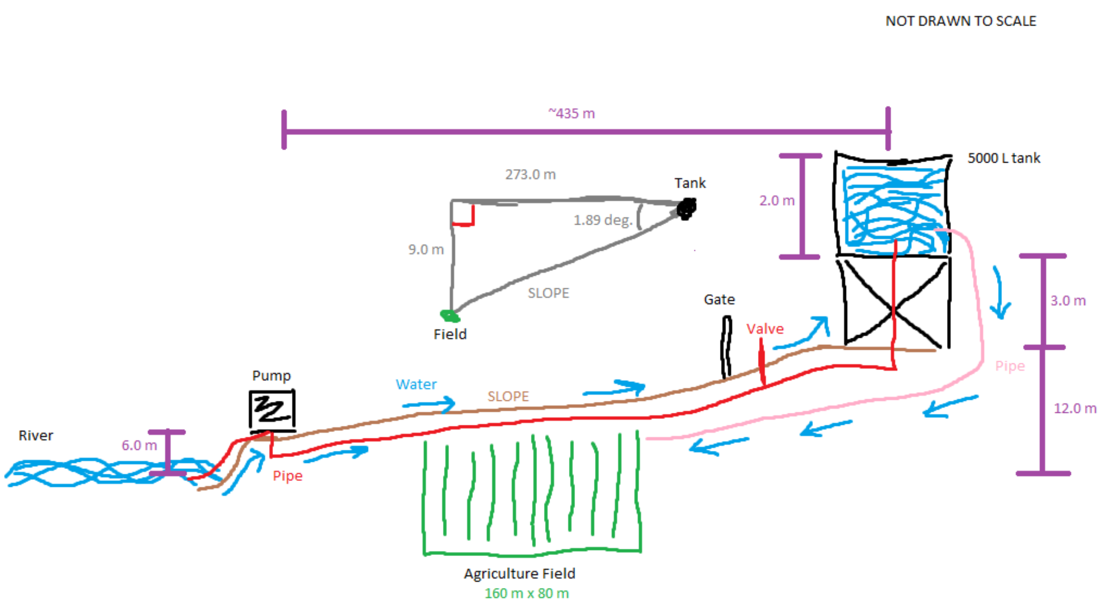



**Figure 2: Sketch Schematic of Irrigation System** – The agricultural plot lies below the reservoir. This difference in elevation provides the gravitational potential energy required to form a hydrostatic pressure head.

**Figure 3** is a satellite image of the entire project site provided by the Google Earth application. The buildings adjacent to the tank pin form the Pawaga Mission compound. Other buildings seen on the left-side potion of the image are residential and commercial structures, parts of the greater Pawaga village.

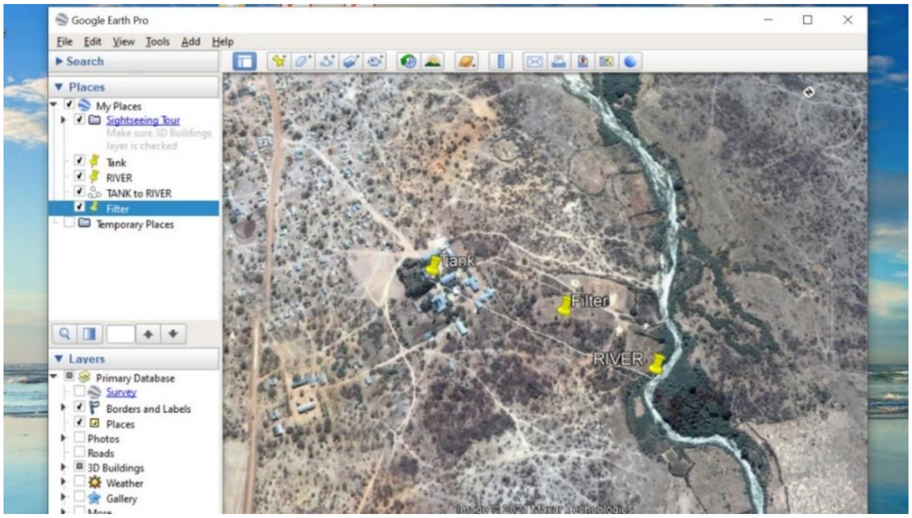



**Figure 3: Satellite Image of Project Area –** Pins mark three important components of the system - the Little Ruaha RIVER, the reservoir tank, and agricultural plot (Filter). The tank is positioned at the highest elevation in the system.

A composition of the irrigation system can be understood by following the streamline of water from its source to its sink. The water enters the system at its source, the Little Ruaha River (**Figure 4-5**). The river is a year-round source of water, though the water level differs between the rainy season and remainder of the year.

**Figure 4: Little Ruaha River -** The river is a lifeblood for the inhabitants of the EARV region. It is a source of food, water, hygiene, and irrigation.

**Figure 5: River Water Level –** The water level ranges by about 4 meters over the year. Notice the steep ledges that are exposed when the water level is low; the people standing in the picture would be underwater during the rainy season.

I determined that the seasonal changing water levels do not affect the system, though a high-water level can bring dangerous wildlife into the system's vicinity. At this point in the system the solar powered electric pump is doing work on the water to raise it from the river to the elevated water reservoir. Moving it from a point of low energy potential to high energy potential. The electric water pump (**Figure 6-7**) is installed adjacent to the river and is what provides the force to move water in this part of the system.

**Figure 6: Pumphouse –** This building houses the electric pump, protecting it from the elements and other dangers.

**Figure 7: Electric Water Pump –** The pump was purchased from the engineering contractor, Davis and Shirtliff, and was installed prior to the start of this irrigation project.

The water is then pumped uphill from the river to a 5000-liter reservoir (**Figure 8**) that sits at an elevated position above the agricultural plot.

**Figure 8: 5000 Liter Reservoir –** Notice that an existing steel cargo container was used to provide elevation.

The incorporation of this tank into the system was our first installation step in this phase of the project, which occurred in week five. The professional design suggested constructing a new structure that would support four 5000L tanks. Due to expense, we scaled down the design to our available resources. The elevated tank serves a similar purpose as a water tower such that, it stores water and opening a valve allows the water to flow into pipes which move the water towards the system sink due its stored gravitational potential. The elevated reservoir is the key component of the system's design. As it provides sufficient water pressure to move fluid further to the agricultural field. Once the reservoir is full, no external power or fuel is required to irrigate the crops. The reservoir is filled quickly when the sun is high due to the efficiency of the solar panels. Ideal operation of the system would be to fill the reservoir by pump during the afternoons and to water the crops in the evenings. Operating the system in this way is sustainable and conservative as all the energy required to run the system is renewable and irrigating when the sun is low reduces the amount of water loss due to evaporation. An irrigation system that operates this way would meet the project's goals.

Once the reservoir valve is opened water flows back downhill and finally arrives at the system's sink, the agricultural plot. Furrows form the fields shape and provide two complementary zones where crops are grown accordingly. Driplines (**Figure 9**) distribute water to the crop's root beds. 3-Acres of dripline was established before my work on the project began. A future goal of the project is to expand the acreage covered by the system.

**Figure 9: Drip-lines –** Black, narrow tubing that spans the horticultural plot distributing water to the crops. The dimensions of the piping are designed such that water is introduced to the soil at a slow and steady rate.

