The Irragators

An autonomous irrigation system for the small Haitian island of Ile-a-vache that minimizes power consumption and maximizes efficient water usage

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Autonomous Irrigation System

An irrigation system for the small Haitian island of Ile-a-vache, Haiti that minimizes power consumption and maximizes efficient water usages

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Customer/Sponsor

Patrick Lucien	EDEM Foundation (www.edem2.org)

Background

Ile a Vache is small island of approximately 15,000 people of the southern coast of Haiti. The island's main export is crops to include beans, peppers, and plantains. The EDEM farm, a 2 acre plot on the heart of the island, is a large producer of goods and sustenance for the citizens. Currently, the farm is 50% irrigated and 50% hand watered from a well and a gasoline powered pump. Not only is hand water laborious, but the gasoline for the pump must be bought from a neighboring island. Because of this, the farm is not achieving it's largest possible output to feed both the citizens, and the consumers.

Objectives

The goal of this project is to design an easily reconfigurable irrigation system that utilizes solar energy and can be transported to or bought on the island of Ile a Vache.

Results

The Irragators have worked with Mr. Lucien, the main customer, and LCDR Lust, the group’s advisor to design the irrigation system for Ile a Vache thus far. The customer requirements specify that the final system must be easily reconfigurable, portable, and efficient in watering crops. Each team member, with these requirements in mind, brainstormed products available to fit each of the 5 components of the system. These ideas were brought together in a morphology diagram. From each section of the project, the most effective product was chosen to be used in its respective portion of the system.

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1 Problem Definition and Need Identification

1.1 Customer's Problem Statement

The initial problem statement given to the student group was:

> *Automated irrigation system for a forestry project using limited water and no- or low-power in Ile-a-Vache, Haiti.*

1.2 What is the problem? What about the current situation is unsatisfactory?

The current farm has only a 200 gallon tank to supply their water needs. This tank is filled by a nearby well and pump. In order to bring the water from the tank to the crops, water buckets are employed by the workers of the farm. This use of manual labor is inefficient and greatly reduces the farm's productivity and overall output. Since many of the workers are required to walk buckets long distances between the water tank and the crops, they are unable to perform other duties on the farm. Below, in Figure 1, the farm is shown and a rough path of how they get to the port in Madame Bernard. Their produce has to be brought to the market on the backs of small moped-style motorbikes. From the port, the produce is transported to mainland Haiti.

Figure 1: Farm to Market Diagram

1.3 Customer Identification

Figure 2 shows the first customer, Jean-Patrick Lucien. Mr. Lucien is the main point of contact for all information about the EDEM farm, Ile a Vache in general, and the desired deliverables. He initiated the project through LCDR Lust, a professor in the mechanical engineering department at the United States Naval Academy. While he grew up in Haiti, he now lives in the United States and gives back Ile a Vache through the nonprofit organization EDEM. As the founder of EDEM, he has led the organization to complete many beneficial projects in the area including the creation of the EDEM farm.

Figure 2: J.P. Lucien, the founder of EDEM foundation and the main customer of the Irragators[1].

[1]Lust, Ethan, LCDR. *Jean-Patrick Lucien*.

The second customer is the agronomists on the EDEM farm. Figure 3 shows Jackson BonAnne, the farm's chief agronomist. He and three other farmers work full time on the plots of land that are of interest in this project. He and the farmers would benefit from a successful project because the ratio of man hours to crop output would decrease significantly through the use of irrigation. Currently, Jackson and his coworkers hand water 50% of the farm using buckets.

Figure 3: Jackson, one of the four agronomists that work full time on the EDEM farm[2].

Another customer is other local farmers. Local farmers would be interested as they may copy the product utilized and easily apply it to their own farms, increasing the overall output of crops for export off the island and to the local citizens.

1.4 Gathering Information from Customers

Sources utilized to gather customer information include written dialogue with Jean-Patrick Lucien, the founder of the EDEM foundation. Additionally, sources include online research, written research, and information gathered from LCDR Ethan Lust's physical trip to the site location.

1.4.1 Customer Interviews

Initial Interview with Jean-Patrick Lucien

On April 26th, 2016, the group was able to talk with Mr. Jean-Patrick Lucien about his overall expectations of the group and insight into the climate of the project. This lasted about 30 minutes. Mr. Lucien talked about the problem of malnutrition in Haiti. With the

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[2] Lust, Ethan, LCDR. *Jackson the Agronomist*.

coming of El Nino, food supplies are dwindling more and more. 70% of the food consumed in Haiti must be imported; the rest is grown and produced in the country. From this, Mr. Lucien recognized the need to improve the output of current agricultural methods in Haiti, notably in Ile a Vache where the EDEM foundation focuses its efforts. To him, the most notable misused resource is water. If the group could create a long-term system to use water more efficiently when growing crops, the quality of life on the island of Ile a Vache would improve greatly. This interview was recorded and saved as an an audio clip.

Second Interview with Jean-Patrick Lucien

The second interaction the group had with Mr. Lucien occurred over email in early September of 2016. The group sent about 20 questions and he replied in a word document with pictures of his descriptions. The full length response can be seen in Appendix E. The interview contains answers to questions about the layout of the farm, the operations of the farm, and the current irrigation system. To summarize, the EDEM farm, our area of focus, normally grows plantains, eggplant, peppers, beans, and cabbage. The farm is approximately 50% irrigated with the worker's hand-watering the rest. The water is supplied from a well 50 ft. deep. Mr. Lucien explained that the water is pulled from the well with a pump attached to a 5 kW gas powered generator. The generator used about 1 gal. of gas per week which is bought from the neighboring town of Madame Bernard.

Mr. Lucien confirmed that the water travels from the well to a 250 gal. tank on top of the neighboring farmhouse. From there, it travels through 100 ft.of PVC piping and slowly disperses through the drilled holes. See Figure 4 for a more detailed layout of the farm.

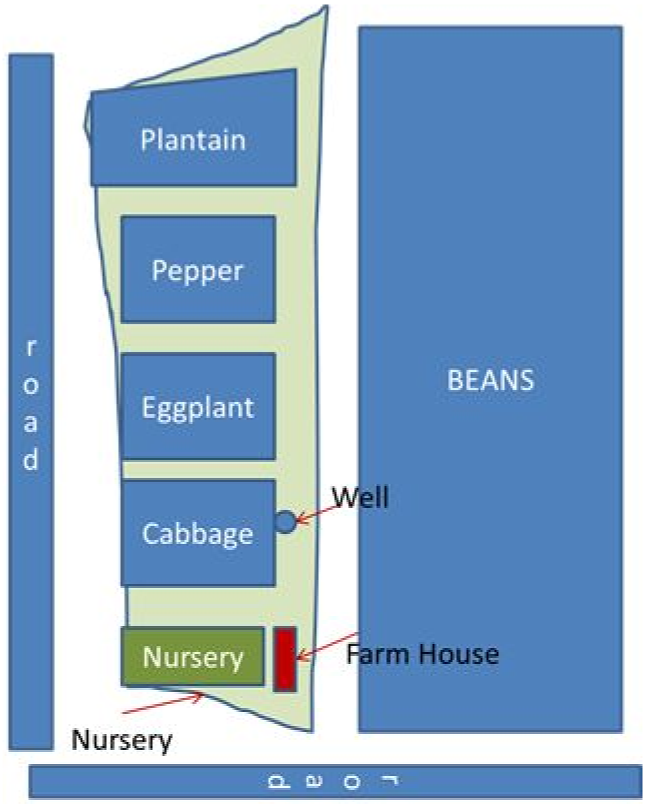

Figure 4: Layout of the EDEM Farm as Explained by Mr.Jean-Patrick Lucien[3].

From Figure 4, one can see the farm is divided into a multitude of plants as confirmed by Mr. Lucien in this interview. The tank he mentioned is above the farmhouse shown in the lower right corner.

Initial Interview with LCDR Ethan Lust

LCDR Lust is the faculty advisor for the Irragators. When initially introducing the project to the group, it was a broad idea of a “home farm kit”, or some type of combination of materials that would allow the citizens of Ile a Vache to be more self sustainable. As his contact with Mr. Lucien, the founder of EDEM, became more frequent, the idea grew into a system to increasing the output of the EDEM farm, a farm that supplies a large amount of produce for use within the island and to export. He began the cooperative partnership with the EDEM foundation and remains the link to connect Ile a Vache and the Irragators. LCDR Lust discussed the background of Ile a Vache. The small island, only eight miles long by three miles wide, is home to over 15,000 citizens. The island is home to two cars and only one way in and out, a ferry port, making access to materials limited. Figure 5 shows a snapshot of the EDEM farmhouse in his trip to Ile a Vache in January of 2016.

[3] Lucien, Jean Patrick. *The EDEM Farm Layout.*

Figure 5: A Snapshot of the EDEM Farm taken in January of 2016 by LCDR Lust[4].

A large portion of the information the group began with was from this recent trip. The initial discussions with LCDR Lust offered insight into the problem statement and overall objectives.

1.4.2 Customer Complaints

Mr. Jean-Patrick Lucien, the main contact for the Irragators to the island of Ile a Vache, brought the project to the attention of LCDR Lust with the fear of a lack of food. Haiti, and notably Ile a Vache, struggles to feed its inhabitants. His complaint was that water in the EDEM farm could be used more efficiently. Currently on the plot of land, while half of the farm is already irrigated, 50% of the crops are hand watered. This not only induces a large amount of man hours, but is bound to lead to a misuse of water resources.

1.5 Revised Customer's Problem Statement.

The revised problem statement is to design a semi-autonomous, portable, irrigation system to raise farm efficiency and output. The system must be able to water a large quantity of crops while using very little user-input. A system of valves and branches of

[4] Lust, LCDR Ethan. T*he EDEM Farmhouse*.

piping will be used to accomplish this. The system must also be portable enough to be broken-down and reconfigured to be used at another farm or on another crop. PVC piping and adjustable joints will be used to accomplish this goal. Farm efficiency and output will be raised since the crops will be watered in a preferable manner and less workers will be required to accomplish the watering.

1.6 Initial Draft of Customer Requirements

Once the customer had been contacted and interviewed, an initial table of customer requirements was able to be made. The initial customer requirements are included below in Table 1.

Table 1: Initial draft of Customer Requirements.

Dimension	**Description**
Performance	Must be semi-autonomous
	Minimize the amount of water wasted
	Easily built
	Should not use outside sources (gasoline) for energy
	Should be solar powered
	Should fill the water tank in a timely manner
	Must branch out to water all crops in a timely manner
Reliability	Should work on its own to fill water reservoir
	Should secure itself when the tank is full
	Inexpensive to build/maintain
Durability	Should last at least a couple of years
	Stowable in the event of turbulent weather
Serviceability	Should use as many existing parts a possible
	Should be portable and reconfigurable
	Easily fixed
	Should be customizable for different farms/crops
Conformance	Should conform with the strictest government standards
Aesthetics	Should look “safe” and secure enough not to be stolen by burglars

Although each of the goals cannot be perfectly met, the team will strive to accomplish each of them to the highest level possible. The client will be contacted and efforts will also be made to synthesize this list to a more manageable number of items.

1.7 Gathering Information on Existing Products

Agriculture projects involving solar pump driven irrigation systems are well established in both wealthier nations and the developing world. Wherever they are implemented, they serve to improve autonomy and efficiency of crop irrigation. However, research must be conducted with the understanding that solar radiation, water levels, flow demands, and elevation differences are highly variable in different parts of the world. A high level of market diversity allows consumers to purchase components to meet exact specifications. In order to devise a system to meet conditions for the farm on Ile a Vache, research was conducted for two aspects. The first involving transportation of water from the well to the storage tank, and the second being irrigation distribution methods from the tank to the crops.

1.7.1 Pump Systems

Substitutes to the current generator powered pump include use of a manual pump, an air compressor, and a solar panel. The manual pump (Figure 6) requires manpowered rotational motion of a lever arm to physically drive water from a well to the surface. While such an application may be useful for shallow wells or low yield applications, the requirements for the farm in Ile a Vache for a more autonomous system are not met with a manual pump.

Figure 6: Hand Pump[5].

A second alternative, the air-operated double diaphragm pump (Figure 7), uses compressed air to drive water flow. As air rushes through valves, diaphragms vibrate across pipes to push and pull water through openings. The additional requirement of a

[5] http://store.waterpumpsupply.com/hand-pump.html

method of air compression decreases its usefulness as an autonomous replacement for the current system. In contrast to these two, solar pumps offer a high degree of autonomy and reliability. By operating in conjunction with a storage tank, water can be pumped from the well during times of sufficient solar radiation.

