Urban Farming Interdisciplinary

Major Qualifying Project

By Sophia Brennan, Brendan Cicione, Nathan Fankhanel, Joseph Kirsh,

Douglas Koethe, Jasmin Sanchez, Mathew Siu, and Jax Sprague

Abstract

Flats Mentor Farm (FMF) currently irrigates 4 acres of farmland by pumping well water to holding tanks, from which farmers must fill buckets and carry some distance to their plots to manually water their crops. The project team, in conjunction with representatives from FMF, developed and proposed alternative irrigation methods to replace the existing system, considering various irrigators, filtration systems, and pump designs, and eventually deciding on a MegaNet sprinkler system driven by a gasoline-powered pump, connected with layflat line and PVC connections. To simulate the system, the project team built a small-scale prototype simulating irrigation for a 25' by 25' plot using a 0.5 hp pump. Difficulties in layflat line and slip-on PVC connections prevented the prototype from reaching the desired pressure (35 psi). Nevertheless, the irrigation system prototype demonstrated proper MegaNet sprinkler function at low pressure (6 psi). Prototype irrigation system function, despite a proportionally weaker prototyping pump, also suggests proper pump function in the full-scale design.

Acknowledgements

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Additionally, the project group would like to express gratitude toward those from Flats Mentor Farm who collaborated with them to create a successful system, including Jessy Gill and Maria Moreira. Jessy and Maria had taken the time to meet with us and confirm details of their farm, which the project group were limited to because of COVID-19 restrictions.

Executive Summary

The main goal of this project was to create an irrigation system for a 4 acre area of Flats Mentor Farm. This area was divided into eight segments containing 25’ x 50’ plots from different farmers. Additionally, this area of land was far away from the primary water source utilized on the farm. With these factors considered, the MQP team designed an irrigation system that both satisfied the farm’s needs.

After proposing several types of irrigation methods to Flats Mentor Farm, it was decided that a sprinkler irrigation system would best suit the farm’s needs. A sprinkler irrigation system is an easier method for farmers to irrigate their individual plots regularly, replacing the need to carry buckets of water hundreds of feet from the holding tanks. Also, since the pump will be transferring water from the river instead of a well, there is an abundance of water available for regular use. The project group had confirmed that the pump available at the farm will adequately support a sprinkler irrigation system spanning more than 3,300 feet using various piping materials, such as aluminum and layflat.

The team calculated the piping and pump requirements, head loss, volumetric flow rate, and dimensions of the required parts to design a sprinkler irrigation system using real-world parts, including MegaNet sprinklers, FlexNet lines, aluminum piping, and camlock connections. When operating at full capacity, a MegaNet sprinkler has a 46-foot spray diameter covering approximately half of each adjacent 25’ x 50’ family plot. The FlexNet lines have sprinklers placed every 24 feet, and this piping attaches to the aluminum via camlocks, clamps, bushings, and tees.

The project group ordered irrigation supplies that would support one 25’ x 50’ plot. With these materials, the project group designed and constructed a prototype to gain hands-on experience, test the pressure drop of the system, and confirm its efficiency.

The prototype design was successfully able to transfer water through the system to operate the MegaNet sprinkle using one 0.5 hp pump. The pump pressure output was measured at 40 psi and the pressure gauge at the end of the system was measured at about 6 psi; therefore, the pressure change was about 34 psi. This high pressure drop value was likely a result of leakage throughout the system. The layflat lines were also freshly unwrapped and had not opened entirely, thus they did not expand to their rated diameter and prevented water from flowing through.

The prototype was greatly limited due to using PVC pipes instead of aluminum, creating makeshift connections in place of welded parts, and insufficient drying time for the liquid Teflon sealant. For these reasons, the prototype had trouble staying together; however, it demonstrated that the system could operate at 6 psi compared to the optimal working pressure of 26 psi. Some recommendations for reducing the change in pressure are to secure the fittings with liquid Teflon and allowing 24 hours to dry before using it. Also, additional clamps could be added to the camlock connections. The connections need to have compatible threads and properly tightened fittings to reduce leakage.

Overall, the prototype was successful since the MegaNet sprinkler was operational. The team recorded experimental data from which they performed calculations to include in a publicly published technical report. Since the farm would have extra land that the proposed system would not cover, the team created a mini guide that described how the farmers could design and implement a sprinkler irrigation system to cover their plots of land.

Authorship

Sections	Primary Authors
Client Statement	Jasmin & Jax
World Farmers	Douglas
World Farmers' Mission	Jax
Purpose of This Project	Jax
Objectives of this Study	Together
Irrigation Systems	Douglas & Jax
Water Source and Distribution	Jax
Shallow Wells	Joseph
Power	Mathew
Pumps	Jasmin
Filtration System	Mathew
Piping	Sophia & Jasmin
Water Hammer Effect	Jax
Farming in Massachusetts	Sophia
Irrigation on Massachusetts Farms	Sophia
Irrigation System Standards	Joseph
Functional Requirements	Brendan & Jax
Axiomatic Design	Brendan & Jax
Optimization	Douglas & Joseph
Required Irrigation Rate	Jax
Pump Requirements	Jasmin
Piping Requirements	Sophia, Douglas, & Jasmin
Failure Analysis	Douglas
Cavitation & NPSH	Mathew

Design Iterations	Together
The MQP Team's First Design	Brendan
Brookdale Fruit Farm's First Design	Together
Brookdale Fruit Farm's Updated Design	Nathan
MegaNet Water Output	Joseph
Design Efficacy	Jasmin
Pressure Loss Over Entire System	Sophia
Total Flow Rate Following the Sprinkler	Brendan
Mini Guide for Farmers	Jasmin & Jax
MegaNet Water Output (Results)	Jax
Design Efficiency (Results)	Jasmin
Pressure Loss Over the System (Results)	Together
Total Flow Rate Following the Sprinkler (Results)	Jax
Prototype Recommendations	Brendan
Design Calculations	Jasmin
Engineering Ethics	Jax
Societal and Global Impact	Joseph and Douglas
Environmental Impact	Mathew
Codes and Standards	Brendan
Economic Impact	Douglas
Conclusion	Jasmin & Jax
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1. Introduction

1.1 Client Statement

The Major Qualifying Project (MQP) group received the following statement from the project sponsor, World Farmers: “World Farmers offer mentoring, training, and hands-on assistance when working with each farmer to build the capacity needed to operate individual farming enterprises. We enact our mission through various initiatives, the most prominent of which is the Flats Mentor Farm program. Since 1984, Flats Mentor Farm in Lancaster, Massachusetts has provided the space and infrastructure for small immigrant and refugee farmers to get started. The farmers at Flats Mentor Farm produce over 55 acres of ethnic specialty crops.