A filter (**Figure 10**) clears all debris in the fluid before water enters the driplines. Once in the driplines, water is emitted from small holes that appear as punctures along the tubbing. These small holes could be easily clogged by dirt or rock. The filter must be cleaned periodically to continue operating properly. Installation of the filter was completed during the sixth week on site. **Figure 11** shows one of the seven valves that are placed along the agricultural plot. These valves can be opened or closed at will allowing for all or specific zones to be watered. Having one or more zones closed off raises the flowrate and therefore pressure of the water in other parts of the system. A similar result happens when one decreases the volume of a container which holds a liquid. Constraining the liquid to a smaller space increases its pressure.

**Figure 10: Filter** – It is positioned at the intersection of which the water arrives at the plot. There is a drop in pressure that occurs as the water passes through it.

**Figure 11: Valves –** At points throughout the whole agricultural plot valves like this allow for the control of water flow in the greater system.

The streamline that the fluid follows between the components of the system is formed by its connective tubing (**Figure 12**). New tubing and previously established pipes were both used to connect the system. New tube was installed to connect the reservoir to the filter. All other connections were made by already established segments. Tubing and connections consumed much of the projects funding. Multiple spools of tube with varying diameters were purchased to complete all the system's connections (**Figure 13**).

**Figure 12: Connective Tubing**

**Figure 13: Varying Diameters** – The tubes and pipes that connect all components of the system change diameter at certain connections, like the filter and driplines. The properties of the fluid changes with the pipe diameter.

With a complete path of the fluid traced, what remains of the irrigation system is its power source. A schematic (**Figure 14**) depicts the electrical grid of the irrigation system which is powered by solar panels (**Figure 15**).

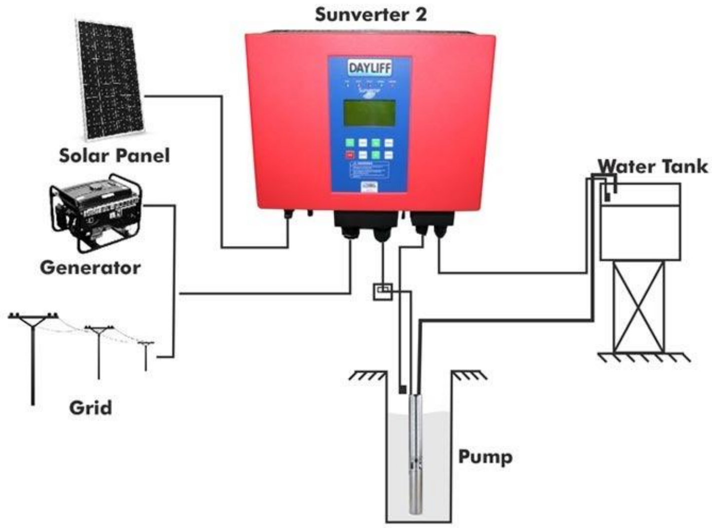



**Figure 14: Electrical Schematic** – The solar panels operate most efficiently when the sun is highest.

**Figure 15: Solar Panels -** The panels antenna acts as a ground connection preventing any short circuits that could be due to bad weather.

As a major improvement to the mission infrastructure, the solar panels main priority is to run the pump but is also wired into the compound's electric as supplemental power during times of regional black outs. The pump is switched on manually or when a sensor alerts to water level in the tank. The national grid can also run the pump if necessary.

Throughout the project the design was adapted from its original plan when necessary. Major adaptions included confirming the use of the elevated 5000 L water reservoir as a viable option from our initial list, creating a connection directly between the dripline field and the pump's mainline (**Figure 16**), patching and replacement of failing infrastructure (**Figure 17**), and construction of a new structure that will support multiple supplemented reservoir tanks. Located directly adjacent to the dripline field for future expansion (**Figure 18-20**). The connection between the dripline and pump's mainline provides a high hydrodynamic pressure from the pump.  This connection is shorter and more direct that the previous connection from the 5000 L reservoir to the filter and field.

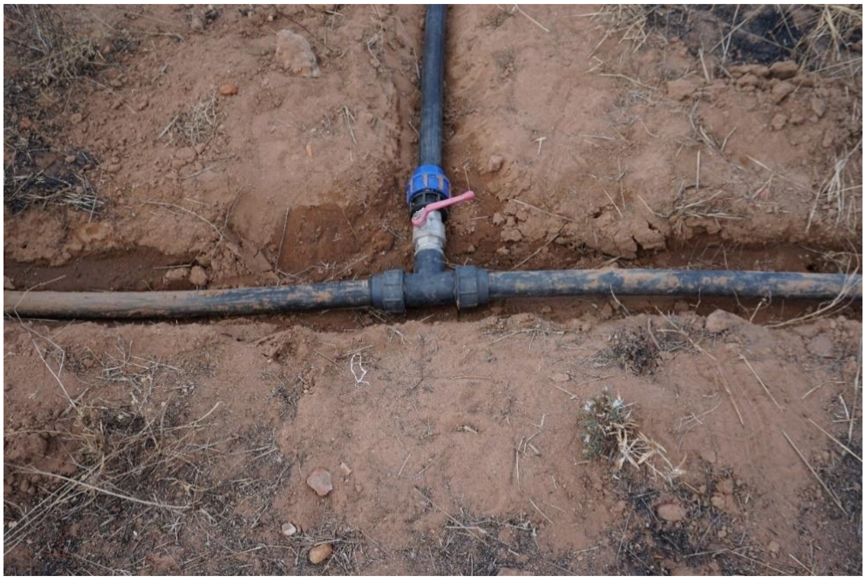


**Figure 16: Main-line Source –** the red valve opens and closes the connection to dripline field. At this T-intersection the pump is to the right and left, uphill, is the mission compound.

**Figure 17: System Improvements –** As we incorporated old and new piping into the system, time was taken to assess and repair the tubing that runs along the agricultural plot. Any damage here results in sections of the dripline system becoming inoperable.

**Figure 18: Reservoir Structure (a) –** Local bricks made from crushed stones and clay form the walls of the structure. Pigs can be housed inside the structure as a source of manure. The roof will hold two 10,000 L tanks.

**Figure 19: Reservoir Structure (b) –** cement is incorporated into design to strengthen critical points.

**Figure 20: Reservoir Structure (c) –** more cement pillars and metal rebar further strengthen the roof. The roof must support 20,000 L, 22 tons of water at max capacity.

When selecting the source of water for the irrigation system our options were between an elevated 5,000 L tank, elevated 15,000 L tank, forming a connection directly to the pump's mainline, or constructing a new elevated reservoir adjacent to the agricultural plot. The irrigation system's source that was chosen was to be isolated from the remaining plumbing of the mission compound that also relied on the river pump, like faucets (**Figure 21**), toilets, showers, kitchen-garden's sprinklers, and livestock (**Figure 22**). Doing so separates the potable and non-potable water that moves through the system.

**Figure 21: Spigot –** located in the mission courtyard, accessible to anyone.

**Figure 22: Livestock Improvements –** since the electric pump was installed, transporting water to livestock has become easier. These ducks, adjacent rabbits and pigs all receive water from a tube that is connected to the pump and a reservoir.

Doing so allows for control over the irrigation system's water without effecting the water of other plumbing systems in the compound. The source also had to be constructed from resources that were available to us at the time. Thus, we proceeded with incorporating the 5000 L elevated reservoir into the design as it was isolated, and the tank used was available. As it turns out, this single tank elevated ~5 meters above the sink, did not form a great enough pressure-head to successfully irrigate the dripline fields. This error will be discussed further.