Figure 7: Air-Operated Double Diaphragm Pump[6].

1.7.2 Solar Pumps

Three solar pump kits were researched, combining both solar panels and submersible well pumps. These kits integrate the two components well in terms of expected electrical power and hardware mating. Additional accessories such as tank level meters and voltage controllers can be purchased to further improve the system. The Advanced Power solar panel and pump is listed as a 500 gal. per day system at $1,700 (Figure 8). This is a competitive price for such a high flow rate, but the small size of the panel presents challenges for achieving sufficient wattage.

Figure 8: Advanced Power Solar Panel[7].

The second system combines a Shurflo pump with an AltE panel. This combination provides the best price at $850 while meeting all engineering model requirements. The

[6] http://www.northerntool.com/shop/tools/product_200322263_200322263
[7] http://solarpumps.com/products/complete-systems/k85sr2-500-gpd

Solardyne system is the most expensive at $2,600 due to its increased flow performance and electrical power. The characteristics, however, far exceed the requisite values.

1.7.3 Irrigation Systems

The following Irrigation Systems are all largely used across the United States and work best for the plants that are planted on the farm. In Table 2 below, the optimal distance between plants and where each plant absorbs the most amount of water is shown. All numbers are from the Food and Agriculture Organization of the United Nations (FAO).

Table 2: Requirements for plants

Plant	Optimal Spacing (m)	Depth the Roots take in water (m)	Ideal Type of Watering
Plantain	2-5 X 2-5	60% = 0-0.3 100% = 0.5-0.8	Overhead watering system Low flow/drip
Bean	0.05-0.1 X .5-.75	100% = 0.5-0.7	Water levels alter
Cabbage	0.3-0.5 X 0.5-0.9	100% = 0.4-0.5	Sprinkle or trickle system
Pepper	0.4-0.6 X 0.9	90% = 0-0.3 100% = 0.4-0.5	Sprinkler (reduces leaf burning) or Drip Irrigation

The percentages for depth of roots shows how much water is taken at that distance. For example: the bean plant has absorbed 60% of the water it will absorb at 0.3 meters. At 0.5 to 0.8m, the bean has absorbed all the water that it will take in. Anything below 0.5 to 0.8m (the depth depends on the maturity of the plant), the bean plant will not absorb. Overall, all the plants take in the most amount of water in the first 0.4 meters.

The systems that are listed below are ones that could be used due to the parameters each plant needs above. The cost of the following systems varies. The cost can't be the only main part of the decision process, the maintenance and overall cost over a 10 year period must be taken into account as well. The cost varies slightly between all systems, reference section 2.3.5 for cost differences. With that being said, each system is relatively low cost, low flow rate, and durable irrigation systems. Each system has parts that can be substituted, but overall, the design of each system is simple and easy to create.

- Deep Pipe Irrigation: This systems delivers water to deep roots (Figure 9). It is a PVC pipe that is dug into the ground and has holes drilled into it (4 to 5 cm in diameter) and is about a meter deep. There is a screen on top of the PVC to stop any bugs from getting into the PVC and the bottom of the PVC is blocked off in order for the water to be directly delivered to the plant. This system reduces water evaporation and efficiently delivers water to the plants at a slow rate. This system is also not easily moveable if the farm layout is changed in any way.[8]

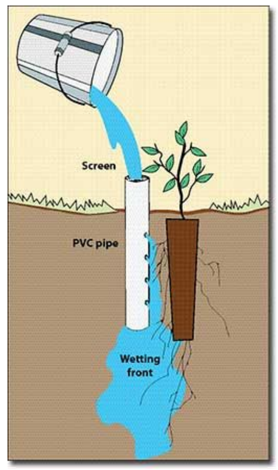

Figure 9: Deep pipe irrigation system.

- Juab County PVC Drip Irrigation System: This drip irrigation system delivers water to the soil that the roots are directly under (it does not deliver water to the leaves which wastes the water). The system uses ½ to 1 inch (in diameter) PVC pipe. It uses fittings that are either glued or are left unglued so the system can move (making this system adjustable to any farm/garden size) and ball valves. It can save up to 75% of water that is generally lost when hand watering or watering via a sprinkler system. It saves up to 90% of time spent on delivering water to plants.[9]

[8] http://permaculturenews.org/2014/04/24/get-started-efficient-irrigation-systems/
[9] http://extension.usu.edu/juab/ou-files/ez-plug/uploads/horticulture/juabpvcdripsystempresentation_.pdf

Figure 10: Drip irrigation system.

- Wick Irrigation: This irrigation system delivers water to the plants on an "as needed" basis. The plant will retrieve the water from the wick when the moisture of the soil gets low. This system is largely for farms that have ground that can't hold onto water (drains quickly). The system can deliver water to the plants over an extended period of time, allowing the farmers to put water in the bottle and leave the bottle for a few days or until the water level gets low in each individual bottle. This system allows for very little evaporation. This system is also not easily moveable if the farm layout is changed in any way.[10]

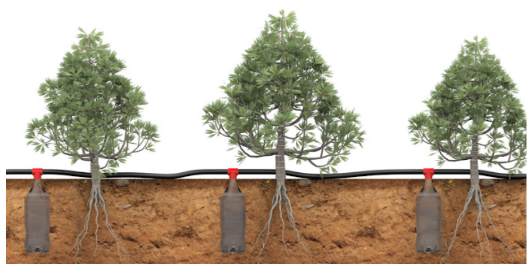

Figure 11: Wick irrigation system.

- Buried Clay Pot Irrigation: This irrigation system is very similar to the deep pipe irrigation system in that it delivers water to plants underground via holes drilled into the clay pot. The system delivers water to roots that are closer to the surface. The user just has to fill the buried pot with water and the water seeps through the holes drilled into the sides to the roots of the plant. This ancient Chinese practice reduces The pot is filled to with water and the water seeps out through out the holes that are drilled in, it's an ancient Chinese practice. This system is also not easily moveable if the farm layout is changed in any way.[11]

[10] http://extension.usu.edu/juab/ou-files/ez-plug/uploads/horticulture/juabpvcdripsystempresentation_.pdf

[11] http://permaculturenews.org/2014/04/24/get-started-efficient-irrigation-systems/

Figure 12: Buried clay pot system.

1.7.4 Applicable Codes and Standard

The US Navy, when building outside of the US, still has to follow US codes and regulations involving the actual construction and the final product. So along with Haiti and the few codes in regards to irrigation that they have, here are the codes mandated by the US for irrigation systems and pumping systems.

Each of these codes are major groups of codes, each one has smaller codes below it to help engineers follow it specifically. Below are the overall description of the general codes that we will need to follow throughout the project:

- Code 4971: establishments primarily engaged in operating water supply systems for the purpose of irrigation
- Code 4941: systems distributing water primarily for irrigation service are classified; furthering definitions for code 4971
- Code 9511: Environmental concerns when dealing with drainage development, and consumption of water resources.
- Code 221310: operating water treatment plants and/or operating water supply systems. Pumping, distribution mains. Used for drinking, irrigation, and other uses.
- Code 237110: Rules regarding building any system involved with getting water. Well digging, pumping of water, holding that water in a storage tank, delivering that water to the crops via an irrigation system (largely the pipes involved)

These codes come from Standard Industrial Classification which has lists of all codes involving industry.[12]

1.7.5 Social, Economic, Environmental, and Cultural Context

When traveling to another country and providing any type of aid or volunteer-work, the utmost concern must be taken in order to avoid impacting the lives of the people you are working for in a negative way. In order to ensure this, one must consider the social, economic, environmental, and cultural impact of their actions.

In the case of Haiti as a whole, the Haitians have been victims of non-government organizations taking advantage of them in the wake of the 2010 earthquake. We must consider that the people native to Ile-a-Vache may know about this or were personally

[12] http://siccode.com/en/search/Irrigation

victimized by similar situations. This could affect the trust that they give us and they could even view us as an intrusion to their everyday lives. Also, a poor impression could result in it becoming more difficult for future volunteers or visitors to become acclimated with the people of Ile-a-Vache as well.

In an attempt to gain and maintain their trust, we must travel to Ile-a-Vache aware of and empathetic to their situation. This requires working to improve their lives in a long-term way without impacting their day-to-day living. Additionally, developing an understanding for their culture and language will show an interest in their lives and help form a relationship with them. This was conducted through the reading of *The Big Truck That Went By* by Jonathan Katz and *Haiti: The Aftershocks of History* by Laurent Dubois and by the recorded Creole lessons in order to become familiar with their native language. As a group, we understand that simply attempting to learn a bit of Creole is not enough to counterbalance the prevailing idea of the United States' somewhat intrusive involvement in Haiti throughout history. We acknowledge that this is an enormous barrier to overcome, but we believe we are more empathetic and understanding of the situation and that we will work to assist the Haitians rather than using this project for our own personal gain.

Working on or attempting to change their irrigation system could have many unintended consequences that could impact their lives greatly if not implemented properly or not considered with due diligence. We do not want to implement a system that is too difficult or costly to maintain as this could cause an undue stress on their food production or the profit made by the farm. If food production is decreased, it could mean that workers go without pay, people go hungry, or it could even impact the market-economy of the island as whole. Additionally, if we are able to implement a better irrigation system, it could result in a higher output of crops. This could create more food for the locals at a cheaper price and it could boost their market-economy by allowing them to sell more. The new technology and techniques could be taught to other local farmers as well.

In contrast, we also must consider that the system could reach a point of such high output, that it begins to affect the community negatively. Although a farm with a higher output would mean that more food is available, it could also have grave effects on the local economy. A larger yielding farm could lead to a flooded market. This would mean more money for the EDEM farm, but it could affect other farmers from making enough money as well. A large increase in yield could cause congestion along their already less-than-ideal roads and it could lead to other farmers being put out of business as well.

Finally, we must also be cognizant of the impact that we could have on their environment. Not just common considerations such as water availability, power usage, and the impact to local flora and fauna, but also to their infrastructure. Haiti has been plagued with poor infrastructure due to building codes and standards not being enforced. We must not exacerbate this already prevalent issue by following all necessary codes and standards put in place by both domestic and international organizations. Also, we do not want give them a system that is too powerful, leading to overuse and eventual water shortages.

1.7.6 Engineering Models

In order to adequately estimate the requirements of the pump-solar panel system, a mathematical model was created. Figure 13 below depicts the configuration for the system at the farm in Ile-a-Vache, Haiti where water will be pumped from a well in the ground to a collection tank on top of the farmhouse before it is distributed to the crops.

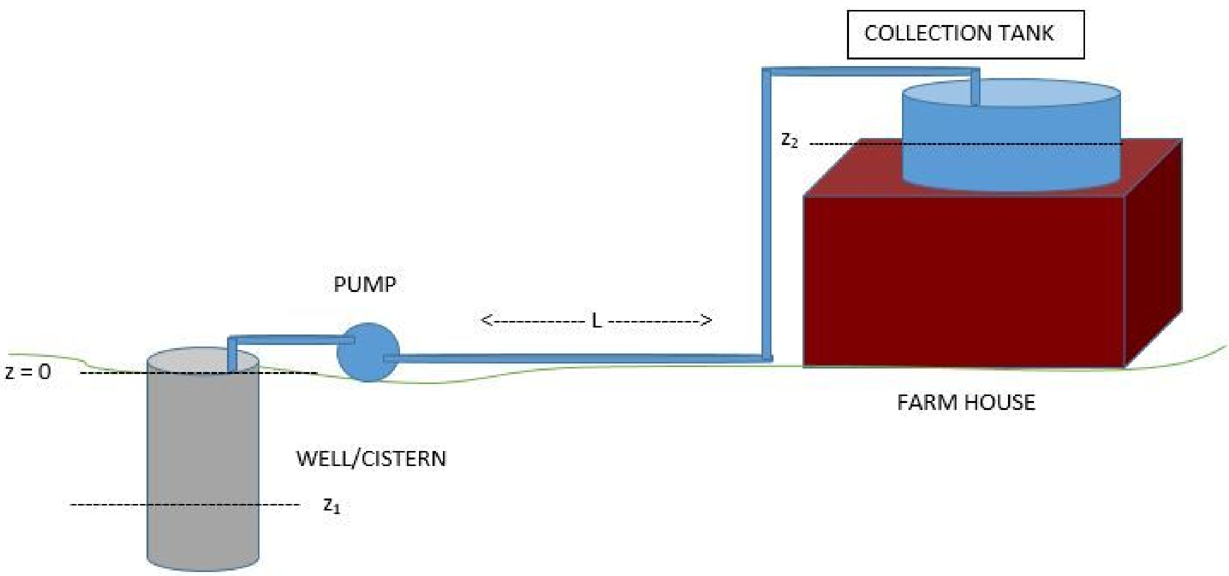

Figure 13: Diagram of System.