The objective of this project is to build an irrigation system for the small scale farmers in a 4 acre segment of the overall farm. The irrigation system would pump water from a nearby river to a water storage tank, and would deliver water at consistent rates to the farmers. Ideally, the irrigation system would be powered from a renewable source such as solar radiation.”

1.2 World Farmers

Flats Mentor Farm is a 70 acre river bottom parcel of land in Lancaster, Massachusetts. The farm hires and supports small-scale farmers who came to the United States from around the world by allowing them to use the land and providing them marketing assistance. Flats Mentor Farm employs a manager and a sustainability coordinator to ensure that the farmers can access all the available resources (World Farmers, n.d.c).

1.2.1 World Farmers’ Mission

World Farmers creates jobs for refugees and immigrants with agrarian backgrounds, providing sustainable agricultural production and marketing practice experiences. They connect the farmers to retail, wholesale, and farmers' markets in New England, allowing them to preserve their cultural identity while making a living in the United States (World Farmers, n.d.b).

To further assimilate the farmers to the New England lifestyle, the World Farmers' Mentoring Program trains them in agricultural production, marketing, and business development. The program is done in a respectful environment, facilitating cross-cultural learning between the farmers, the staff, and the volunteers (World Farmers, n.d.b).

At Flats Mentor Farm, the farmers grow over 70 different crops, including traditional East African and South Asian vegetables (World Farmers, n.d.a). Seeing as the native climates of these crops differ significantly from Northeast America, the organization trains the farmers in region-appropriate growing practices (World Farmers, n.d.b).

1.3 Purpose of This Project

The purpose of this project is to design an irrigation system for World Farmers that can satisfy the watering needs of a 4 acre segment of Flats Mentor Farm. Previously, the farm did not have an irrigation system that could provide water to the plots on the far east side. By using a pump to direct water from the Nashua River to one or more hydrants, a piping and watering system could transfer water directly to the crops.

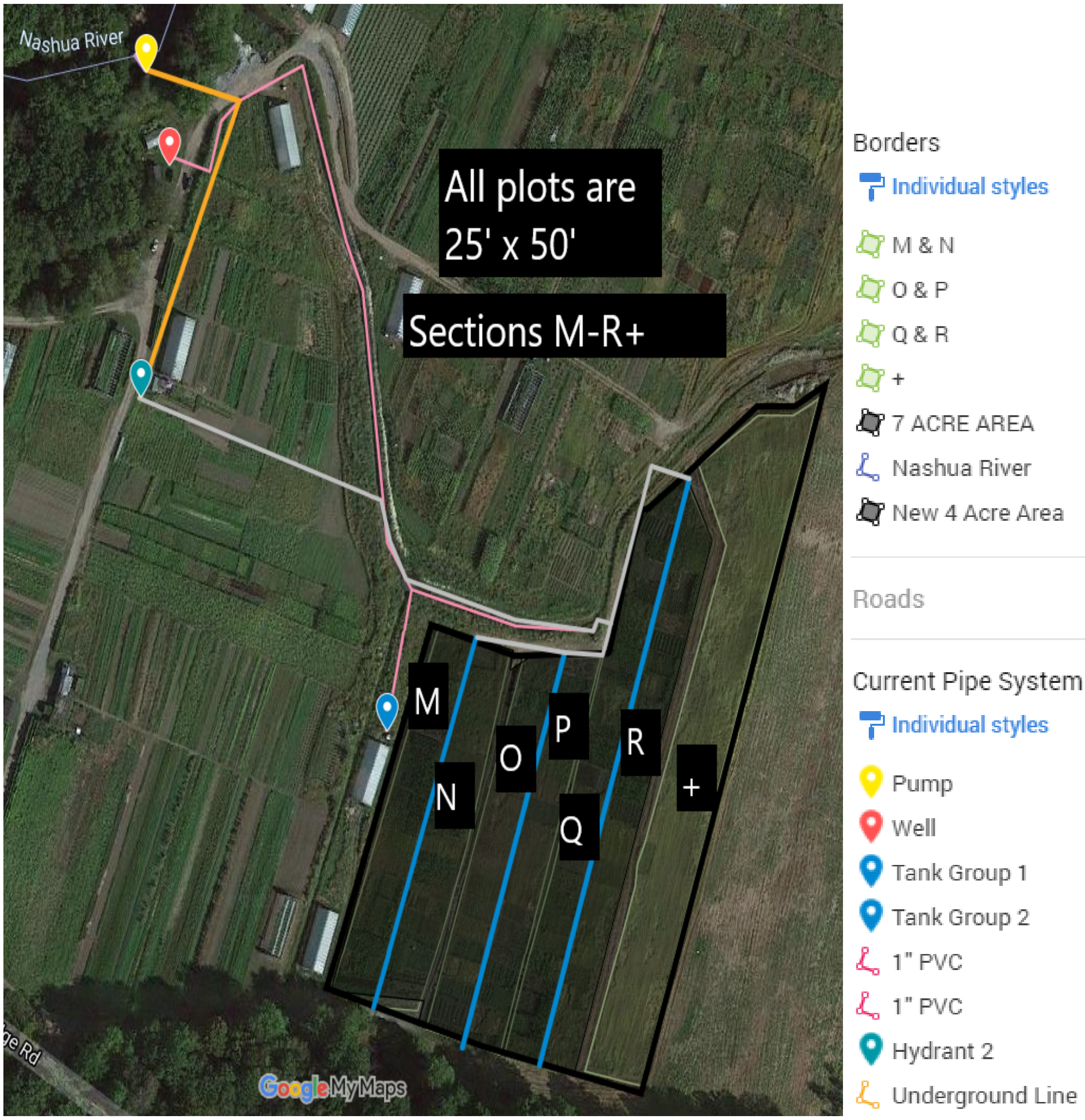


Figure 1: The map shows the proximity of the farm to the Nashua River as well as the sections comprising the 4-acre area, outlined in lime green and labeled M, N, O, P, Q and R. The thick black outline includes Plot + and is a total of 7 acres.