A challenge regarding the lack of sufficient pressure led to another major adaption to the system – having the pump directly irrigate the fields instead of an elevated reservoir. So far, the system works as it should but it no longer draws its pressure from gravity. Still achieving a sustainable design, a new support structure is constructed and awaiting two 10,000 L tanks that will serve as the new elevated water reservoirs for the irrigation system. Designing the system this way was suggested by the Davis and Shirtliff engineer but was previously adapted as the labor and material costs were too high. Dividing the project into phases and priorities allows progress incrementally over time as funds are available. The recent construction of the 20,000 L reservoir structure is an example of how the project can be done in affordable steps. The materials available were enough to build out the foundation and basic structure, while awaiting funding to purchase two 10,000 L tanks. Two other improvements to the system are a more robust electrical cable which connects the solar panels and pump. Doing so helps reduce wear on the pump. The second improvement is expanding the drip-line acreage as a means of increasing crop production.

## Relevant Physics

I was able to develop a physical model using the irrigation system's parameters and other data that pertains to the site. The model will study the flow of fluid through the system. The irrigation system is designed to do work on liquids, and therefore fluids. A fluid is a material substance that flows and has no definite shape, they can be either liquid or gas. Fluids can be understood through continuum mechanics which is concerned with regions of space rather than individual particles seen in early Newtonian mechanics.

Liquids are nearly incompressible such that they have a definite volume and mass density. The SI unit of volume v is m^3. The SI units of density p are mass/volume kg/m^3. The mass of a liquid is then m = pv, units kg. The density of water is 1 kilogram/liter (kg/L). Liquids that are contained in a vessel exert pressure against the surface in all directions. Pressure is a scalar quantity and defined as force per area, P = F/A, its SI units are Newtons/meters squared (N/m^2). Pressure is not a force itself but rather a ratio of force - meaning the vessel's surface area will experience the force of a fluid. The reason that pressure results as a scalar quantity from a force vector is due to the properties of a fluid. Pascal's Principle states any force exerted on a fluid is felt equally and uninterrupted in every direction within the fluid, $\Delta P = P_2 - P_1$. Therefore, no directional quantity needs to be clarified. This equation should look familiar as an analogous description of the law of conservation of energy.

A liquid within a container has pressure due to gravity. Pressure increases with depth relative to the surface of the liquid. You may perhaps feel this while swimming in a lake or pool. If you dive down more than a few feet, the increased pressure is very apparent, especially in your eardrums.

The pressure exerted by a liquid in equilibrium due to gravitational force is called hydrostatic pressure and can be calculated for any liquid using the equation

$$P_{static} = \rho g d$$

where rho ρ is the liquid's density, the gravitational constant is g = 9.8 m/s^2, and depth d is measured from the surface. Liquids in hydrostatic equilibrium have the same pressure at all points along a horizontal line, so water flowing along a horizontal line, like a pipe, will have the same hydrostatic pressure at all points of equal height along the pipe. To properly measure the pressure of a fluid within a container we want to know its absolute pressure P, absolute meaning the pressure due to the fluid alone. Containers on earth experience an external pressure pushing inwards due to air pressure, so we must subtract that pressure from the total pressure that we measure, call it the gauge pressure $P_g$. Then,

$$Pg = P - 1atm$$

1 atmosphere (atm) is the standard air pressure at sea level and P is the absolute pressure of the fluid. Recognizing this source of error is necessary for taking accurate pressure readings throughout the irrigation system. It should be clear now that an elevated source of water (**Figure 23**) will produce a hydrostatic pressure due to its gravity. The elevated 5000 L water tank used in the design functions in just this way. Due to gravity, water flows downwards from an elevated starting point to a lower ending point. Hydrostatic pressure contributes to the total water pressure in a pipe that runs along a decline.

**Figure 23: Concrete Water Tower –** This tower stands ~9 meters high. It is the primary tank for the plumbing in the mission compound.

When employed, this system will use the principles of dynamics fluids or fluids in motion. An ideal fluid has three properties – the fluid is incompressible, the fluid is non viscous (low kinetic friction), and the flow of the fluid is steady. This last property is defined as laminar flow, fluid flow where the velocity at each point in the fluid is constant. Turbulent flow is the converse as seen in rushing river rapids. All design decisions were made to maintain laminar flow through the system and measurements of the system assumed an ideal fluid.

We've discussed static fluids, but fluids in motion require a correction for dynamic pressure loss. When a fluid accelerates, the change in velocity must be balanced by a change in pressure according to Bernoulli's Principle. The flow rate of liquid in a streamline can never be zero, else there would be no hydrostatic pressure to move the fluid. The hydrodynamic pressure loss of a fluid will drop over time along the streamline of a horizontal pipe. Hydrodynamic pressure is analogous to kinetic energy: losses due to friction.

$$P_{dynamic} = \frac{1}{2}\rho v^2 \ (ideal\ fluid\ case)$$

$$P_{dynamic} = \frac{1}{2}\mu v^2 \ (reality)$$

where in the ideal case pressure is the product of its density rho ρ and is velocity v. In practice, frictional forces oppose the flow and thus fluids have viscosity – a resistance to flow. The viscosity of water is small compared to other fluids, $\mu_{water}$ = 8.005 x 10^-7 m/s^2, meaning it flows easily.

The path a single particle traces through a fluid is called a streamline. Per design, the pipe diameter throughout the irrigation system changes. These changes will affect a streamline and thus the flow of the water because the hydrodynamic loss depends on velocity which is influenced by the pipe diameter and flow rate. As the diameter of the pipe changes, the fluid velocity changes resulting in a change of pressure. By measuring the rate of water passing through a cross sectional area, at one point, one can determine the velocity of the water at another point in the system. This is possible using the equation of continuity from continuum mechanics. The equation states the following is true for an ideal fluid:

$$v_1 A_1 = v_2 A_2$$

where v is the velocity of the fluid and A is a cross-sectional area. The equation states that flow is constant from point 1 to point 2. The volume of incompressible fluid entering a streamline is equivalent to the volume leaving. From this relationship we see a changing pipe diameter will change the size of the cross-sectional area and thus the flow rate from one section to another.

Bernoulli's Equation (**Figure 28 - 29**) and Navier – Stokes Theorem (**Figure 30**) are the final physical concepts that remain to be understood before physical problems of the irrigation system can be asked and answered. The Navier – Stokes Theorem is a set of partial derivates that describe the motion of viscous fluids, it is analogous to Newton's Second Law - describing the force and momentum of the fluid. With Bernoulli's equation all kinematic problems involving fluids can be answered and the Navier – Stokes Theorem will give the total pressure of the fluid at any point in the system.

Pascal's Principle and Bernoulli's Equation shows that changing the pressure at one point in the system will also change pressure at another point. Then, if the desire is to increase pressure at the sink, one must increase the pressure at the source. In this system, the pressure change can be accomplished in three ways – the reservoir tank can be open to the air which will add air pressure to the total pressure $P_1$ at the system's source, raising the source to a higher elevation will increase the reservoir's hydrostatic pressure, and creating a vertical displacement between the source and sink.