Using Equation 1 below:

$$\frac{P_2}{\gamma}+\frac{V_2^{\,2}}{2g}+z_2=\frac{P_1}{\gamma}+\frac{V_1^{\,2}}{2g}+z_1+h_P-h_L-h_T \qquad (1)$$

along with the assumptions that both the well and the collection tank are open to the environment, velocity of the fluid is negligible, and that there is no turbine present, we are able to rearrange the equation for hump head (h_p). This can be referenced in Equation 2 below.

$$h_P = (z_2 - z_1) + h_L \qquad (2)$$

Equation 2, shows that the required pump help, h_P, must overcome both the height difference in the water levels as well as any losses (h_L) that occur within the flowing liquid. In the equation, z_2 represents the height of the water above the farmhouse, z_1 represents the height of the water in the well underground, and h_L represents both the major ($h_{L,major}$) and minor ($h_{L,minor}$) losses. The head loss equations can be viewed in Equations 3 and 4 below.

$$h_{L,major} = f\frac{L}{D}\frac{V^2}{2g} \qquad (3)$$

$$h_{L,minor} = K_L\frac{V^2}{2g} \qquad (4)$$

The preliminary engineering model showing the derivation of Equation 2 can be viewed in Appendix A. Using the parameters included in Table 3 and the annotated MATLAB script available for reference in Appendix D, the pump-performance curve and the required power for the system was determined.

Table 3: Assumptions Made for Engineering Model.

Factor	Variable	Value	Units
Height of Water	z_1	17	ft
Depth of Water	z_2	-100	ft
Length of Pipe	L	200	ft
Diameter of Pipe	D	2	in
Loss Coefficient	K_L	13	unitless
Darcy Friction Factor	*f*	0.02	unitless
Acceleration due to Gravity	g	32.2	ft/s^2
Specific Weight of Water	γ	62.4	lbf/ft^3

A Loss Coefficient of 13 was used in order to account for four 90-degree elbows, a sharp entry pipe in the well, a sharp exit pipe in the collection tank, and one fully-opened globe valve. Additionally, a Darcy Friction Factor of *f*=0.02 was used due to the assumption that we would be working with smooth PVC piping.

As a result of these assumptions and by using the specifications for the 1 hp High-Head Circulation Pump for Water[1] listed on the McMaster-Carr website, a pump-performance curve was constructed. Even if this pump is not chosen, the MATLAB script is written in such a way that it will allow us to insert any pump's specifications and determine the resulting pump curve.

Using these pump specifications, the ideal flow rate, *Q*, was found to be 19 gpm. Resulting in a required pump head, h_P, of 0.562 hp or 0.419 kW. Showing that their 5 kW gasoline generator is massively overpowered. If it is running at part-load, this could lead to an opportunity to significantly improve performance. Additionally, this resulted in a time of approximately 63 min. required to fill 1200 gal.-worth of collection tanks that the farm is looking to purchase. This means that the amount of power required is approximately 0.441 kWh. The pump-performance curve can be viewed in Figure 14 below.

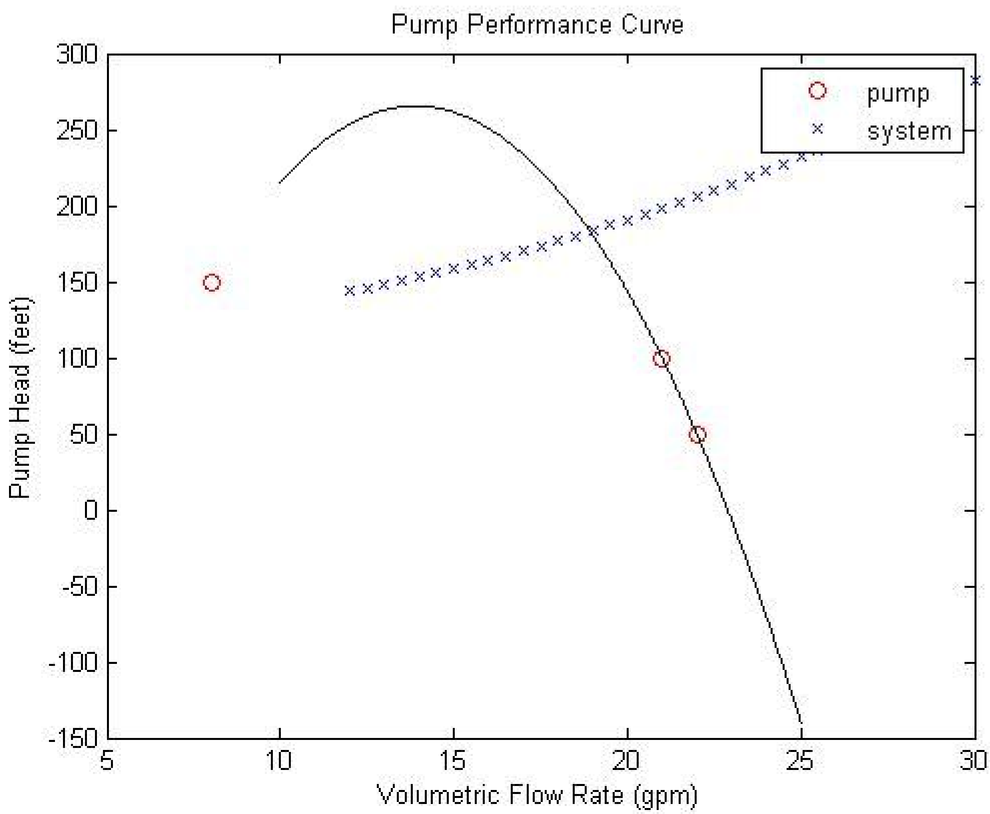

Figure 14: Pump-Performance Curve.

1.8 Quality Function Deployment

1.8.1 Customer Requirements

After speaking with Mr. Lucien a few more times via email, a much more focused table was made. Mr. Lucien was able to shed light on what he considered to be the most important aspects that would be needed for the irrigation system. Below, in Table 4, the aspects are ranked in their priority from lower to higher. A numerical method was used to rank the different important characteristics, 1 being the lowest ranked and 5 being highest ranking. This table will allow for more precise engineering and brainstorming to occur vice being misguided and striving for unimportant objectives.

Table 4: Revised Customer Requirements.

A Successful Design Should should have these characteristics:	**Priority**
Easy to reconfigure	5
Portable	5
Efficiently water existing crops	5
Greatly reduce manual labor	4
Solar powered	4
Use existing irrigation equipment	3

1.8.2 Customer Assessment of Competing Products

Available products were broken down between those related to pumps and those relating to irrigation. Due to the utilization of tank storage, water can be pumped from the well at a rate that does not directly impact distribution to crops. Any pump can be coupled with any irrigation system, provided the flow rate is sufficient to keep water levels in the tanks sufficient for distribution. As evaluated by the customer requirements, an optimal combination would include a solar pump and drip irrigation. These two components are the most adaptable, autonomous, and efficient while maximizing use of existing equipment. A solar pump can be setup to run autonomously during sunlight hours using a timer and water level meters. While it may not be an ideal solution for portability and use of existing equipment, it outperforms the other due pumps in all other categories. Drip irrigation allows for efficient and autonomous water distribution by placing adaptable piping networks through crop fields. Water collected in storage tanks can be turned on and off quickly and effectively. Values for adaptability and portability are based on manual labor required to configure a new system and daily requirements for watering. The latter is given greater weight because daily efforts are more crucial in overall man hours than the periodic requirements to move the system.

Table 5: Customer Assessment of Competing Products.

	Pump System			**Irrigation System**			
Customer Requirements	**Solar Pump**	**Hand Pump**	**Air Pump**	**Deep Pipe**	**Drip Irrigation**	**Wick Irrigation**	**Clay Pot**
Easy to Reconfigure	5	5	5	3	5	3	1
Portable	3	4	3	1	5	1	1
Efficiently Waters Crops	N/A	N/A	N/A	3	5	5	5
Reduces Manual Labor	5	3	4	1	4	4	1
Includes a Timer	5	1	1	1	1	1	1
Solar Powered	5	1	1	N/A	N/A	N/A	N/A
Use Existing Equipment	3	3	1	3	3	3	1

1.8.3 Engineering Characteristics

In order to have tangible parameters that can be measured, engineering characteristics were formed from the provided customer requirements. These can be viewed in Table 6 below.

Table 6: Engineering Characteristics.

Customer Requirements	**Engineering Characteristics**	**Units**	**Direction of Improvement**	**Target Values**	**Rank Order**
Efficiently Waters Crops	Volume	gal	↓	4124 gallons	1
Portable	Weight	lbs	↓	800 lbs	2
Easy to Reconfigure	Time	min	↓	4 hours	3
Include a Timer/autonomous	Yes (1) / No (0)	unitless	↑	yes	4

Reduce Time to Water	Operator Man-Hours	hrs	↓	2 hours/day	5
Solar Powered	Minimize Gasoline Use	gal	↓	zero	6
Minimize System Cost	Cost	Haitian Gourde	↓	265,000 (~$4,000)	7

Specifically, we hope to decrease the volume of water wasted by ensuring that crops are efficiently watered, decrease weight so that the system is transportable using the trailer design from the transportation group, decrease time required to setup and reconfigure the system, include a timer or automated control system, decrease man-hours required to water crops, decrease gasoline usage by making the system solar powered, and minimize the system cost.

1.8.4 Technical Assessment

The technical assessment compares individual solar pump components by cost, wattage, depth, and flow rate. The target values provide a benchmark comparison to expected requirements on the farm. According to this comparison, the Shurflo pump and AltE solar panel combination offers the optimum solution that minimizes cost while meeting customer constraints.

Table 7: Technical Assessment.

	Cost	**Solar Panel Wattage**	**Depth**	**Flow Rate**
Units	$USD	W	ft	GPD
Advanced Power	1,700	85	90	500
Shurflo and AltE	850	100	230	864
Solardyne	2,600	185	75	800
Targets	2000	100	150	300

2 Concept Generation

2.1 Physical Decomposition

The irrigation system that is being designed has many predecessors. Due to the large amount of already implemented and successful irrigation systems, it was determined that studying past models and altering them to the EDEM farm would work best. The farm was split into five components in order to focus on the functions of each portion of the farm and who they could be combined in many ways to create a successful system. The five subsystems of the irrigation system are the well to the pump, the pump to the tank, transitions, the tank to the plot, and the plot to the plants. The well to the pump system determines how the water will be pulled from the well onto the ground level of the farm. This includes the pump in the well and the solar panel system to power the well. The next subsystem, the pump to the tank, looks into how the water flows from the pump to the tank. This includes the optimal hose diameter for pumping water more that 10 ft. up into the tank. Thirdly, the transitions include the various attachments that connect the hose and isolate the plots in order to redirect and stop water flow to chosen plots. Additionally, the tank to plot system looks into piping that can be used in part with the transitions for the water flow from the storage area to the desired plot. The last subsystem is the plot to the plant. This analyzes the most effective option to deliver water to the plant without wasting it. From these subsystems, several options were investigated. This can be seen in Table 8 below.

Table 8: Morphology Chart Indicating the Subsystem Options.

Well to Pump	**Pump to Tank**	**Transition**	**Tank to Plot**	**Plot to Plant**
pumps and solar panels	*hose type and layout*	*collars, valves, and fittings*	*hose type and layout*	*water distribution to plants*
Advanced Power	PVC	PVC	PVC	Wick Irrigation
Shurflo and AltE	Garden Hose	Rubber transitions	Drip Irrigation Tubing Coil	Deep pipe Irrigation
Solardyne	Expanding/Contracting Hose	PVC Valve Tree	Garden Hose with holes in it	Drip Irrigation System
	Strongway PVC Discharge Hose	adapter add-on	Strongway PVC Discharge Hose	Buried Clay Pot Irrigation
	Vacuum Duct Hose		Small Diameter Fire Hose with Holes	Sprinkler system
	Flex-Drain Hose		Drip Tape	

The ideas for each subsystem were listed in a morphological chart. Because this was a multidimensional problem, the morphology diagram best allows the group to bring together various ideas and explore how they connect as an entire system. The three step morphological approach includes dividing the problem into subsystems, create solutions for each subsystem, and combining the subsystems into a system and evaluating various combinations.[13] This process is detailed in the above chart and the following report.