The aforementioned 4 acre section of Flats Mentor Farm has two large holding tanks, one with a 1,500-gallon capacity and the other with 1,000. This farm section also has three 270-gallon Intermediate Bulk Container (IBC) tanks. The section is divided into seven segments:

M, N, O, P, Q, R, and +. There are 130 family plots, each 25’ x 50’ in size. Between N and O, P and Q, and R and + are 10-foot segments of service road (Figure 1). Water comes from a well and travels to the holding tanks with 1” PVC lines. The only power source is a diesel generator. The farm also has hydrants which may be used as a secondary water source. The hydrants connect the pump to the piping to transport the water from the river to the crops. The placement of these features is shown in Figure 1. Farmers have to walk across the property to the holding tanks and carry water to their crops in buckets. This process is tedious and strenuous, especially since many of the farmers are senior citizens.

Much of the watering depends on rainfall. During drought years, World Farmers utilizes a 3” aluminum surface irrigation system to transport water from the Nashua River to the plots. This system differs from the holding tanks in that the tanks are filled with well water and used year-round for manual irrigation while the surface irrigation takes water directly from the river and is used in emergency situations. They have found issues with farmers running over these pipes, so they only use them when necessary.

By designing a new irrigation system for Flats Mentor Farm, the MQP team will help the farmers water their crops more efficiently. Instead of carrying buckets back to their plots, they can have their crops watered automatically. With a sprinkler irrigation system, the water will travel from the river to the farm, watering a wide area of crops quickly without requiring the farmers to plant their crops in specific spots.

The goal of this project is to work with World Farmers at Flats Mentor Farm to design a cost-effective irrigation system that spans across the 4 acre farm section and irrigates the 130 25’ x 50’ family farm plots in the seven segments.

After selecting the most appropriate materials and components, the MQP team built a working prototype large enough to supply the watering needs of one family farm (25' x 50'). From there, World Farmers could gather the funding necessary to scale the project up to fulfill the needs of Flats Mentor Farm. The MQP team conducted research and performed experiments to optimize the system design over the given land area using a combination of equipment provided by Worcester Polytechnic Institute and parts purchased from vendors like Brookdale Fruit Farm and Home Depot.

1.3.1 Objectives of this Study

1. Determining the functional requirements for a farm irrigation system.
2. Designing an irrigation system for a seven acre segment of Flats Mentor Farm.
3. Building a smaller scale design and prototype that supports one 25'x25' family farm.

2. Background

2.1 Irrigation Systems

When cultivating crops, many farmers turn to irrigation to meet their water needs. Irrigation is the process of artificially applying water to crops to fulfill their requirements. It can also add nutrients to the artificial water supply for additional benefits. Irrigation ensures that plants receive the necessary water for proper growth, development, and seed germination (Byju, n.d.).

Typical water sources for irrigation include wells, ponds, canals, lakes, and storage tanks. Water is pumped from the source to the crops using piping and some form of emitter, the type depending on the chosen irrigation method. Each crop has different requirements for frequency, time, flow rate, and quantity of water. These factors also depend on the soil type and quality, geographical region, and season (Byju, n.d.).

2.1.1 Types of Irrigation Systems

Figure 2: A channel-based surface irrigation system that distributes water by having it travel from a higher elevation to a lower one (Jamal, 2017b).

There are multiple types of irrigation systems. The first to be discussed is surface irrigation, which involves water distribution through a field using gravitational flow (Figure 2). Soil stores the water in the channels and helps distribute it. It has three stages: Advance, Storage, and Recession. Advance is when the water moves down the soil channel, Storage is when the water ponds at the bottom until it reaches the required depth, and Recession is when the water drains. The main advantage of this type of irrigation is that it is easy to use and requires little capital investment. Because it uses gravity to move the water, it also has a small energy requirement. However, it varies in availability depending on the soil's elevation, and it is not very efficient. It also requires significant labor to set up, and poor choices can result in the crops not receiving enough water (Jamal, 2017b).

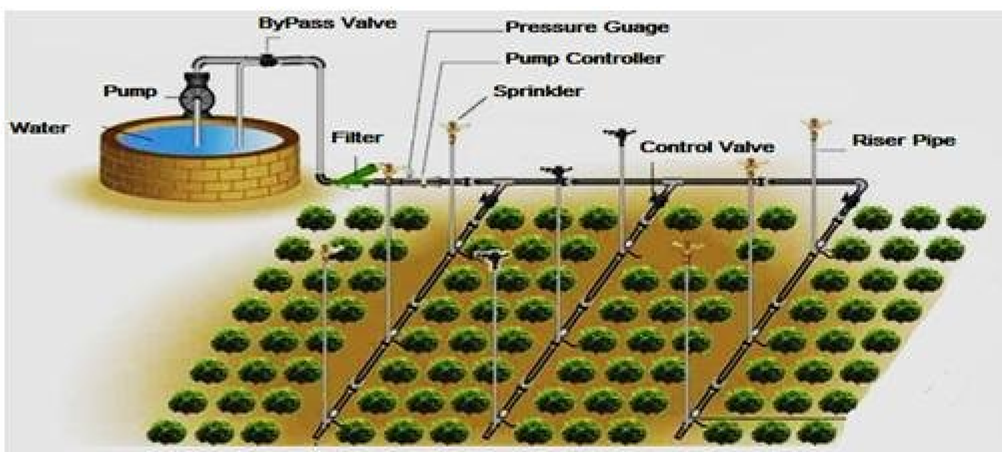


Figure 3: A sprinkler irrigation system drawing water from a well (El-Shimy & Abdo, 2017).