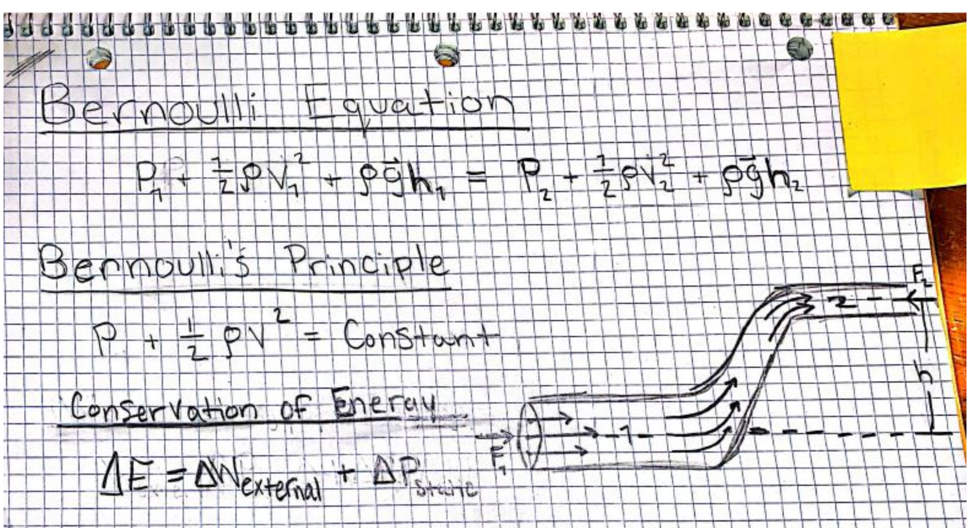



**Figure 24: Bernoulli's Concepts –** Bernoulli's Equation states the law of conservation of energy for fluids, Bernoulli's Principle states that flowrate will decrease over distance, and possible streamline measurements are depicted.

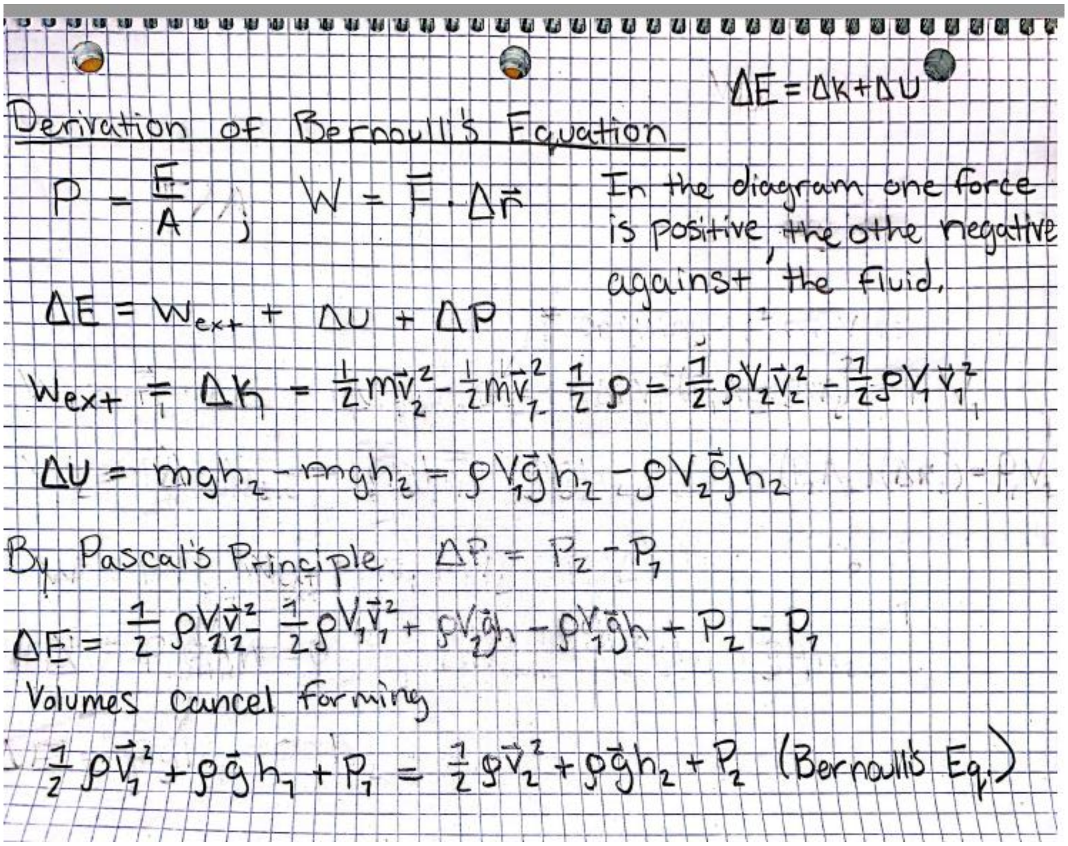



**Figure 25: Derivation of the Bernoulli Equation –** The Bernoulli Equation is a direct derivation of the conservation of energy. Potential energy is analogous to hydrostatic energy and kinetic energy is analogous to hydrodynamic energy.

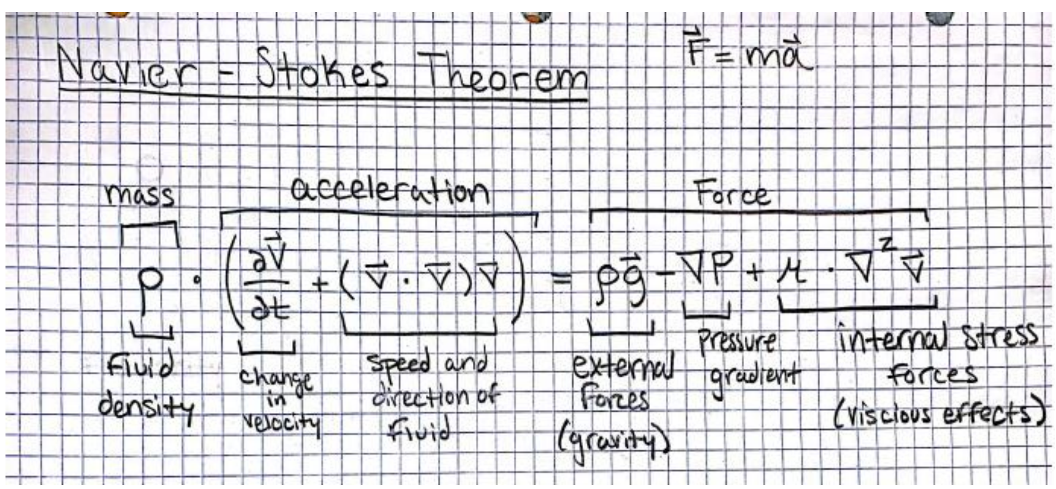



**Figure 26: Breaking down the Navier-Stokes Theorem -** characteristics of the fluid, like velocity and density seen on the left-hand side of the equation, are the products of its net force see on the right side. Concluding that the continuum mechanics that describe a continuous region of fluid directly coincided with the mechanics of a point particle. Meaning a fluid acts like a region of many particles.