2.2 Creative Thinking Methods

In addition to the consolidation of ideas as shown through the morphology diagram in the previous section, creative thinking was incorporated into the combination of the subsystems and the initial design of the composition of the subsystems. To initiate design, the five member group verbally brainstormed and independently researched entire irrigation systems used in the past. When the group met a second time and discussed how to break up the system, all already had an idea of how an irrigation system works and how portions of it could be applied to the 2 acre EDEM farm. The third brainstorming session consisted of listed all ideas under each subsystems and discussing which ones would fit together the best.

2.3 Design Concepts

2.3.1 Well to Pump

The first phase of the design includes the solar pump system that raises water from the well to the storage tank. Based on measurements of the farm, a total height of 130 feet was used in system design. The second constraint, daily flow rate was estimated based on daily hours of sunshine, crop requirements, and interviews with farmers on current water usage. In order to pump 500 gallons per day with 10 hours of sunlight the requisite flow rate is 50 gallons per hour. Surpassing the daily needs by a sufficient margin allows for days with little or no pump operation due to poor solar irradiance.

Figure 15: Shurflo 9325 Submersible Pump.

Based on these constraints, the Shurflo submersible pump (Figure 14) was determined to be the most cost effective solution. Publicly available height and

[13] G. Dieter and L. Schmidt, *Engineering Design, 5th Ed., McGraw-Hill, New York, 2013, pg. 234*

flow rate tables for the pump demonstrated that a 24 volt system with a minimum solar array of 120 watts would be necessary. In order to provide sufficient room for error, a 200 watt solar panel was selected. The purchase of a panel mount will also be required in order to securely position the array at the ideal angle for Haiti of 72 degrees from the horizontal.

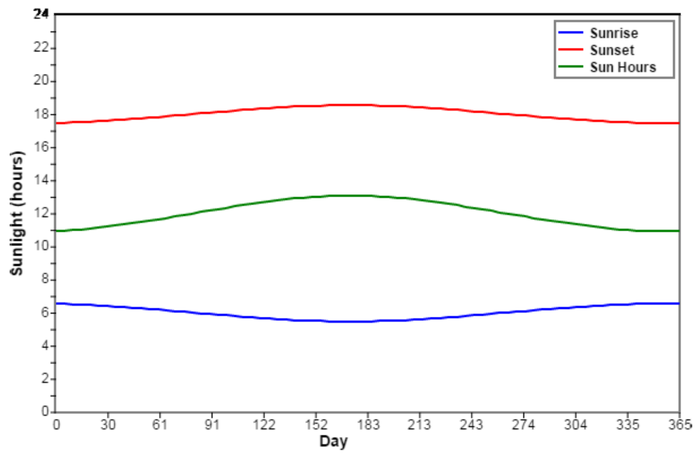

Figure 16: Daily Hours of Sunlight in Haiti.

The above plot (Figure 16) shows daily sunlight hours throughout the year. These values include times just after sunrise and before sunset when solar irradiance is insufficient to activate the pump. To assist with this, a pump controller will be purchased to boost power during these low-light times. In addition, the controller allows for the installation of a float switch, which detects water level in the storage tank and sends signals to the pump to turn on or off accordingly.

2.3.2 Pump to Tank

The next section of the morphology diagram focused on transporting water from the pump to the collection tank tank located on top of the farmhouse. Many types of hoses and pipes were researched but ultimately our options were narrowed to PVC piping, a traditional garden hose, an expandable hose, a vacuum duct hose, and a PVC discharge hose. Examples of each of these can be viewed in Figures 17 through 21 below.

Figures 17 to 21: top left - garden hose, top middle - PVC pipe, top right - vacuum duct hose, bottom left - PVC discharge hose, bottom right - expandable hose.

In order to best meet the customer requirements and our corresponding engineering characteristics, we believe that the expandable hose is the best option for transporting water from the pump to the collection tank. While the garden hose is adjustable to different locations, it can also be very heavy. The PVC piping can only be configured to one system, unless all systems were designed identically. Additionally, the PVC discharge hose appeared to present chances of rupturing if the pressure within it became to high. Ultimately, this led to our selection of the expandable hose as the most viable option for transporting water from the pump to the collection tank.

Not only is the expandable hose lightweight, but it is reinforced with durable fabric built to withstand high pressures as well. It is also lightweight and easily transportable. We believe that it is wise to save both space and weight in as many ways as possible. Finally, it can be purchased in rolls as long as 150 feet for as little as $100.

2.3.3 Transitions

The next section of the morphology diagram is focused on the system transitions. These mainly include the different types of materials used to carry the water to the plants and in between the different subsystems. Between each of the systems there will need to be distribution piping and fittings to connect each length of piping. In order to reduce weight and complexity, PVC piping will be used for the distribution headers, this piping will be slightly larger diameter than the rest so that it can carry a larger flow of water. For valves, mainly ball-valves will be used due to their simple design and resistance to corrosion, they will be a great choice to use in the system. To equip the entire system with the correct valves, it will only cost roughly $150. Below, in Figure 22, is a diagram of the valve that will be used for the system. A “valve-tree” will be used to distribute the water from the tank to the different plots of produce.

Figure 22: Ball-Valve

2.3.4 Tank to Plot

The fourth section of the morphology diagram focused on ensuring that water was properly transported out of the piping and onto the plants. We believe that this could be achieved in one of two ways: using materials designed specifically for this task or with materials that were altered to meet the system’s needs. Examples of each of these can be viewed in Figures 23 through 27 below.

Figures 23 to 27 : top left - garden hose, top middle - PVC pipe, top right - drip irrigation tubing coil, bottom left, PVC discharge hose, bottom right - drip tape.

In the cases of the garden hose, PVC piping, and the PVC discharge hose, these materials were not specifically designed to transport water to crops for irrigation. Although they could be cheaper options, we run the risk of not transporting a sufficient amount of water to the crops and/or damaging the material by altering the structure of the material for irrigation. Because the farm does not consist of a single type of crop, using a universal spacing for holes added to the material may not provide an adequate amount of water the plant could wastewater, or could cause the hole size to increase due to the pressure within the hose. Taking this into consideration, we believed that the garden hose, PVC pipe, and PVC discharge hose ‘do-it-yourself’ options were not ideal. This left the drip irrigation tubing coil and the drip tape that were designed specifically with irrigation in mind. The drip tape seems like the most viable option as it has the ability to efficiently water an entire row, can be secured easily with stakes, and can be purchased in rolls of up to 4000 feet for as low as $460.

2.3.5 Plot to Plant

The final section of the morphology diagram was how to exactly water the plants and what system would be most successful. The four systems that we looked at were Wick Irrigation , Deep Pipe Irrigation, Drip Irrigation System, and Buried Clay Pot Irrigation. All 4 systems are shown in section 1.7.3.

The main aspects that the irrigation system are as follows:

- Inexpensive
- Low maintenance
- Can easily be moved if necessary (a big example of this is Hurricane Mathew. The current method and farm were completely wiped out due to the high winds, rain, and flooding. The system that is chosen needs to be able to be easily moved if necessary)
- Long lasting

With all of this in mind, the below table shows the initial costs of the wick irrigation, buried clay pot irrigation, deep pipe irrigation, and drip irrigation systems. All prices were taken from Home Depot as a general and low cost store.

Table 9: Plant Type with Irrigation System Type and Costs.

System					**Clay Pot Irrigation**	**Wick Irrigation**		**Deep Pipe Irrigation**	**Drip Irrigation**
Type	length/row space= # of rows	Width/ space= # column	# Plant	Length Hose (ft)	Clay Pots = 0.78 $/pot ($)	Wick rope = 0.05 $/m ($)	Bottles= 0.38 $/ bottle ($)	Deep Pipe 1.25 $/m ($) - 1 m/plant	PVC= 1.25 $/m ($)
Beans	107/.75= 142.6	15/0.1= 150	21390	2140	16684.2	107	8128.2	26737.5	2675
Plantain	15/5=3	15/5=3	9	72	7.02	3.6	3.42	11.25	90
Pepper	15/0.9= 16.6	15/0.6= 25	415	400	323.7	20	157.7	518.75	500
Eggplant	15/0.9= 16.6	15/0.2= 75	1245	350	971.1	17.5	473.1	1556.25	437.5
Cabbage	15/0.9= 16.6	15/0.5= 30	498	250	388.44	12.5	189.24	622.5	312.5
Nursery	15x0.5= 30	15/0.5= 30	900	270	702	13.5 Total= $174.10	342 Total= $9,293.66	1125	337.5
1yr cost					Total= $19,100.00	Total= $9,500.00		Total= $30,600.00	Total= $4,400.00
10yr cost					$19,100.00	$94,700.00		$30,600.00	$4,400.00

Maintenance					Yearly	Yearly		Yearly	None

*The number of plants and row lengths are numbers from the UN and FAO for optimal distance between these plants
**For drip irrigation, PVC was used as a general piping system, it is one of the more expensive options, so actual cost may be lower than that projected

The cost of the clay pot irrigation is 4 times more than the drip irrigation. The cost of the deep pipe irrigation is 7 times more than drip irrigation. The cost of the wick irrigation is 2 times more expensive than the drip irrigation per year. Wick irrigation systems have to be changed due to the water bottle being torn or broken as well as the string. This means that over a 10 year period, the wick irrigation is 22 times more expensive than the drip irrigation. Cost wise, the drip irrigation system is the optimal system.

In regards to maintenance, the wick irrigation and clay pot irrigation has to be dug up and moved slightly each year. The plants won't be planted in the exact place as the previous year due to depleted nutrients in the soil in the previous place. Not only would the farmers have to replant their field, they would have to dig up the pots, water bottles, and the pipes; fill in the holes; and dig a new hole to put the systems in that place so that the field still gets watered. The drip irrigation does not have to be moved. The pipes running each row can be moved slightly to adjust for the new placement of the plants. This system can also easily be moved in case of a natural disaster or if it needs to be moved quickly, it can be moved quickly.

The best irrigation system to use for this situation is drip irrigation. This system is cheaper than the other systems explored, can easily be moved, requires very little maintenance, and depending on the hose used, can last for a long time.

Figure 28: Drip Irrigation.

2.4 Summary of Predicted Performance

2.4.1 Prediction of Length of Hose

The length of the hose can largely affect the cost of the piping and help determine the type of hose used. The system that will be used is the drip irrigation system where hose is laid across the rows right next to the plants and a hole in the hose drips water directly to the plant.

In order to decrease the amount of hose used and therefore decreasing the total cost for the project, the following system will be used. The hose will be on the top or half of the rows and be watered for the first half of the watering time. Then the hose will be dragged down to the other row of plants directly below it, moving the entire system should not be hard, it will just take a person on either side of the field to slide the system down.

Below is the first part of the plan where the first half of the rows will be watered for a set amount of time.

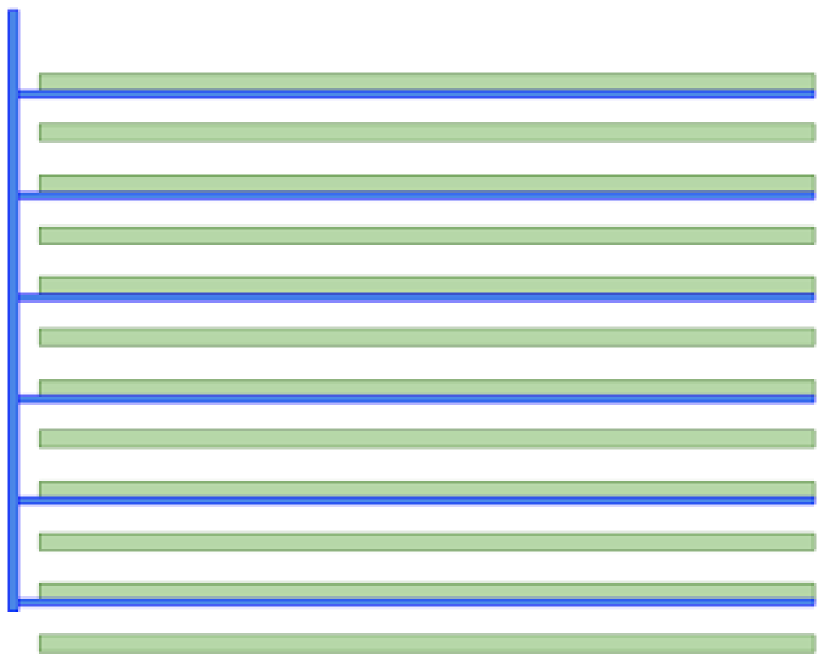

Figure 29: Hose System.