Another type is sprinkler irrigation, which is when sprinklers water the land in a rain-like manner (Figure 3). The water is distributed through pipes using a pump, and it is sprayed through the air by sprinklers causing it to break apart. This breakage creates an effect similar to rain. Usually, the wetting pattern for the sprinklers is circular, but it is not uniform. Sprinkler irrigation is suitable for most crops, but it can damage crops with delicate leaves like lettuce. One advantage is that it reduces soil compaction and prevents major damage from the frost. Furthermore, it requires very little work to upkeep after its initial installation. However, it requires a relatively high upfront cost, and it is fairly inefficient because of evaporation. Additionally, the sprinkler pattern can be blown away by the wind, making it vulnerable to the weather. As such, it works best for small backyard gardens (Velez, 2017).

Different types of sprinklers can be used with sprinkler irrigation. One such type are mini gun sprinklers which are portable and can be easily automated. They cover a large area and release water at a high pressure. However, they are typically sold at a high price point compared to other sprinkler emitters. Another kind is the solid set sprinkler, which is immobile and applicable over large areas. They have a relatively low operational pressure and volumetric flow rate, and they require a lot of maintenance (Byelich, Cook, & Rowley, 2013).

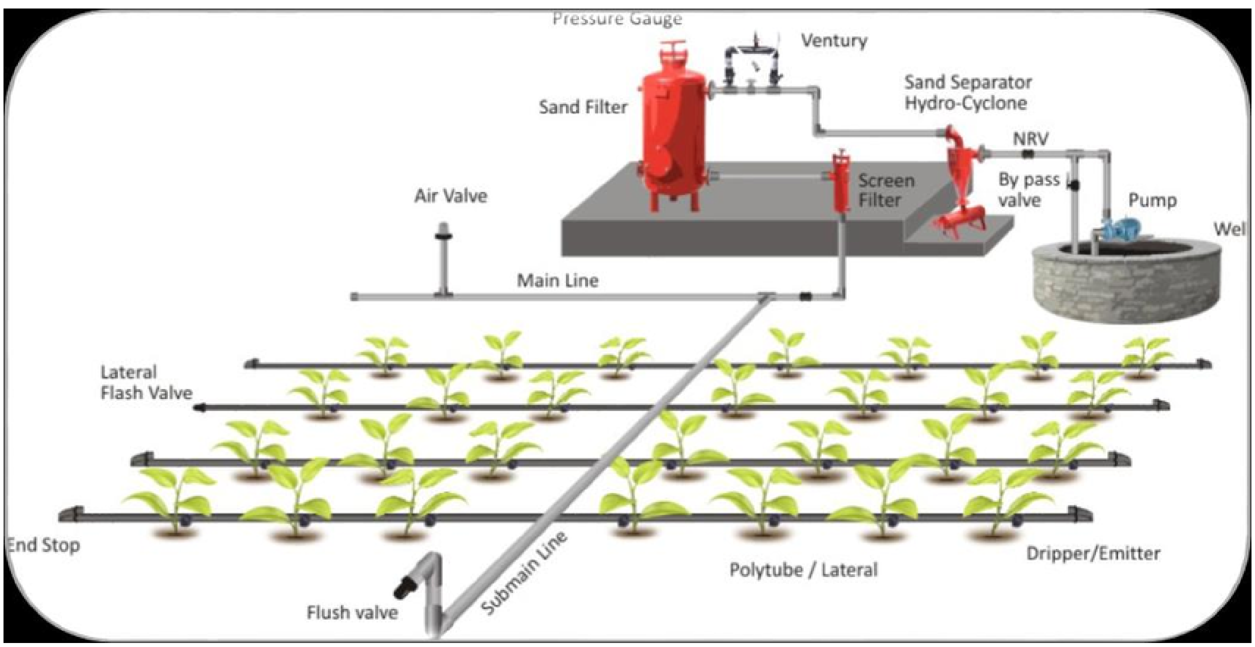


Figure 4: A diagram of a drip irrigation system (Jha, Mali, & Naik, 2015).

Drip irrigation is another form of irrigation that works best for organized rows of crops (Figure 4). It involves installing pipes right above each row and poking holes in them to allow the water to “drip” into the soil, letting the plant absorb the moisture. It can be controlled manually or with a timer and is one of the most efficient irrigation methods in terms of water cost. Because the water drips at soil level to only the desired crops, drip irrigation prevents the growth of nearby weeds and water wastage from evaporation or wind. However, it is difficult to install, and can lead to roots dying if installed improperly (e.g. overly wide emitter placement). It also has minuscule openings, meaning it can clog up and require drainage. It isn’t good for sprawling crop areas either, since the piping should be straight, and it covers a tiny region. However, as long as one is attentive to its installation and upkeep, drip irrigation works well (SF Gate, 2020; “The Pros and Cons of Drip Irrigation,” n.d.).

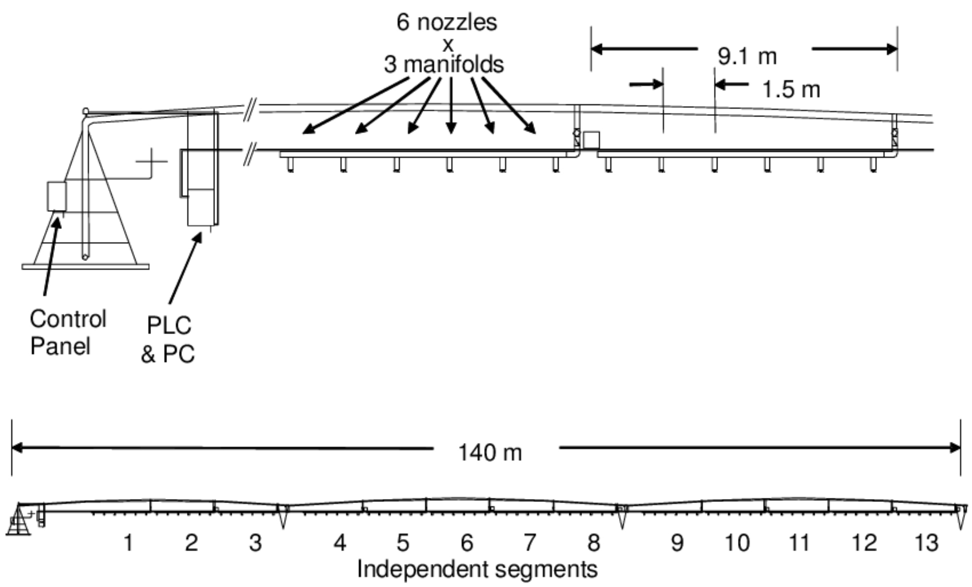


Figure 5: A profile schematic of a pivot irrigation system with 13 segments, with each segment applying 12.5 mm of water at 50% travel velocity (Stone, Sadler, Millen, Evans, Camp, 2006).