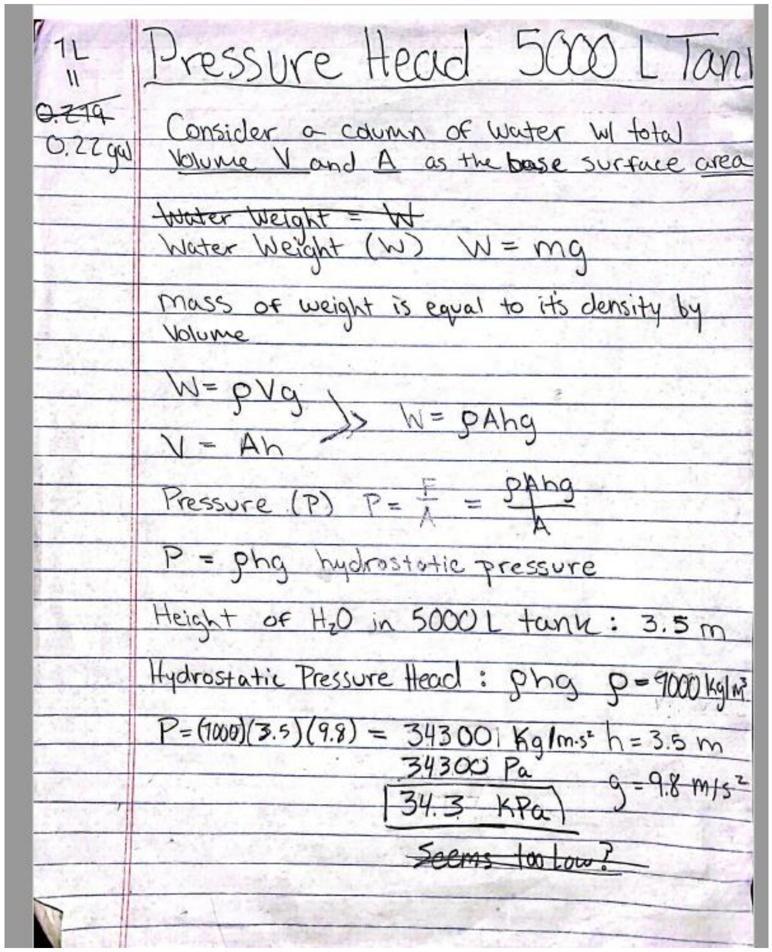
A challenge of the project stated earlier was the scaling up of dripline irrigation systems to large agricultural plots. The low-pressure gravity driven water flow does not help against this challenge. The equations and concepts of fluid mechanics can model the system and provide analysis when problems in the system arise.

## Measurements and Calculations

Measurements were taken repeatedly throughout the project's schedule. Specifically, I measured distances, diameters, flow rates, and air pressure. With these measurements I calculated hydrostatic and hydrodynamic pressure, measured the angle of the slope that separates the tank and river, and modeled the water moving from elevated source to sink. Qualitative assessment of the project site and system was conducted during weeks 1 - 4 of the project. With a design in place and physical dimensions of the system measured, supplies were purchased to construct the complete irrigation system.

A calculation of the hydrostatic pressure produced by the 5,000 L elevated source is presented below (**Figure 31**). The amount of pressure created by that elevated column of water if very low, for reference the average pressure of a household tap is around 200 - 300 kPa. To reach that level of pressure the tank would need to be at a height of at least 25 meters. The average height of water towers in the USA is 40 meters[5]. At that height water creates a pressure of ~400 kPa, four times the amount of pressure as the air on earth.

[5] https://en.wikipedia.org/wiki/Water_tower



1L
11
~~0.274~~
0.22 gal

Pressure Head 5000 L Tan

Consider a column of water w/ total Volume V and A as the base surface area

~~Water Weight = W~~
Water Weight (W) $W = mg$

mass of weight is equal to it's density by Volume

$W = \rho V g$
$V = Ah$ $\gg$ $W = \rho A h g$

Pressure (P) $P = \frac{F}{A} = \frac{\rho A h g}{A}$

$P = \rho h g$ hydrostatic pressure

Height of $H_2O$ in 5000 L tank : 3.5 m

Hydrostatic Pressure Head : $\rho h g$ $\rho = 1000\ kg/m^3$

$P = (1000)(3.5)(9.8) = 34300\ kg/m \cdot s^2$ $h = 3.5\ m$
34300 Pa $g = 9.8\ m/s^2$
34.3 KPa

~~Seems too Low?~~

**Figure 27: Calculation of Hydrostatic Pressure -** The result of elevating 5000 L of water 5 meters is a 34.4 kPa hydrostatic pressure head.

A calculation of the project site's slope formed by the natural terrain that separates the river and elevated reservoir is presented (**Figure 32**).

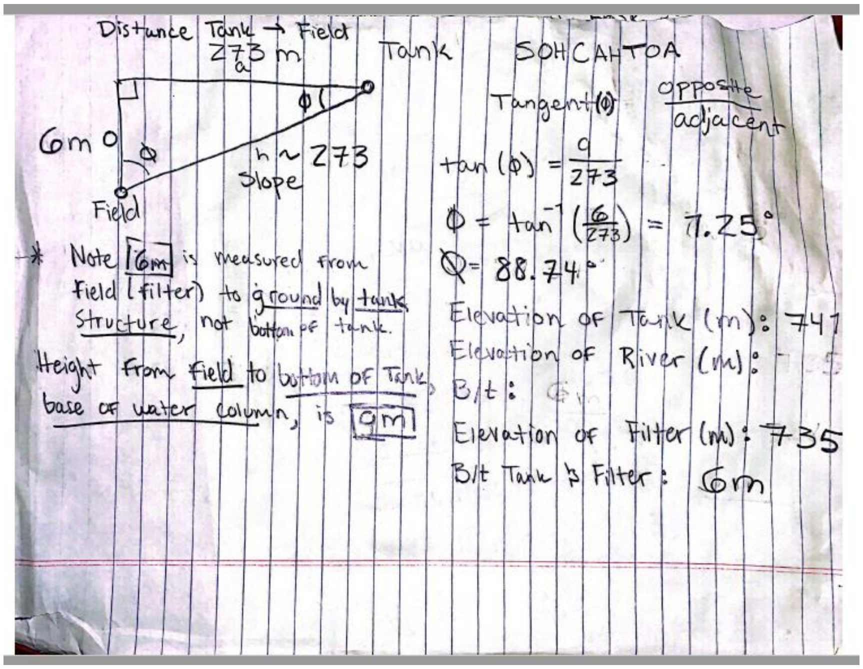



**Figure 28: Calculation of Site's Slope**

Gerard, in "Gravity Driven Water Flow"[6] states that water traveling up or down a slope will have a max velocity and pressure that is determined by degree of the slope. As one might expect, water traveling down a steep slope will move faster than water traveling down a gradual slope. Gravity is the constant acceleration that is driving the flow of the fluid down the slope. The resulting force is being opposed by frictional forces within the fluid itself (viscosity) and friction forces between the fluid and the surface of its container. The report considers these forces and presents a list of expected flowrates with respect to a slope's degree. Based on our calculated average slope of 1.26 degrees and a pipe diameter of 2 in we would expect a flow rate of ~0.3 L/s The flow rate that we measured at the sink is – Q = 0.2857 L/s. As expected, the flowrate depends strongly on the slope. Knowing the slope's degree and the pipe diameter one can determine the fluid's flowrate (**Figure 29**).

Measurements of the dripline field are presented (**Figure 30**).