The entire system will then moved down less than a meter down to water the other half of the plants.

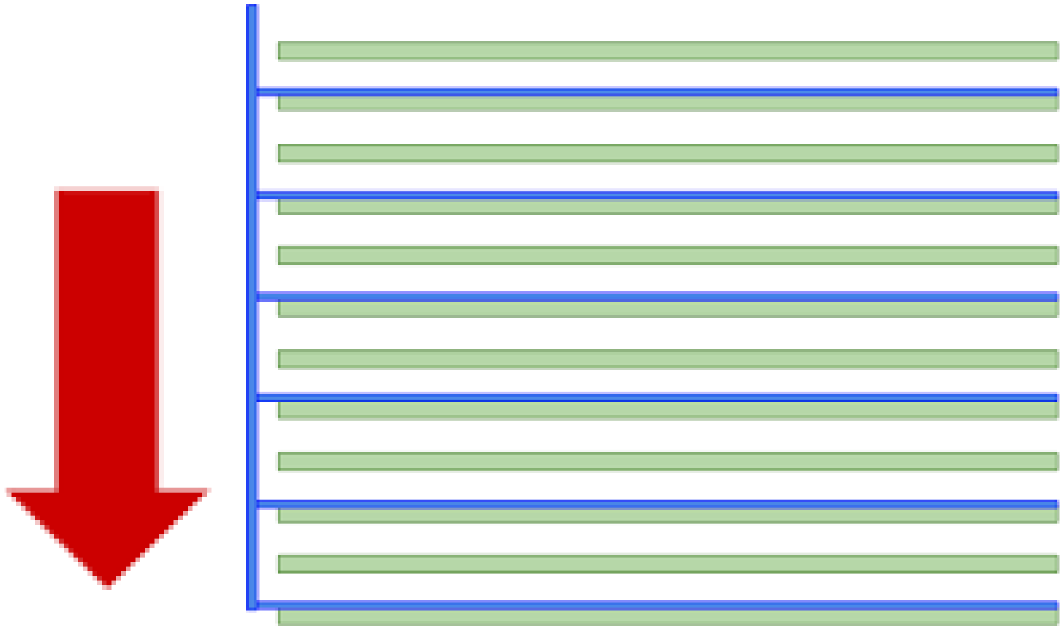

Figure 30: Hose System.

With this system, the length of hose required is decreased by 50%, so the cost is decreased by 50%. The below table shows the length of hose needed. The distance between the plants uses the optimal distance between plants from the UN and FAO.

Table10: Plant Spacing Requirements.

Type	**Area of lot that the plant takes up(m^2)**	**Percentage of farm that plant takes up**	**Optimal Spacing *assumes largest optimal distance**	**Length of Hosing (down every row at optimal spacing) (m) SPLIT IN HALF WITH NEW SYSTEM**
Beans	15x 107= 1626	53%	0.1x0.75	15*(107/0.75)*(½)= 1070
Plantain	15x24= 372	12.1%	5x5	15*(24/5)*(½)= 36
Pepper	15x24= 372	12.1%	0.6x0.9	15*(24/0.9)*(½)= 200
Eggplant	15x21= 325	10.6%	0.2x0.9	15*(21/0.9)*(½)= 175
Cabbage	15x15= 232	7.57%	0.5x0.9	15*(15/0.90)*(½)= 125

Nursery	15x9= 139	4.4%	0.5x0.5	15*(9/0.5)*(½)= 135
***13OCT**	Total Planted Area= 3066 (¾ acre)		Average Optimal Spacing= 0.79 *excluding plantains	1741 meters of hose (5711.5 ft) (Previous number 3482 m)

2.4.2 Prediction of Optimal Watering Amounts

The amount of water delivered to each plant is very important in order to determine pressure needed and clarify what type of hose is ideal in this situation. The numbers used for each plant are the optimal amount for the plant according to the UN and FAO. These numbers do not take into account weather (in the form of rain) or humidity. Even if these numbers were factored into the current calculations, the total amount of water needed to water the entire farm seems to be extremely excessive. We are going to be contacting professionals who will help us clean up these calculations and be able to accurately predict how much total water the farm needs on a daily basis.

Table 11: Plant Spacing and Water Requirements.

Type	Area (m^2)	Optimal Spacing *assumes largest optimal distance	Number of Plants Per Plot	Water Needed (mm/day)	Water Needed Per Plot
Beans	15 x107 =1626	0.1x0.75	15/0.1*107/0.75 =21400	5	0.005*1626 =8130 L
Plantain	15x24 = 372	5x5	15/5*24/5 =14.4	6	0.006*372 =2232 L
Pepper	15x24 = 372	0.6x0.9	15/0.6*24/0.9 =666.7	6	0.006*372 =2232 L
Eggplant	15x21 = 325	0.2x0.9	15/0.2*21/0.9 =1750	5	0.005*325 =1625 L
Cabbage	15x15 = 232	0.5x0.9	15/0.5*15/0.9 =500	3	0.003*232 =696 L
Nursery	15x9 = 139	0.5x0.5	15/0.5*9/0.5 =540	5	0.005*139 =695 L

	Total Planted Area= 3066 (¾ acre)	Average Optimal Spacing= 0.79 *excluding plantains			Total Liters= 15610 L/day

*We do not know what plants are in the nursery, so we choose a generic space between plants = 0.5 x0.5 m

The next table shows the flow rate in order for the entire farm to be watered.

Table 12: Plant/Farm Water Requirements.

Water Requirements	
Liters/day	15610
Liters/min *working 8 hours a day	32.6
Gallons/day	4124
Gallons/hr *working 8 hours a day	515.5
Gallons/min *working 8 hours a day	8.6
Gallons/min *working 10 hours a day	6.9
Gallons/min *working 12 hours a day	5.7

As mentioned before, these numbers seem very off. We will be consulting with professionals who can steer us towards numbers that are accurate and attainable for the farm.

2.4.3 Pump Head Predictions to Achieve Optimal Watering

In order to determine if the pump head provided by the hydrostatic forces in the collection tank is sufficient to supply water to each of the plots, a MATLAB script was written to model the farm layout. This script can be found in Appendix E for reference. The calculations were conducted using several assumptions. First, it was assumed that the entire farm was on level ground rather than sloped. This was considered as the worst-case scenario. Additionally, it was assumed that the farm would be irrigated for 10 hours each day and that only one type of crop would be watered at a time. Finally, it was assumed that all of the crops in each plot would be watered at once, except for the beans, which would be split into 8 sections due to its large plot area. A representation of the piping configuration for the farm layout is provided in Figure 31 below.

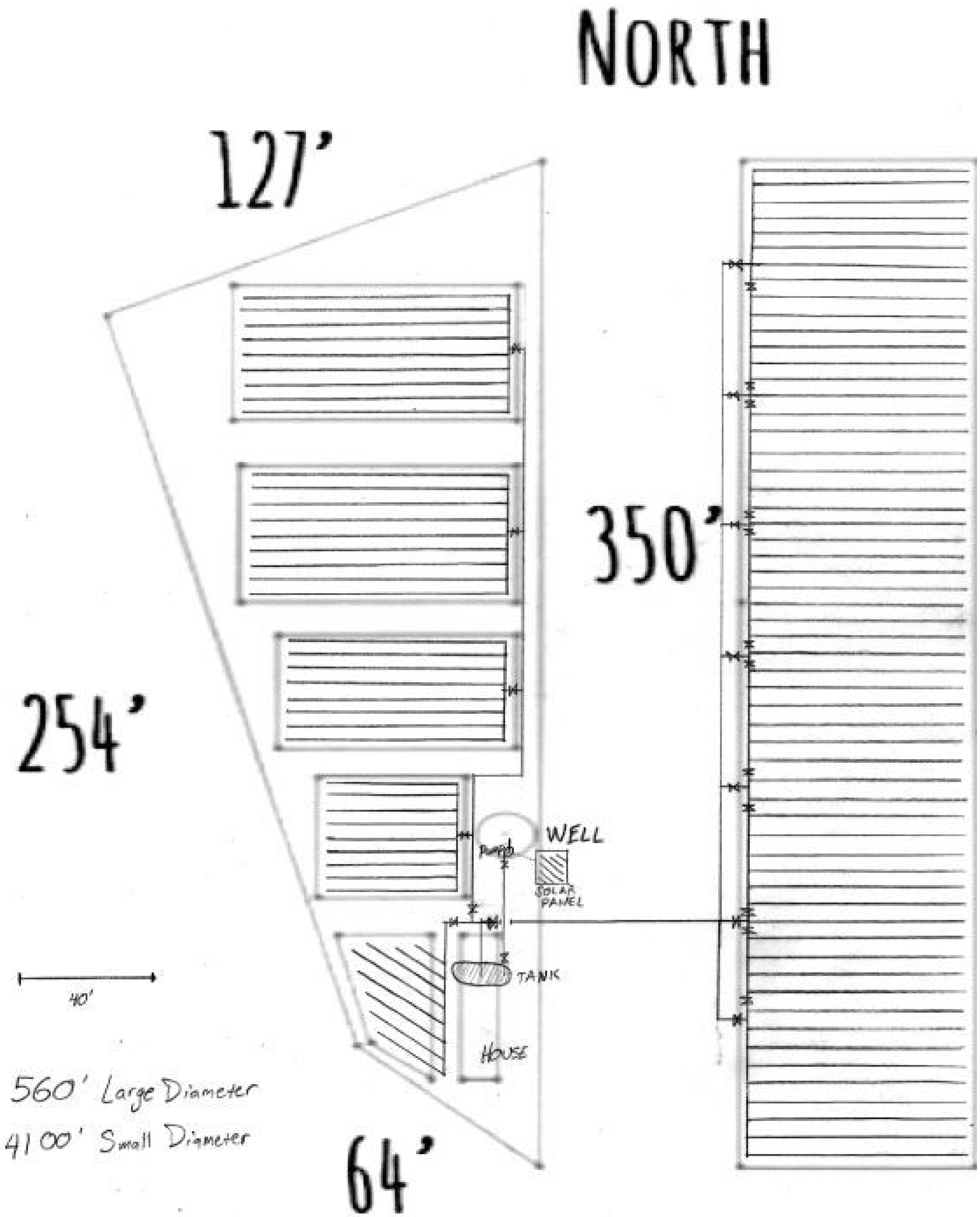

Figure 31: Representation of Piping Configuration for Farm Layout.

Table 13 below provides a summary of the assumptions and the calculated values obtained for each type of crop. Flow rate was calculated using the optimal amount of water provided in section 2.4.2 above.

Table 13: Summary of Values from Pump Head Prediction Calculations.

Plant Type	Number of Sections	Hours per Section	Flow Rate (m^3/s)	Length (m)	Loss Coefficient	Pump Head (m)
Beans	8	0.625	4.51e-4	116	6.85	5.02
Plantains	1	1.5	4.13e-4	85	8.25	3.27
Peppers	1	1.5	4.13e-4	73	8.25	2.84
Eggplant	1	1	4.51e-4	55	8.25	2.58
Cabbage	1	0.5	3.87e-4	30	6.25	1.15
Nursey	1	0.5	3.86e-4	24	5.45	0.92

From the table, it can be seen that the maximum pump head required is 5.02 meters or approximately 16.5 feet and that it is required by the furthest section of the bean plot. This appears to be quite a reasonable value but could require the collection tank to be pressurized a bit, if possible, depending on the height of the tank. These calculations were determined using 1-inch piping.