Another kind is center pivot irrigation, in which a pivot lies in the center of equipment with attached sprinklers that water crops (Figure 5). It covers a wide circular area called a crop circle, and it uses water efficiently, causing little runoff. It works best on bigger farmlands and has a low labor cost. However, the equipment requires upkeep and can permanently deplete groundwater supplies, damaging soil composition in the long run (UN Food and Agriculture Association, 2007).

Figure 6: A woman manually irrigating her crop with a bucket (Ronzio, 2012).

The most labor-intensive method is manual irrigation, which involves carrying a water source to the crop (Figure 6). Flats Mentor Farm utilizes manual irrigation, and it is the MQP team's job to design a more suitable system for the farmers' needs. While manual irrigation allows one to choose exactly how much water they want each crop to receive, it is also very time-consuming and laborious (Kankam, 2017). By watering crops manually with buckets, the farmers use less water than they would with an irrigation system. Unless the farmers carefully transport the buckets to their plots, they will likely spill some, which may lead to water wastage while still not thoroughly watering their crops (Kankam, 2017).

Figure 7: A raingun used for water gun irrigation (Indiamart, n.d.).

One other type is raingun irrigation, also known as water gun (Figure 7). This micro-irrigation system has a high-performance value, covering an extended water radius with a high volume flow of water. Many raingun irrigation systems have adjustable jet breakers and interchangeable nozzles that one to control the droplet size to water more delicate crops. This feature helps with evenly watering crops. These systems have fewer components than others, lessening the maintenance requirements (“The Complete Guide to the Raingun,” n.d.).

Compared to drip irrigation, raingun irrigation has a lower cost, has no clogging problems irrespective of water quality, works well with all crop orientations, and needs less maintenance. Raingun irrigation generally saves labor, money, and electricity costs, allowing for a wider irrigation coverage, adds nitrogen to the soil, washes away pests, and facilitates the fertilization process (“Rain Gun Irrigation System for Agriculture,” 2019).

Water gun irrigation is energy-efficient, durable, inexpensive, and allows for control if it has interchangeable nozzles. It is easy to operate and maintain, and the large land mass covered allows one to install fewer units. However, it does not sprinkle uniformly without extensive control over the nozzles, speeds, and pressure. Also, it is susceptible to evaporation and can be thrown off the trajectory by wind. The initial cost of the gun can be high, and if it breaks, a professional needs to repair it (Titus & Pereira, 2008). For Flats Mentor Farm, a water gun or sprinkler irrigation system would allow the farmers to plant their crops as they please and have a decent stream of water.

2.1.1 Water Source and Distribution

There are three types of water sources available for irrigation: surface, ground, and public water. For this project, the MQP team accessed surface water from the Nashua River. When using a river as a water source, the state of Massachusetts requires the filing of a permit with the Department of Environmental Protection if one takes more than 100,000 gallons of water per day for three consecutive months or 9 million unregistered gallons over three months (University of Massachusetts Amherst, 2020). There are other considerations to keep in mind when pumping from a river. The pumping should not directly affect fish downstream from the site. The best time to pump the water is during high flow to avoid disturbing the ecosystem (Broz, Milholin, & Zulovich, 2017).

Since the river is far from the farm and about one to two feet lower in elevation, the farm needs a powerful pump to transfer water to the crops (Jamal, 2017a). If the pump at the farm cannot transfer water to the far east side of the farm, an alternative option would be to pump river water to holding tanks next to the river. A second pump can then be used to move water to the farm plots. However, rather than using a second pump, the tanks could potentially be raised high enough on a concrete foundation to allow gravity to transport the water to the crops.

The total water capacity of the tanks located at the Flats Mentor Farm is approximately 3,310 gallons. According to World Farmers, these tanks are able to provide enough water for at least one day of irrigation. The limiting factor of the irrigation needs at the farm would be the volumetric capacity of the tanks. These tanks have a relatively small total volumetric capacity, so they would need frequent refilling from the primary river pump. If tanks are not used, the limiting factor may be the amount of diesel generator fuel that the farm is willing to use in one day. (See Appendix A for pump related calculations).

2.1.1.1 Shallow Wells

An alternative water source for the irrigation system considered was a shallow well. A shallow well is a type of well that derives water from the uppermost saturated aquifer in a specific location. The aquifer's relatively lesser depth means a less powerful pump is required to bring up the water, making shallow wells less costly than deeper wells. This reduced depth also means less filtration by the soil above, so the aquifer is more likely to be contaminated by surface water. Furthermore, the aquifers utilized by shallow wells are more likely to dry up during periods of drought (Environmental Protection Agency, 2019).

There are two primary types of shallow wells: driven and dug. Driven wells require driving a pipe into the ground. They are typically used to reach aquifers 30 to 50 ft below the surface. They are cased continuously, which helps to mitigate contamination of the water compared to dug wells. Dug, or bored, wells are large diameter holes dug into the ground via shovel or backhoe, and they are cased with stone or brick to prevent collapse. This casing is not continuous, so these wells have a greater risk of contamination than driven wells, although they are cheaper to make (About Shallow Wells, 2016).

The MQP team considered creating a shallow well for the area of interest on the farm to reduce the water source's distance from the tanks, reducing piping material and costs. The farm regularly tests the local water and has not run into contamination issues, so one of the most significant disadvantages of a shallow well would not apply.