[6] *Gravity Driven Water Flow*, Jones Gerard

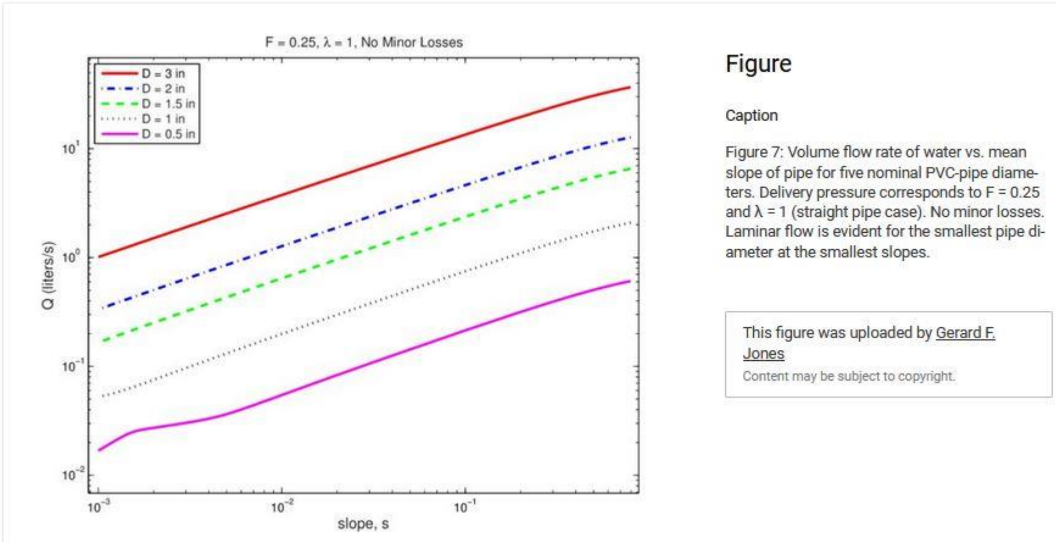



**Figure 29: Volume Flowrate of Water vs. Mean Slope**

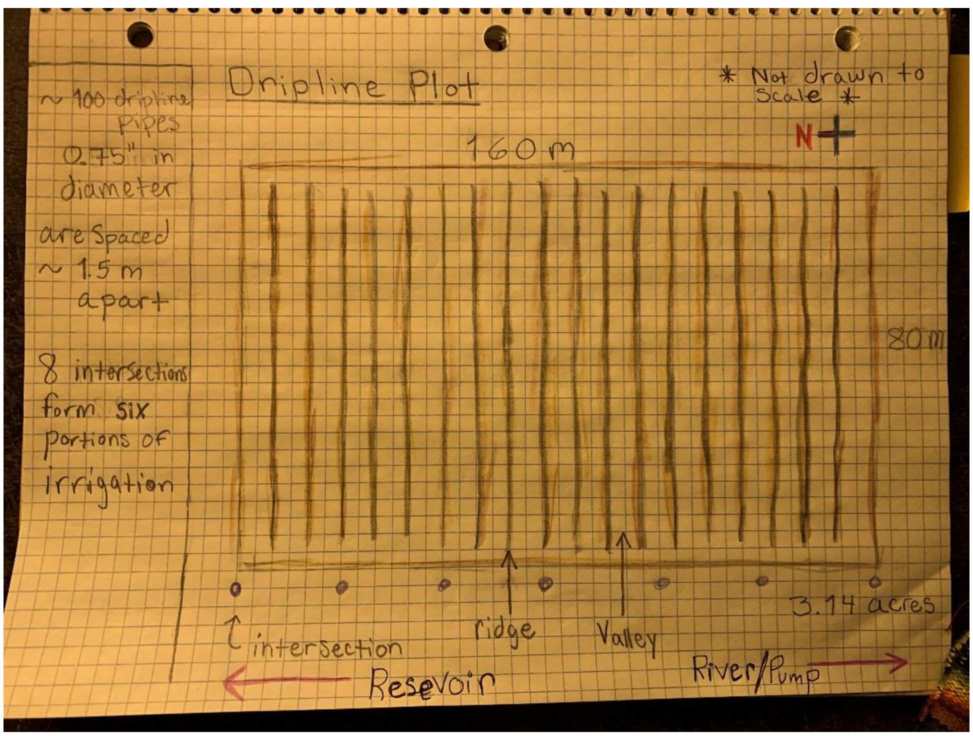



**Figure 30: Dripline Schematic –** Driplines run across the agricultural field parallel to the North and South sides of the plot. Intersections are spaced ~20 m along the East side of the plot.

**Figure 31** is a photo of the barometer that I assembled at the project site to measure air pressure. If accurate and precise measurements of the irrigation system were to be taken in the future, a professionally made barometer and pressure gage would be needed. I discovered the do-it yourself design online along with the physics of how a barometer worked. The apparatus was in no way precise but presented qualitative data on air pressure through an increase or decrease in the water level from day to day.

**Figure 31: Home-made Barometer** – A plastic water bottle the basin of water. A straw, gum, and tape form the chamber in which the liquid can rise and drop with air pressure.

I apply the Bernoulli Equation as a means of determining pressure at points throughout the system (**Figure 32-33**). The continuity equation calculates the flow rate of the fluid as the pipe diameter changes. The flow rates at multiple points in the system are presented in **Table 1**. **:** Flowrate was measured at three locations using a bucket and stopwatch. The first is taken at the position of the elevated tank where pressure is highest. The next two are taken just before the filter at the agricultural field where one flow rate is due to the electric pump and the other is due to the elevated tank. Next the measured flow rate along with pipe diameter calculates the velocity of the fluid. Bernoulli's equation can then tell us the pressure we should expect at the system's sink based on the pressure at the system's source. If we were to measure different values of pressure at the sink than what we expected, it would suggest blockage or another problem to the system between the source and sink.

| Position | Flowrate (L/s) |
|---|---|
| 5000 L Reservoir | 9.33 |
| Before Filter (reservoir) | 0.29 |
| Before Filter (pump) | 4.7 |

**Table 1: System Flowrates -** Notice the large decrease in pressure from the reservoir to the field when the tank is acting as a source.

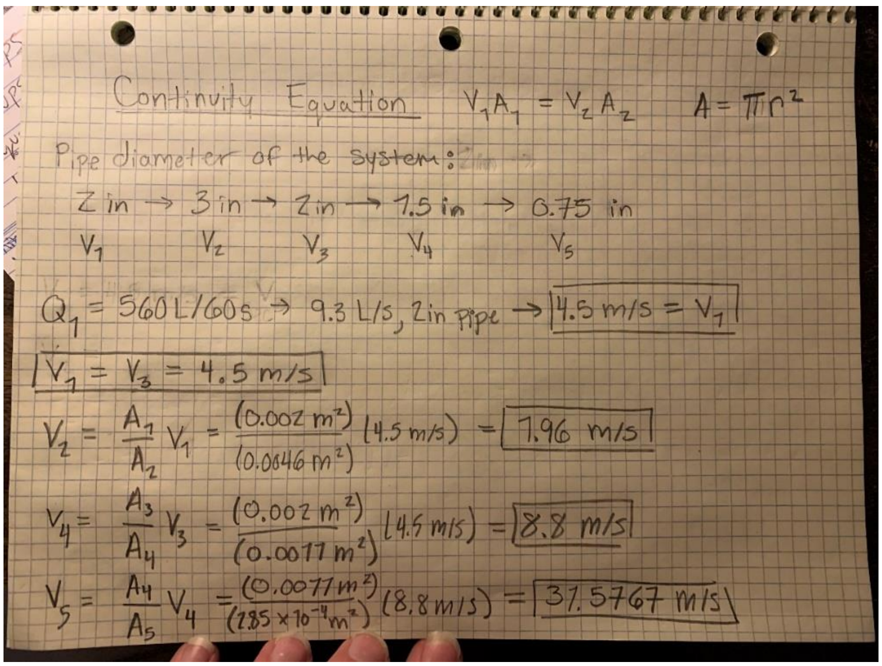



**Figure 32: Application of the Continuity Equation –** $v_1$ is the estimated velocity of water at the tank, $v_5$ is the estimated velocity of water moving in the driplines, $v_3$ is the estimated velocity of water before the filter as it reaches the agricultural field.