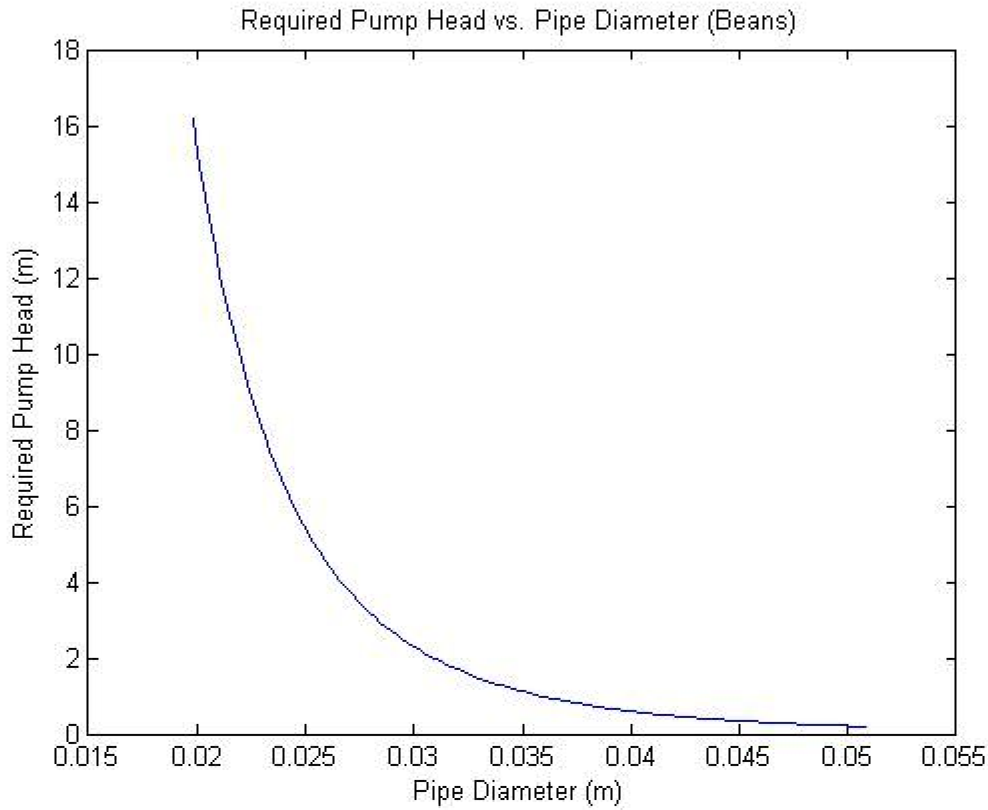

Figure 32: Pump Head as a Function of Pipe Diameter.

Figure 32 above shows that as pipe diameter increases, the required pump head decreases. With this in mind, if the predicted pump heads calculated above are too high, the pipe diameter could be increased to 1.25 or 1.5 inches to lower the required pump head.

2.5 Design Concept Selection

Once all columns in the morphology diagram were completed, the best selection from each column was chosen. Each was chosen from it's ability to fulfill the customer requirements and pass the constraints. The constraints included reconfigurable due to the constant changing of the crops on each plot, water efficient due to the current small tank size (200 gal.) and the single source of water, and transportable due to the lack of materials on the island. All selected ideas are easily bought on the consumer market and can be broken down to transport via ferry to the port on the island. All irrigation systems were chosen with the intent to preserve water through thoughtful placement of the hose and holes. The final design not only incorporates the best ideas from each subsystem, but the best ideas that could be combined to form the most effective overall system. This includes characteristics like cheaper, reusable and reconfigurable, and effective coverage over a 2 acre plot.

2.6 Selected Design

The final selected design is highlighted below in Table 14. Each of the 5 subsystems had a chosen selection as detailed in Section 2.3 of the report. The selections include the Shurflo and AltE pump and solar panel system combination, the expanding and contracting hose for the flow between the pump and the tank, the PVC valve tree to connect the hose and isolate plots, the drip irrigation coil for the plots, and drip irrigation for the type of irrigation. While this design has yet to be tested, the group plans on moving towards small scale testing as their next task to include evaluating flow rates, fitting of various piping sizes, and pump and solar panel performance.

Table 14: The Final Selected Design.

Well to Pump	Pump to Tank	Transition	Transition to Plot	Plot to Plant
pumps and solar panels	*hose type and layout*	*collars, valves, and fittings*	*hose type and layout*	*water distribution to plants*
Advanced Power	PVC	PVC	PVC with holes	Wick Irrigation
Shurflo and AltE	Garden Hose	Rubber transitions	Drip Irrigation Tubing Coil	Deep pipe Irrigation
Solardyne	Expanding/Contracting Hose	PVC Valve Tree	Garden Hose with holes in it	Drip Irrigation System
	Strongway PVC Discharge Hose	adapter add-on	Strongway PVC Discharge Hose	Buried Clay Pot Irrigation
	Vacuum and Duct Hose		Small Diameter Fire Hose with Holes	Sprinkler system
	Flex-Drain Hose		Drip Tape	

3 Project Administration

3.1 Project Management

Listed below is the project plan for the student design team broken down into a month by month basis. The larger areas of concern are the two different possible times to travel to the farm as well as the final dates for submitting the aforementioned deliverables. The initial Fall trip to Ile a Vache has been postponed due to Hurricane Matthew. The Spring trip in March is still being planned and has not been finalized.

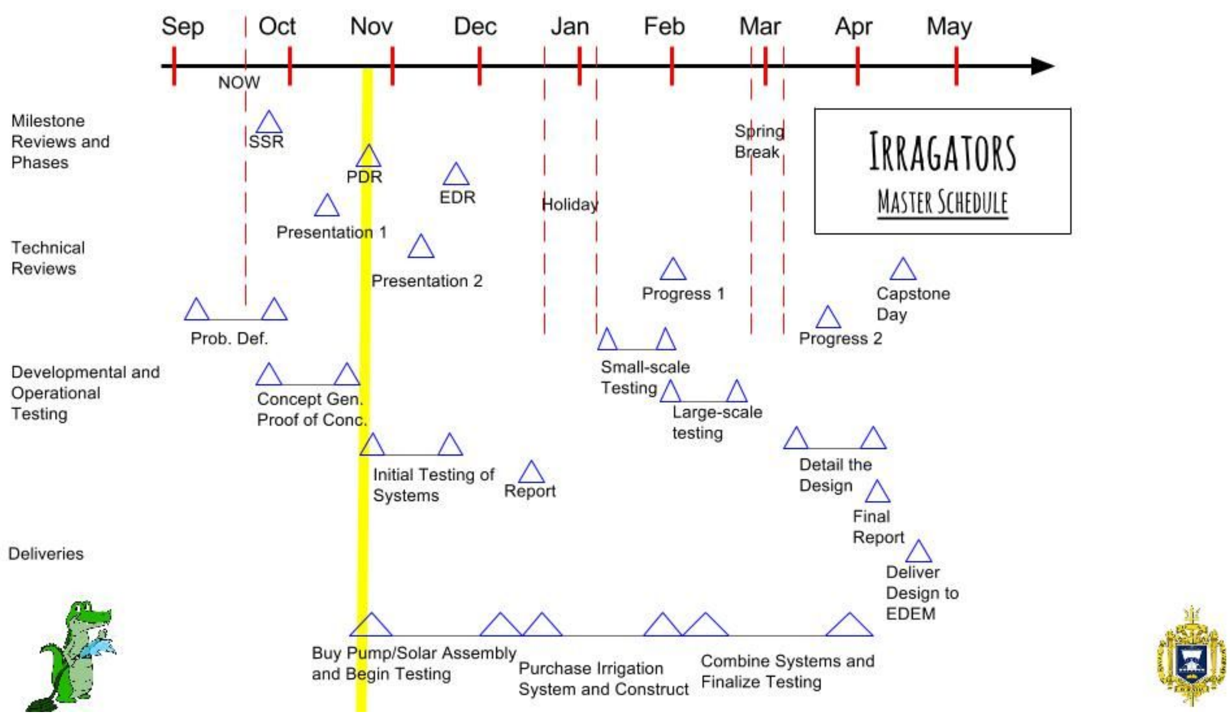

Figure 33: Monthly Plan for Irragators.

3.2 Budget

For total completion of the project, a budget of $9,980 is requested. Travel costs constitute the primary usage of funds, requiring an expected total of $7,500. This includes one trip down to the farm in Haiti for members of the team. This trip will seek to implement and analyze the success of a final system in order to make recommendations at project completion. The Shurflo pump, controller kit, and float switch combine for a cost of $980. A solar panel and mount will cost $450. Installation of a drip irrigation system is estimated to cost the remaining $1,050. Use of existing pipes takes away a significant amount of necessary funds that would otherwise be needed.[14]

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[14] http://www.mcmaster.com/#well-pumps/=145knws

Appendix A - Preliminary Engineering Model of the System

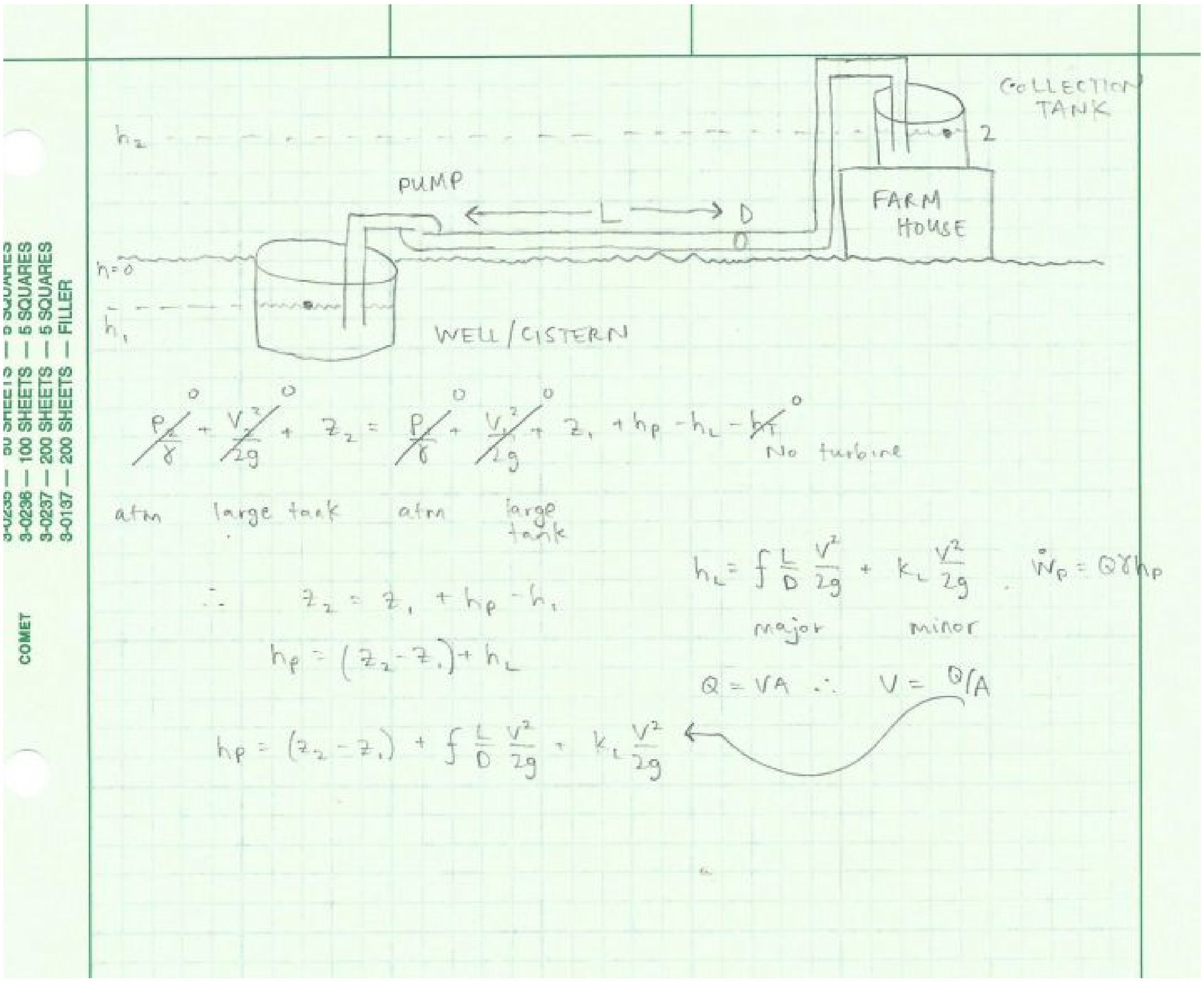


Figure A1: Written Engineering Model.

Appendix B - Agreement of Project Deliverables (Version 1)

Design Project Deliverables
Agreement between
USNA Student Design team (“Irragators”)
and Customers
Version 1

The purpose of this document is to clearly outline the expectations in regard to the separate project deliverables. These deliverables have been decided upon and chosen based on customer preference and need-assessment. The deliverables have been communicated and agreed upon by the student design team, faculty advisors, and project customers. This is by no means intended to be a contractual or legally-binding document.

In general:
We, the students, will work to expend all resources and avenues to produce a product that will efficiently satisfy many if not all of the customer’s requirements.