Ultimately, the MQP team dropped the construction plan for a shallow well. The primary reason was that the river should provide all the water necessary for irrigation. The farm was most concerned with reducing the farmers' distance traveled to retrieve water, not lessening the distance to the water source. Another issue with the shallow well was that it would run the risk of drying up during a drought, whereas the river would still provide the necessary water.

2.1.2 Power

Irrigation systems require a power source for pumps to operate. These can be one of three types: gasoline or diesel generators, electric power, or solar-power photovoltaic cell (PV) systems. Each power source type has its benefits and drawbacks.

Conventional gasoline generators use an internal combustion engine to drive the irrigation pump impeller. These generators are coupled to pumps by direct mounting, drive belts, or driveshafts (Yiasoumi, n.d.). They have a high fuel efficiency and are readily available and reparable. Gasoline generators have a lower startup cost than PV systems, but they require continuous fuel and routine maintenance to function.

Solar-powered systems use a photovoltaic cell to store energy in a battery, which powers an electric pump. Solar-powered pump systems require other components to function, including:

- A **solar charge controller** to control battery charging and discharge,
- **Cables** to connect components,
- A **water pump timer** to control the pump operation.

Combined with the panel cost, these added components make solar-powered pump systems more expensive than a gasoline-powered pump (Maximum Off Grid, 2020). However, operating costs are near zero, and maintenance is minimal, consisting of only periodic cleaning. On average, a PV cell lasts 15-25 years at above 85% performance as long as it is cleaned when dirty, and can be repaired or replaced under warranty. Solar pump systems also pose less environmental risk than gasoline-powered pumps, with no exhaust or fuel to store or spill (Michigan State University, 2013; Solar Reviews, 2020). Solar panels have an average efficiency of 15%, meaning that only 15% of the solar radiation that meets the cells will convert to useful energy. As a result, a solar pump will provide significantly less power and take many years to repay the capital investment (Aggarwal, 2021).

2.1.3 Pumps

A pump is a device that transforms mechanical energy into hydraulic energy used to move fluids (Gerhart, Gerhart, & Hochstein, 2016). Pumps may fall within four main categories: positive displacement pumps, centrifugal pumps, jet (mixed-flow) pumps, and propeller pumps. Figure 8 depicts a centrifugal pump.

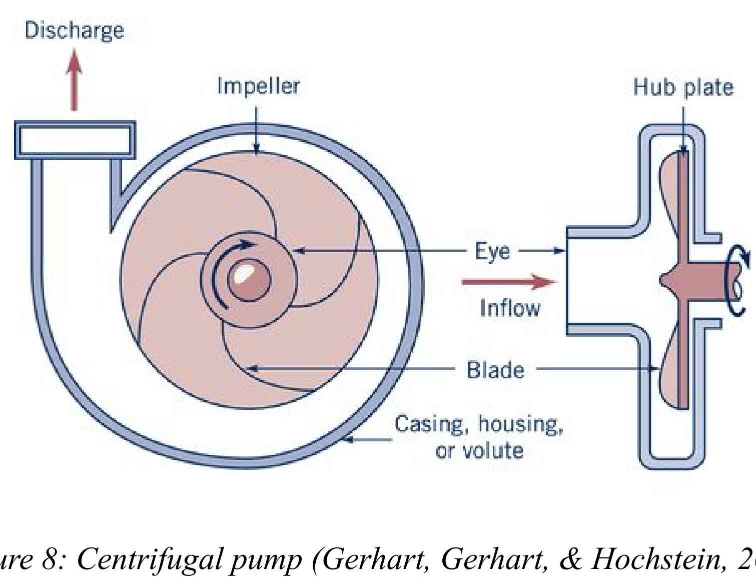


Figure 8: Centrifugal pump (Gerhart, Gerhart, & Hochstein, 2016).

Centrifugal pumps are turbo-hydraulic pumps, which move fluid by rotating vanes, which are curved chambers on the impeller, or by another fluid (Figure 8). Centrifugal pumps can either work submerged in water or placed on the ground. The head is expressed in pressure or distance units, while volumetric flow rate units are defined as volume over time. Irrigation sites commonly utilize centrifugal pumps to transfer water. The available pump at Flats Mentor Farm is a non-submersible, diesel-powered centrifugal pump with adjustable rotational speeds. Centrifugal pumps use the mechanical energy produced by an electric motor to convert velocity to pressure by the use of vanes on a rotating impeller (see Figure 8).

The type of pump chosen for a particular application depends on the pressure head (referred to as head) and volumetric flow rate requirements expected to transfer fluid.The pump's impeller has a known thickness and diameter. Pumps with larger impeller sizes can produce higher velocities and pressures. Changing the impeller size or changing the rotational speed influences the flow rate. From the pump efficiency, e_p, and the power input, P_i, the power output of the pump, P_o, can be calculated using Equation 1:

$$P_o = e_p P_i \tag{1}$$

Knowing the power output and pump efficiency, one can find the input power that the pump requires to operate. One can also calculate power output at peak efficiency using the specific weight of water, γ (at a given temperature), the pump head (H_p), and the desired flow rate (Q) defined below as Equation 2:

$$P_o = \gamma Q H_p \tag{2}$$

To calculate the pressure head of the pump, H_p, or the distance that the pump is able to move water, the vertical and horizontal distance between the river and the farm land must be determined. Setting the source head, H_S, or river elevation, as the datum point (0 ft), the receiving body head, H_R, or farm elevation, becomes positive. The pump pressure head can be found from Equation 3:

$$H_p = (H_R - H_S) + h_L \quad (3)$$

The variable h_L signifies the head losses that the pump must overcome. Generally, head loss accounts for the friction of the pipe material that the fluid experiences. Head losses are influenced by the length of the piping and the bends, or elbows, of the design configuration.