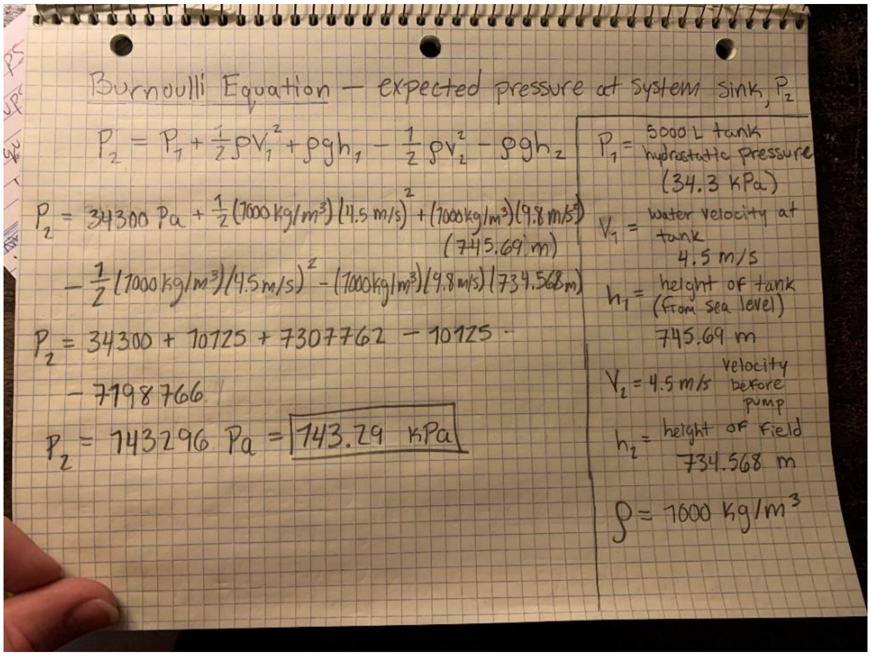



**Figure 33: Application of the Bernoulli Equation –** $P_2$ is the expected water pressure just before the filter and field. Reliable measurements of flow rate were taken at this point in the system which provides a calculation of hydrodynamic water pressure. This calculation could be compared to a measurement of the ideal pressure at the same point to see how expectation match results.

There are five terms that contribute to the fluids final pressure $P_2$. They are the initial pressure $P_1$ of the fluid along with its initial and final kinetic and potential energies. The potential energy terms are determined from the water's initial and final height, $h_1$ and $h_2$. The kinetic energy terms are determined by the water's velocity at its initial $v_1$ and final $v_2$ position. I determined the initial position to be at point the reservoir structure, the final position is at the filter.

This SIP resolves with a successful installation, and function of a sustainable irrigation system. 3-acres of productive land is now incorporated into the mission's many resources. The 3-acres will produce crops staple crops year-round (**Figure 34**).

**Figure 34: First Fruits of Labor**

The first successful harvest yields crop like sunflowers, watermelon, green beans, and corn. This nutrient rich food can now be reliably cultivated and then incorporated into the diet of Pawaga mission's community members.

## Results

I present the following observations as the result of designing and analyzing the functional irrigation system. Generally, a fluid flowing through a wide pipe will have low velocity and yields high pressure, fluid flow through a narrow pipe will have a high velocity and low pressure. To move water long distances, a wider pipe will help maintain a steady pressure for the distance. It is also true that the volume flow rate will be higher in a wide pipe than a narrow pipe. The irrigation system uses 3-in pipe at its widest diameter and within the system is located between the reservoir and filter, this is the longest distance that water in this system must travel. It is also worth mentioning that the water pump's main line is wide to maintain the high-volume flow rate from the river to water tanks around the mission. If higher pressure within the system is desired, locate the sink well below the source to form a large hydrostatic pressure head. 40-m is a large enough displacement to produce adequate pressure. When the desire is to conserve water, use a narrow pipe as volumetric flow rate will be low. The system's dripline emitters achieve this.

During my time at the project site two water sources were used for the irrigation system. Each source provided pressure to the system in different ways. The elevated reservoir as a source relies on conservation of energy to maintain pressure throughout the system. The water pump acting as the direct source adds energy to the system externally to maintain the system's pressure. Through trial and error, the elevated source failed to provide adequate pressure to the system to get the flow rates we needed. The construction of the new reservoir structure is an attempt at improving the design by elevating the water column higher and being placed adjacent to the field to lessen the hydrodynamic pressure loss that occurs over distance. Until that step's completion the system function with the electric water pump as the source of its water and pressure.

As with any project or research there is a notable level of error that must to be considered if to proper analyze the results. This irrigation project exhibits error due to multiple sources. To begin, three significant leaks became apparent during the system's first test. As previously mentioned, the system incorporates old and new pipes in its design. The leaks were in the old pipes that run between the elevated reservoir and dripline field. It is very likely that these leaks inhibit the system's water pressure, causing it to decrease as the fluid travels from source to sink. Ideally, pressure would be maintained along the connective piping. The new elevated reservoir structure that is currently under construction would not be connected to any of the old piping, avoiding any future error due to leaks.

In addition to the leaks other sources of error included the lack of accurate measurements. I was unsuccessful in measuring the actual pressure at any point in the system as they had no pressure gauge apparatus available. Therefore, all pressures of the system presented are calculations, expected values, not actual measurements. With access to the proper tools for taking said measurements, I could perform a greater analysis comparing expected values to accurate measurements. Finally, it is important to recognize that all calculations were done using the assumed ideal fluid model, while the fluid traveling through the system likely displayed characteristics of turbulence, friction forces, and some compression of the fluid. Characteristics that are not considered when making calculations with the assumption of an idea fluid model. Since the fluid in the irrigation system wasn't ideal, it's calculated values have a percentage of error to them. The hydrodynamic pressure of a realistic fluid decreases with distance. I note this reality as another source of error within the system. As the fluid moves the long distance from the elevated 5000 L reservoir to the filter there is a greater pressure decrease with distance. The failure of water to pass through the filter as a consequence of this pressure drop. Decreasing the distance between the source and sink will relieve this pressure lose as the water covers less distance.

The irrigation project is an overall success. This project is an ongoing one as I depart from the project site. Since my departure updates on the project and communication with the student's SIP mentor has been maintained. Shortly before the student's departure from the project site an interview was conducted between the student, Sam Meyer, and his project mentor, Evarist Mngulu[7]. During the conversation we review the project and next steps of the project are discussed. As a continuous project, I can stay invested in the project from his remote location. I am currently tasked with seeking additional funding for two 10,000 L tanks that will serve as new reservoirs for the system. Evarist was grateful for the student's contribution the project – "A large step forward with Sam's contribution."