We, the faculty, will work to aid the students wherever possible. We will help in areas where students lack the technical expertise or are not sufficiently able to acquire necessary resources/products. We will aid in creating timelines to follow and push students to their limit in order to culture a healthy growing environment.

We, the customers, understand that students’ education is the main benefit from the design project. We understand that students will be given a certain range of freedom when making choices pertaining to the design project, some of which may lead to failure.

In detail:
On Capstone Day, Wednesday, April 26, 2017, the team will provide the following:

A Bill of Materials for the customers/clients to purchase in order to accomplish their goals. Drawings and instructions will also be included to advise the customers on how to put together the different pieces of equipment. Lastly, a troubleshooting guide will also be included with any deficiencies found during the students’ testing. Problem solving techniques will be documented during students’ testing period. In the end, the system will be totally disassembled and rebuilt by a third party using only the written directions. This event will allow for any errors/ambiguities to be addressed.

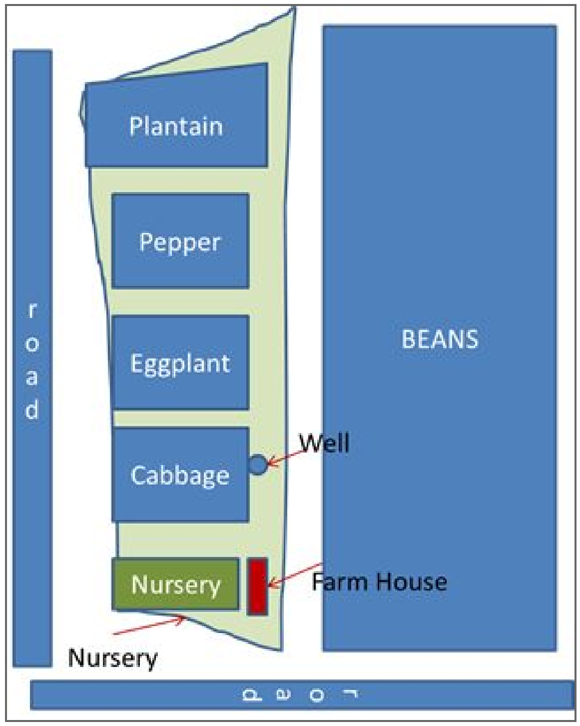


Figure B1: Overhead View of the Farm

Table B1 shows the revised customer requirements and engineering characteristics.

Table B1: Revised Customer Requirements and Engineering Characteristics

Customer Requirements	Engineering Characteristics	Units	Direction of Improvement	Target Values	Rank Order
Efficiently Waters Crops	Volume	gal	↓	4124 gallons	1
Portable	Weight	lbs	↓	800 lbs	2
Easy to Reconfigure	Time	min	↓	4 hours	3
Include a Timer/autonomous	Yes (1) / No (0)	unitless	↑	yes	4
Reduce Time to Water	Operator Man-Hours	hrs	↓	2 hours/day	5

Solar Powered	Minimize Gasoline Use	gal	↓	zero	6
Minimize System Cost	Cost	Haitian Gourde	↓	265,000 (~$4,000)	7

Appendix C- Team Charter

Team Name: The Irragators

Project Description: An irrigation system for the small Haitian island of Ile-a-vache that minimizes power consumption and maximizes efficient water usage.

Goals:
The team goal is to create a successful design layout that can not only benefit the EDEM farm, but also the citizens of Ile a Vache. Additionally, to improve the team's ability to work with each other with the understanding that all have varying approaches to problems.

Contact Information:

Name	**Role**	**Number**	**Room Number**
Kelsey Hastings	Safety Officer	206-455-4757	B3326
Kyle Ritterbeck	TSD Liaison	662-420-3630	B5303
Kevin Saxton	Design Communication Editor	843-367-7005	B5360
Luke Sullivan	Purchaser	781-640-0544	B5303
Rachel Wible	Team Lead	717-676-0791	B3426
LCDR Ethan Lust	Faculty Advisor	757-636-8727	RI114B

Meeting Schedule:
Monday: 1430-1520, RI216
Wednesday: 1430-1520, RI216
Thursday: 1330-1520, RI216

Conflict Resolution Statement:

As a team, communication is vital. Through an open channel to express ideas, concerns, and criticisms, the group will work more cohesively and accomplish more. This will be done through email, personal phones, and google doc weekly assignments. If disagreements were to occur, they will be resolved through discussion with each other. This is aided through fostering an environment where helpful criticism is accepted.

Personal Statements:
"From this project, I hope to gain insight into how to approach a large scale project through smaller achievable checkpoints. Additionally, I hope to develop a more creative approach to problem solving vice only utilizing my classroom knowledge."- Rachel Wible

"While completing this project, I hope to gain a better understanding of how to make multiple pieces and parts work together to produce a favorable outcome for a group of people. I want to develop my ability to integration skills in using different systems/resources to attain a common goal." - Kevin Saxton

"Through this Senior Capstone project, I hope to continue developing my ability to think through a problem when a situation is not ideal. For developing countries such a Haiti, it is crucial for engineers to be able to take the limited or not-so-perfect resources that they are given and be able to develop a solution to the problem." - Kyle Ritterbeck

"Over the course of this project, I look forward to gaining a better understanding of the requisite steps involved with carrying an engineering task through to completion. I hope to build on established research and contribute to the wider conversation on solar driven irrigation systems in developing nations." - Luke Sullivan

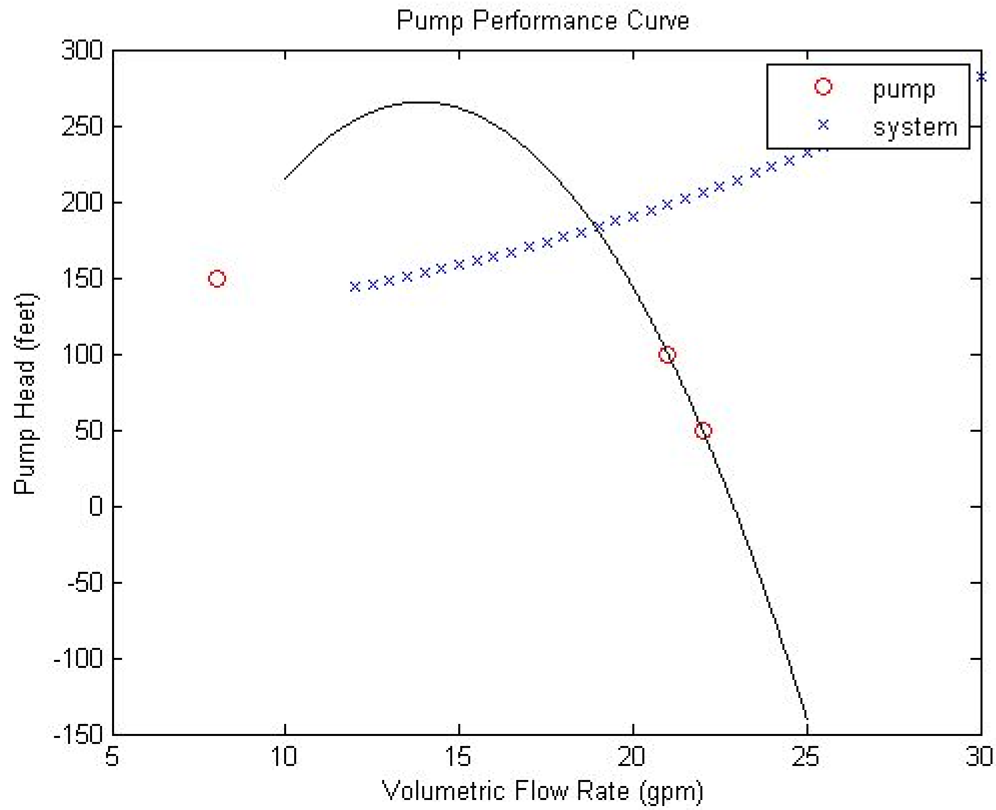
"While working on this capstone, I hope to gain knowledge and understanding on how a real world engineering problem is solved and the steps needed in order to solve the problem. I also hope to learn how to overcome any design or developmental issues involving an engineering project. Finally, I hope to be able to come up with a pump and irrigation system that not only works for our client, but could potentially work for many farmers all over Ile a Vache and Haiti." -Kelsey Hastings

Appendix D - Sample MATLAB Script for Engineering Model

```
clear all
close all
clc

z1 = -100; %depth of water level in well in feet
z2 = 17; %height of water level in collection tank in feet
L = 200; %length of piping in feet
D = 2./12; %diameter of pipe in feet

% assume reentrant in well, 4 90-degree elbows, reentrant in tank, one globe value
kL = 0.8 + 4.*0.3 + 1.0 + 10.0; %minor-loss coefficient

f = 0.02; %Darcy friction factor constant; assume PVC, E = 0, smooth

g = 32.2; %gravity constant in ft/s^2
A = pi.*((D./2).^2); %cross-sectional area of piping in feet
sw = 62.4; %specific weight of water in lbf/ft^3
Q = 12:0.5:30; %gallons per minute
v = Q.*A; %velocity of flowing water

h_p = (z2 - z1) + f.*(L./D)*((v.^2)/2.*g) + kL.*((v.^2)/(2.*g)); %pump head

%create pump-performance curve
%values based on the 1 horsepower 'high-head circulation pump for water' on
%http://www.mcmaster.com/#well-pumps/=145knws
x = [22, 21, 8];
y = [50, 100, 150];
p = polyfit(x,y,2);
xfit=linspace(10,25,1000);
yfit=polyval(p,xfit);
plot(x,y, 'ro');
hold on
plot(Q, h_p, 'bx');
hold on
plot(xfit, yfit, 'k-')
xlabel('Volumetric Flow Rate (gpm)');
ylabel('Pump Head (feet)');
title('Pump Performance Curve');
```

```
legend pump system

%based on plot, assume ideal Q is 19 gpm
Qi = 19*0.002228; %ideal volumetric flow rate in ft^3/s
vi = Qi*A; %ideal velocity of flowing water
%pump head at ideal Q
h_pi = (z2 - z1) + f.*(L./D)*((vi.^2)/2.*g) + kL.*((vi.^2)/(2.*g));

Wp = (Qi.*sw.*h_pi)/550; %required power of pump in horsepower
Wp_kW = Wp*0.7457; %required power of pump in kilowatts
time = 1200/19; %time to fill tank
hours = time/60; %time in hours
kWh = Wp_kW*hours; %required power in kilowatt-hours

fprintf('The power needed to run the pump at 19 ft^3/s is %.3f horsepower.\n', Wp);
fprintf('The power needed to run the pump at 19 ft^3/s is %.3f kW.\n', Wp_kW);
fprintf('The time needed to fill the 1200 gallon collection tanks is %.3f minutes.\n', time);
fprintf('The amount of power required is %.3f kWh.\n', kWh);

%below is a link for a 1 kW solar panel system
%http://www.wholesalesolar.com/1890815/wholesale-solar/complete-systems/1-kw-grid-tied-solar-s
ystem-with-4x-astronergy-260w-panels
```

```
The power needed to run the pump at 19 ft^3/s is 0.562 horsepower.
The power needed to run the pump at 19 ft^3/s is 0.419 kW.
The time needed to fill the 1200 gallon collection tanks is 63.158 minutes.
The amount of power required is 0.441 kWh.
```



Published with MATLAB® R2014a

Appendix E: MATLAB Script for Pump Head Predictions

Beans, 2-inch pipe diameter everywhere

```
clear all
close all
clc

q = (8130/8)/(1000*0.625*3600); %flow rate neceessary for beans in m^3/s over 8 sections and 5
total hours; equates to 0.625 hours/section

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(380, 'ft', 'm');
K = 7*0.7 + 3*0.05 + 1.0 + 0.8;% 7 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Beans, constant pipe diameter\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Velocity = %g m/s is %g meters.\n\n', v(end), h(end));
```

```
figure(1)
plot(v, h)
xlabel('Velocity (m/s)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Beans)')
Beans, constant pipe diameter
Reynolds Number = 20215.1, Friction Factor = 0.0256797, Flow Velocity = 0.891376 m/s
The required pump head for Velocity = 0.891376 m/s is 5.01958 meters.
```

Plantains, 2-inch pipe diameter everywhere

```
q = 2232/(1000*1.5*3600); %flow rate neceessary for plantains in m^3/s over one hour

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(280, 'ft', 'm');
K = 9*0.7 + 3*0.05 + 1.0 + 0.8;% 9 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Plantains\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Flow Velocity = %g m/s is %g meters.\n\n', v(end),
h(end));

figure(2)
plot(v, h)
xlabel('Velocity (m/s)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Plantains)')
Plantains
Reynolds Number = 18499.4, Friction Factor = 0.02626, Flow Velocity = 0.815724 m/s
The required pump head for Flow Velocity = 0.815724 m/s is 3.27221 meters.
```