When finding values related to the head of a pipe, K refers to the loss coefficient, g refers to the gravitational constant (9.81 m/s^2), and Q refers to the volumetric flow rate of the fluid in the pipe. The loss of fluid along a pipe in head terms is represented in Equation 4:

$$\Delta h_L = \frac{Kv^2}{2g} \quad (4)$$

For rotodynamic pumps, the generated head is a function of discharge. When they operate in conjugation with pipe systems, the head from the pump equals the system energy requirement of the flow rate because they share volumetric flow rates. To maintain the flow Q and raise it against gravitational force from the reservoir height difference ΔZ, energy E must be supplied in head terms as Equation 5:

$$E = \Delta Z + \frac{KQ^2}{2g} = h_L \quad (5)$$

The system loss coefficient K in Equation 5 can be written in terms of the entry loss and friction loss of the suction pipe h_s and the losses due to bends, friction loss and exit loss h_d. If the system is altered (such as closing a valve) the K will change. Thus the total head loss can be written as in Equation 6:

$$h_L = \Delta Z + h_s + h_d \tag{6}$$

The solution is the intersection of the pump and the system characteristic, or operating point. This point is where the pump and system operate at the same rate. The process of choosing the correct pump is known as pump matching. The point on the system that corresponds to the required flow rate is the duty requirement, which means the operating point must correspond with it. This requirement means that different operating points can be chosen depending on the selected pump.

To operate the pump available at the farm, the inlet goes into the river. The pump inlet pipe should have a filter fixed to its base and float at least one foot above the river bottom to minimize the amount of sediment that enters. Debris entering the pump can damage or reduce the lifespan of the pump. The river's depth varies throughout the year and has an estimated minimum depth of three ft. The pump motor must then be filled with fuel and turned on by an employee to generate the pump. A sprinkler irrigation system will then irrigate each farm plot.

2.1.4 Filtration System

Pumped water, especially from surface water sources with fluctuating contaminant levels, must be filtered before irrigating crops. Most filtration systems remove larger suspended solids and certain organic materials such as algae and mold, but they will not remove microorganisms (e.g., bacteria, protozoa, plankton). A membrane can remove microorganisms from the water if that issue arises. World Farmers tests their water sources regularly and have found no harmful components. Filtration arrangements will consist of a primary filtration method, often followed by a second filter for materials not separated by the first stage. Commonly used filters include:

1. **Media Filters** - These separate suspended material by forcing water through a container filled with sharp-edged media, such as gravel or sand. They excel at removing organic material, but these filters should be followed by a secondary filter to prevent media leakage into the irrigation system (Netafim, 2015).
2. **Screen Filters** - These pass water through a metal screen, or net, to trap inorganic matter; however, they do not reliably filter slimy organic matter. Screen filters are commonly used as secondary filters when drawing from surface water sources. (Netafim, 2015).
3. **Disk Filters** - These share characteristics of screen and media filters as they employ a stack of abrasive mesh disks. Disk filters have greater filtering surface area and can handle higher flow rates compared to screen filters (Netafim, 2015).
4. **Conical Filters -** These filters remove debris that passes through the foot valve of the pump. They are placed between connecting pipeline flanges after the pump and require frequent cleanings. The orientation of the conical strainer can be flipped horizontally. It is recommended to orient the strainer so that the flow and particles are pushed toward the outer edges where the strainer is strongest ("Introduction to Permanent and Temporary Strainer Types," 2019).
5. **Centrifugal Filters** - These are cone-shaped hydrocyclone sand separators that use centrifugal force to remove larger inorganic matter (less than 50 microns). Since these neither separate inorganic matter nor pass water through a physical barrier, they need a secondary filter, such as a media filter (Netafim, 2015; Stryker, n.d.a).

Filtration system choices will depend on the chosen water source. At Flats Mentor Farm, drawing from the Nashua River may require multiple filter types because it is a surface water source. On the other hand, drawing from a well with frequent water testing may only need a single filter type. Each filter produces a drop in pressure. Pressure drop can be calculated or interpreted graphically. Pressure drop depends on the flow rate of the system and the dimensions for that specific strainer model. To calculate the change in pressure due to a strainer, use Equation 7:

$$\Delta P = [\frac{Q}{C_v}]^2 \tag{7}$$

ΔP is the pressure change, Q is flow rate, and C_v is the flow coefficient. The flow coefficient is specific to a particular strainer model and is obtained from the manufacturer. Alternatively, the manufacturer can provide a graph that relates flow rate and pressure loss given a particular strainer (with known diameter and perforation size). If the system has additional mesh lining, then multiply the calculated pressure drop by a correction factor to find the final pressure drop.

2.1.5 Piping

Irrigation systems require pipes that transport the water from a source to its destination. Piping can vary by its material and its diameter. For irrigation, the two most common piping materials are white PVC (polyvinyl chloride) and black pipe (polyethylene) (Smith, 2018). When selecting piping, the factors to consider are the volumetric flow rate of water in the pipe, the density and velocity of water, the elevation change throughout the piping, the pipe's roughness, and friction factors affecting head (pressure) loss. These factors affect the pipe's pressure, diameter, Reynolds Number, and the total head required.

Below are the equations to determine the proper piping for the irrigation system. Equation 8 finds the diameter (D_{pipe}) of the pipe using the water's volumetric flow rate (Q) and velocity (v).

$$D_{pipe} = \sqrt{\frac{4Q}{\pi v}} \tag{8}$$

Equation 9 determines the Reynolds number (Re) using the water's density (ρ), the velocity (v), the pipe diameter (D_{pipe}), and the dynamic viscosity (μ).

$$Re = \frac{\rho v D_{pipe}}{\mu} \tag{9}$$

Equation 10 gives the major head loss ($h_{L,major}$) due to friction using the friction factor (f), pipe length (L), pipe diameter (D_{pipe}), velocity (v), and gravity (g). Equation 10 is known as the Darcy-Weisbach equation.

$$h_{L,major} = \frac{f*L*v^2}{2*g*D_{pipe}} \tag{10}$$

The piping selection affects the total head needed, which then affects the pump choice. The pump selection also comes from the volumetric flow rate required. The MQP team made a piping variable calculator, which takes the input variables for piping and calculates the resulting values. Table 1 shows a sample calculation from the calculator.