As the system exists now there are 3-acres of irrigated soil. Since its construction, the system has yielded one successful season of crops. The goal of a conservative design has been achieved through the dripline instillation. While the completed system isn't the same as originally designed, it was

[7] Sam Meyer - "An Interview with Father Evarist"

changed when required and still the agricultural plot offers more acreage to expand the dripline into, encompassing more soil while conserving water and work required for tending. The system's source is designed to be an elevated reservoir, it is the component that makes the system sustainable. That reservoir when incorporated with solar panels and an electric pump achieves goal of a sustainable design. Currently, no external power source or fuel is needed to operate the irrigation system and the movement of the river and sun alone irrigate crops daily and throughout the seasons. However, as the system exists now, the water is moved through the system completely by the electric pump through its connection to the main-line. The next step in this irrigation project is to establish these 10,000 L tanks as elevated sources directly adjacent to the agriculture plot, establishing a functional elevated source for the system.

Another future development for the project is to replace the electrical cable between the solar panel and pump (**Figure 41**). The current cable is thinner than the recommended gauge and therefore the pump can become overheated due to drawing to much current from the solar panel batteries. The maximum amount of current that runs through the cable is inefficient to power the pump and draws lots of current over a period of time which leads to the pump running hot and shortening its lifespan. A thicker cable would allow for more current to move through the cable at one time, reducing stress on the pump.

**Figure 35: Water Pump Cables**

Future measurements and calculations may be conducted as further analysis of the system. These future measurements would be preferably more precise and measuring an actual pressure for the system provides for greater comparison to expected results.

## Discussion

With the system complete and functioning, the Mission of Pawaga has a new resource for building a spiritual and human connection with its community. The Mission's nursey and elementary classes specifically benefit from this agriculture project. The mission compound includes a school building were students from Pawaga village attend daily classes (**Figure 41**). Now, with a reliable source of nutritious crops, a meal may be provided to those students. The students have already started to benefit from the irrigation system (**Figure 42-43**) and will continue to receive nutrients that are otherwise absent in their diet. Overall, the introduction of nutrients to the student's diet will combat malnutrition that many in the village struggle with while also establishing a good habit of attending school and directly benefiting from participation in education.

**Figure 36: Nursery/Elementary School**

**Figure 37: Nursery Class**

**Figure 38: Elementary (Primary) Class**

An additional result of the system’s completion is its use as a tool in educating farmers and home gardens in the community. Having a source of education and inspiration will help spread the benefits of a sustainable and conservative agriculture in the arid environment. Finally, having a new resource at the mission allows for improved management of the mission property. As a vital resource to the village, the mission must retain and strengthen its relationship with its community. Doing so will encourage the community to respect and cherish the mission.

The irrigation system that was designed for this project has a broader application to the world outside of the EARV. The irrigation system installed at The Mission of Pawaga is designed to provide irrigation in an otherwise arid environment. In our world there are other environments that cause a challenge to agriculture and irrigation. The substantial droughts that have continued to occur in the western U.S. are a prime example of one of these environments and this irrigation system is a potential solution to the regions problem.

General methods of industrial irrigation that are popular in the U.S. are ditch flooding and sprinklers.[8] Each of these methods are attempts at taming the environment to one that is agricultural friendly, and each method also harms the environment consequently. Flooding ditches and fields distributes large volumes of water in an attempt at being efficient. The drawback of this method is the large consumption of water and agricultural runoff that it produces. Sprinklers are more direct in water distribution and the kinetic energy of the water also rotates the wheels that move the sprinkler. Though these same wheels may crush crops and repeat the same path of crops. This method requires a high level of maintenance and waters sections of agriculture part by part rather than all at once. Of the two methods, sprinklers are the more sustainable and conservative in design.

I support the adoption of dripline irrigation by industrial agriculture and scaling it up to an industrial level of production. Given enough time the irrigation system of this project can function by design and with enough resources it can be adapted to the requirements of industrial sized agriculture. The elevated water reservoir and the dripline emitters are components of the system that highlight its functionality. Adaption to the design required of an industrial scale may look like constructing the elevated reservoir at a great height (40+ meters) to build up a large pressure head required to cover a large area of crops. Identifying adequate sources of water would be determined by the location of the system. Sources may include rivers, lakes, or ground water. Laying out all the drip-line emitters required will be a great challenge for a plot of many acres, but once constructed, maintenance of the system would be low.

Throughout the project I struggled and encountered challenges with regards to the project's success. An unexpected struggle at the start of the project was the language barrier that existed between myself and other project contributors. While the project mentor Evarist spoke fluent English,

[8] "Irrigated Agriculture: Technologies, Practices, and Implications for Water Scarcity."

others who worked on the project did not. This was frustrating when I attempted to communicate current and subsequent steps to those that were required to progress. I relied a lot on Evarist to bridge this gap while also learning and practicing the native language, Swahili daily at the project site. If I continue to work with the project, a proficient understanding of Swahili would aid with communication.

Another challenge was that the project lacked any funding. The project had little-to-no funding, access to local resources provided most of the material for the project. At the project's start I advocated for project funding through academic resources and crowd funding. The GoFundMe platform[9] served as an outlet for the project to bring in funds. A total of $2,000 in project funds were acquired through the platform. In addition to a research stiped of $1,200 provided by Kalamazoo College (**Figure 44**).

For reference, the quote provided by the professional contractor, Dayliff, for the installation of the irrigation system as they designed was ~$16,000. This figure was well out of range for the current project funding and an unrealistic amount with regards to financial resources that the mission has. A total of $3,200 were raised funding the entire project. Had the amount of $16,000 been available and Dayliff contracted for the project, management and success of the project would have looked different, a lower amount of funding was able to achieve the same goals of the professional design.

A final obstacle to the system construction became apparent with the instillation of the filter. Due to the filters location, a significant drop in hydrodynamic pressure occurs between the system source and its filter. A great enough drop in pressure that the fluid was unable to pass through the filter and reach the drip-line emitters. Once discovered, the function of the system was assessed. The leaky pipes, along with the distance of ~100 meters between the source and filter are believed to be the causes of this pressure drop. As the system exists now, the electric pump does provide enough pressure to pass through the filter, and there should be no future problem of pressure with the new 10,000 L

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[9] "Help Provide Water to the Mission of Pawaga, Organized by Sam Meyer."

elevated sources. Repositioning of the pump may also improve its functionality. Rather than it positioned directly before the irrigated field, position it along the pump's mainline where pressure is high and all water passing from the pump to its destination in the compound would be filtered at that point.

## Conclusion

The project goals were to conserve water and operate sustainably. This irrigation system has successfully been designed and installed to serve the Mission of Pawaga's goals. The system was designed to conserve water and operate in a sustainable way. The method of drip-line irrigation functions well as a small-scale system but may struggle with adequate pressure required on a large-scale. This is due to the low water pressure that results from gravity. So, while a gravity powered irrigation system may be advantageous, it must work under the conditions of low pressure. Increasing the diameter of the punctures (~1/16 in) that line the driplines is a method of achieving this. This SIP has presented a dripline irrigation system that successfully functions at a scale above that of a home garden and argues that its design may be implemented as a solution for regions of the world that are challenged with regards to agriculture.

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