Pepper, 2-inch pipe diameter everywhere

```
q = 2232/(1000*1.5*3600); %flow rate neceessary for peppers in m^3/s over 1 hour

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(240, 'ft', 'm');
K = 9*0.7 + 3*0.05 + 1.0 + 0.8;% 9 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Peppers\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Flow Velocity = %g m/s is %g meters.\n\n', v(end),
h(end));

figure(3)
plot(v, h)
xlabel('Velocity (m/s)')
```

```
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Peppers)')
Peppers
Reynolds Number = 18499.4, Friction Factor = 0.02626, Flow Velocity = 0.815724 m/s
The required pump head for Flow Velocity = 0.815724 m/s is 2.84472 meters.
```

Eggplant, 2-inch pipe diameter everywhere

```
q = 1625/(1000*1*3600); %flow rate neceessary for eggplant in m^3/s over 1 hour

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(180, 'ft', 'm');
K = 9*0.7 + 3*0.05 + 1.0 + 0.8;% 9 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Eggplant\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Flow Velocity = %g m/s is %g meters.\n\n', v(end),
h(end));

figure(4)
plot(v, h)
xlabel('Velocity (m/s)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Eggplant)')
Eggplant
Reynolds Number = 20202.7, Friction Factor = 0.0256837, Flow Velocity = 0.890827 m/s
The required pump head for Flow Velocity = 0.890827 m/s is 2.57757 meters.
```

Cabbage, 2-inch pipe diameter everywhere

```
q = 696/(1000*0.5*3600); %flow rate neceessary for cabbage in m^3/s over 30 minutes

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(100, 'ft', 'm');
K = 7*0.7 + 3*0.05 + 1.0 + 0.8;% 7 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Cabbage\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Flow Velocity = %g m/s is %g meters.\n\n', v(end),
h(end));

figure(5)
plot(v, h)
xlabel('Velocity (m/s)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Cabbage)')
Cabbage
```

```
Reynolds Number = 17305.9, Friction Factor = 0.0267094, Flow Velocity = 0.763096 m/s
The required pump head for Flow Velocity = 0.763096 m/s is 1.15458 meters.
```

Nursery, 2-inch pipe diameter everywhere

```
q = 695/(1000*0.5*3600); %flow rate neceessary for the nursery in m^3/s over 30 minutes

d = convlength(1, 'in', 'm'); %diameter in meters
a = (pi/4)*(d.^2); %cross-sectional area of piping in m^2
v = linspace(0, q/a, 1000); %get 1000 points of velocity beginning at zero in m/s
L = convlength(80, 'ft', 'm');
K = 5*0.7 + 3*0.05 + 1.0 + 0.8;% 5 elbows, 3 open ball valves, reentrant entry and exit
re = (v*d)/(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Nursery\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Flow Velocity = %g m/s is %g meters.\n\n', v(end),
h(end));

figure(6)
plot(v, h)
xlabel('Velocity (m/s)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Flow Velocity (Nursery)')
Nursery
Reynolds Number = 17281.1, Friction Factor = 0.0267192, Flow Velocity = 0.762 m/s
The required pump head for Flow Velocity = 0.762 m/s is 0.920402 meters.
```

Beans - varying pipe diameter

```
q = 8130/(1000*8*3600); %flow rate neceessary for beans in m^3/s

diam = 0.78:0.01:2; %vary diameter from 0.1 inches to 2 inches in 0.01 inch increments

d = convlength(diam, 'in', 'm'); %diameter in meters
a = (pi./4).*(d.^2); %cross-sectional area of piping in m^2
v = q./a; %get velocity beginning at zero in m/s
L = convlength(380, 'ft', 'm');
K = 7*0.7 + 3*0.05 + 1.0 + 0.8;% 7 elbows, 3 open ball valves, reentrant entry and exit
re = (v.*d)./(1.12e-6); %calculate reynolds number
e = 0; %smooth pipe
f = (1./(-1.8.*log10(((e./d)./(3.7)).^1.11 + (6.9./re)))).^2; %calculate darcy friction factor
h = ((f.*L./d) + K).*(v.^2/(2.*9.81)); %solve for required pump head

fprintf('Beans, changing pipe diameter\n');
fprintf('Reynolds Number = %g, Friction Factor = %g, Flow Velocity = %g m/s\n', re(end),
f(end), v(end));
fprintf('The required pump head for Velocity = %g m/s is %g meters.\n\n', v(end), h(end));

figure(7)
plot(d, h)
xlabel('Pipe Diameter (m)')
ylabel('Required Pump Head (m)')
title('Required Pump Head vs. Pipe Diameter (Beans)')
Beans, changing pipe diameter
Reynolds Number = 6317.23, Friction Factor = 0.0351868, Flow Velocity = 0.139277 m/s
The required pump head for Velocity = 0.139277 m/s is 0.0860915 meters.
```

Appendix F- Jean-Patrick Lucien Q and A

1. Big picture questions:
    a. *Is there a particular farm you'd like us to concentrate on?*
    The EDEM FARM FOR NOW, SOON A CITRUS PLANTATION

    We will consider two farm in our initial phase.
    b. *Is there a particular crop you'd like us to concentrate on? For example, should we focus on developing a system to manage water resources for a plantain tree?*
    Plantain, eggplant, pepper, green peppers, bean, cabbage

    c. What, if anything, currently limits farm production?

    Having a good and somewhat automated water supply and providing some shade to the farm produce during very hot weather.

    d. Is there enough water available to adequately provide for the farm? Are you water limited in some way? If so, how? How do you know?

    We currently have a well and that water is readily available all the time.

2. Irrigation system questions
    a. Can you describe the current irrigation system?
    Irrigation is done using a pumped tied to a 5kw generator. We pump the water up to the 200 gallon water tank installed on top of the farm house about 10 feet high.

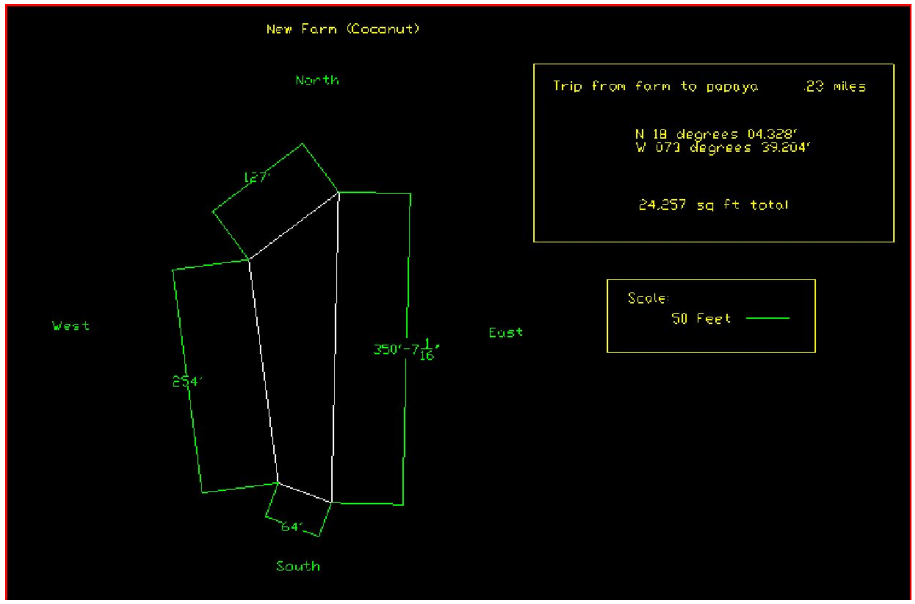
    b. Who designed the current system?
    No design

    c. When was it installed?
    in 2015
    d. Well/cistern

        i. *When was the well dug?* **2015**
        ii. *How deep is it?* **50feet but will dig to 100 feet**
        iii. Do you ever run out of water? **No**
        iv. If so, do you have an idea why? Over-use? Dry season doesn’t replenish the cistern, etc.?

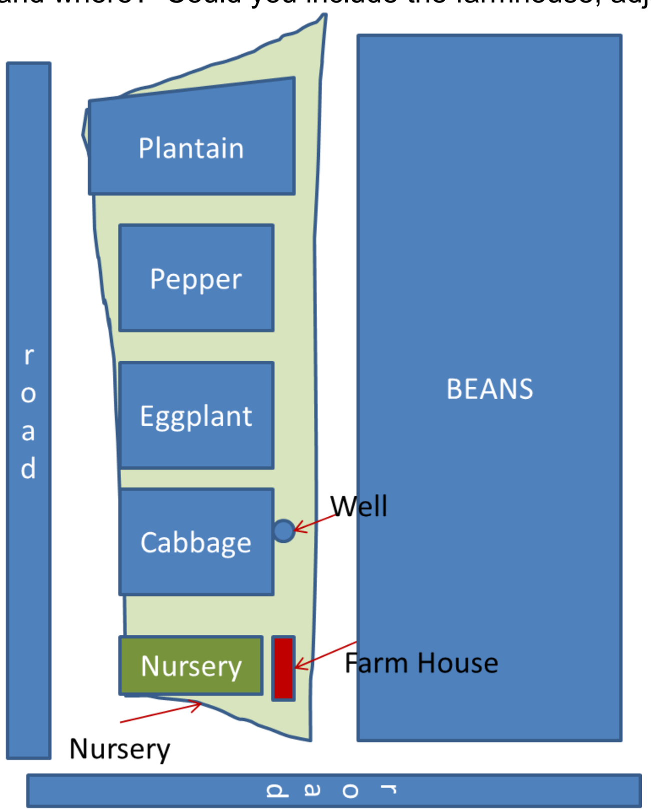
    e. Pump
        i. *What kind of pump is it? Is it located down in the well and pumps the* **Down in the well.**
        ii. Is there more than one pump? **No**
        iii. Do you have spec sheets for it/them*?* ***No, will inquire***
        iv. *Does someone do maintenance on the pump? If so who? When?* **The pump installer, but not specific schedule**
    f. Generator
        i. *What’s the power rating?* **5kw**
        ii. *Is the connection electrical (i.e power output from the generator is connected to the pump motor) or mechanical (i.e. direct drive)?* **Generator, BUT HOPE TO REPLACE WITH SOLAR PUMP**
        iii. About how much gas does it use per hour, day, or week? **1 gallon per week**
        iv. *Where does the gas come from? How does it get to the farm?* **From the town of Madame Bernard**
    g. Pipe
        i. *Approximately how long are all of the pipes you use to irrigate? An estimate would be fine.* **100 Feet**
        ii. *Do you know what the inside diameter of the pipe is?* ***2”***
        iii. *How does the water exit the pipe?* **Drill holes**
        iv.
3. Operations
    a. How big is the farm? Could you mark on Google maps to show where the farm is?

Location: N 18$_0$ 05.947’ , W 073$_0$ 39.093’ Not sure about those numbers



From Massachusettts Maritime Academy

b. Could you provide a quick sketch of the farm(s) showing which crops are grown and where? Could you include the farmhouse, adjacent roads, well, etc.



plantation layout may change at time. Water tank is located top of farm house

c. including an approximate scale? A quick pen and paper drawing would do nicely.

d. What crops do you grow? From the video we saw black beans, green peppers, and eggplants. You mentioned you also grow plantains.
Yes, the plantains recently started

e. How much do you irrigate? How long do you turn on the pump and on what schedule? Every day? Week? Couple of weeks? Month?
Once a day to fill out the water thank as necessary

f. Are some plants irrigated and others not? If so, which ones are watered?
Pepper, Eggplant, Cabbage, Nursery.

g. Do you see a lot of water going where you don't want it? (i.e. wetting the ground between the rows or pooling and running off?
Not really, watering is done mostly by hand

h. Is there a water storage system besides the well? If so, what?
The water tank on top of the farm house. The plan is to install 2 500-gallons water tank and use gravity to setup the irrigation

i. Is the water pumped directly from the well to the plants?

No

j. If possible, could we get pictures of the component parts of the current system?

At the time this picture was taken, water tank was not yet installed on top of the farm house

k. What is the approximate footprint of the farmhouse? I recall it being something like **50' by 10'**
l. Can you describe the soil? Is it sandy? Rocky? Clay-y? Chalky? I recall it being made up of more sand than clay.
   Not sure, see picture