Besides the actual piping, the two other most important components are fittings and valves, which control the pressure, temperature, and flow rate of the transmitted fluid. Fittings connect different sections of pipe in different ways. The pressure of the piping affects the types of fitting an irrigation system will have. With water conservation becoming more of a concern, low-pressure systems are gaining popularity. Some typical fittings are elbows (creates a turn in the pipe), adapter (adapts one type of connection to another), and couplers (a straight fitting that connects two sections). Other types of fittings are caps (close off one end), crosses (connects four sections of pipe), tees (connects one pipe to two others), and valves. Valves are fittings that have on-and-off functionality. The most common valve is a ball valve with a quarter-turn handle. Another prominent type is a pressure control valve, which controls the pressure of the fluid.

2.1.5.1 Water Hammer Effect

The water hammer effect occurs when the liquid pressure is turned on and off too quickly. When at a full capacity, the water flows evenly. Water hammer causes the water to produce a loud, thumping sound, and extreme examples can lead to structural damage. Nonetheless, it is generally harmless to the structural integrity of the system. Factors that affect it include valve closure rate, pipe size, and water pressure ("The Effects of Water Hammer," n.d.). Abruptly closing the valve, long pipes, and a pressure higher than what the pipe can handle can cause the water hammer effect (Madens, 2019).

One way to mathematically observe the water hammer effect is through the one-dimensional wave equation (Equation 11). It can predict the maximum line pressures and disturbance propagation times in a water distribution system with sudden valve closures (Choon, Aik, Aik, & Hin, 2012).

$$\Delta P = \rho a \Delta v \tag{11}$$

ΔP is the pressure rise due to the water hammer in N/m^2, ρ is the liquid density in kg/m^3, a is the impulse wave velocity in m/s, and Δv is the pipeline liquid velocity change. Water in pipes experience impulse waves from a sudden increase in pressure and decrease in flow rate. Other forms of the equation, such as Equation 12, utilize the water column's pressure increase (H) in terms of meters and gravity (g) in m/s^2 (Choon et. al, 2012).

$$\Delta H = a\Delta v/g \tag{12}$$

These equations assume that the friction losses are smaller than the static pressure, there is single phase flow, there are no dissolved gases in the fluid, and the fluid velocity change occurs faster than the critical time. The speed of the pressure waves, as seen in Equation 13, depends on density (ρ), elasticity modulus of the pipe material (E), elasticity modulus of the liquid (k), pipe diameter (D), wall thickness (e), and a constant assumed to equal one (C_1) (Choon et. al, 2012).

$$a = \sqrt{\frac{1}{\left(\frac{\rho}{k} + \frac{DC_1}{Ee}\right)}} \tag{13}$$

Pressure waves that produce the water hammer effect come from non-normal operations. These include opening and closing the valves too quickly, turning the pump on and off too fast, or suddenly changing the pump's rotational speed. Other parameters influencing the attenuation, shape, and factors including pipe pressure, velocity flow, wall material, blockage, leakage, friction, and cavitations (Choon et. al, 2012).

Opting for a high-pressure capacity pipe will prevent water hammer from occurring. Additional parts like a water hammer arrestor, pulsation dampener, pressure snubber, or surge suppressor offer pressure control (DirectMaterial, 2019). Adding one of these parts can decrease the flow velocity of the liquid or increase the moment of inertia of the pump. Installing a flywheel to the rotating axis of the driving motor prevents the rotational speed from sharply reducing. Installing a bypass pipe with a non-return valve will prevent sudden pressure reduction. Surge tanks in the piping system can suppress pressure waves by storing liquid in the tanks as pipe pressure increases, preventing rapid velocity changes. Pressure control and vacuum valves reduce water hammer by bringing the pressure back to normal (Choon et. al, 2012).

2.2 Farming in Massachusetts

Agriculture has been a vital part of Massachusetts since its first settlers came and grew crops to feed themselves. As of 2021, there are 7,241 farms in Massachusetts that encompass 491,653 acres. Farms in Massachusetts tend to be family orientated, with family farms accounting for 94.2% of farms (Inglis, 2017). 13% of all farms primarily grow vegetables (University of Massachusetts Amherst, 2020a). In recent years, CSAs (Community Supported Agriculture) have become very popular as more people want to support their local communities and be more environmentally friendly. The COVID-19 pandemic led to a surge in demand for locally grown fruits and vegetables (Greenberg, 2020).

2.2.1 Irrigation on Massachusetts Farms

To see what other vegetable farms in Massachusetts use for irrigation, the MQP team reached out to 30 farms, asking about their irrigation use and power sources. The farms that use irrigation use either a drip or sprinkler system, powered by electric or diesel pumps. One farmer, Ted Painter from Shelburne Farm, spoke of the challenges that farmers face when it comes to irrigation. While solar power is a good option for many farms, farmers often lack the funds for that transition. The main barrier to expanding irrigation systems is the high cost of wells. Drilling companies charge for wells by the foot, and many do not have the technology to predict the depth before drilling, which makes the cost of a well unknown for many farmers. This uncertainty makes well installations challenging to work into a budget. While it costs a lot to install a well, piping system, and drip lines, maintaining an irrigation system is much cheaper.

2.3 Water Quality Standards for Irrigation

Water used for irrigating crops needs to follow various standards to avoid damaging the crops or rendering them unsafe for human consumption. The water’s pH should ideally be

5.0-7.0, and its alkalinity should be between 0 to 100 ppm Calcium Carbonate (30-60 is ideal for most plants). The salt levels are critical in irrigation water. Furthermore, the salinity levels (measured by the Electrical Conductivity of the water) in irrigation water should be no higher than 1.5 mS/cm (without water-soluble fertilizer added).

Concerning elements, Calcium in water should be within 40-100 ppm, and Magnesium should be within 30-50 ppm. Sodium should be less than 40 ppm, and Chloride should be less than 140 ppm. Potassium, Nitrate, Ammonium, and Phosphate are indicators of possible contamination of a water source. Therefore, water becomes unusable if it has more than 5 ppm of any of them. Iron should be below 0.3 mg/L for micro-irrigation to mitigate clogging, and levels beyond that can also damage plant foliage. Likewise, Manganese compounds should be below 0.05 mg/L in water to avoid crop damage and irrigation clogging. Fluoride should be below 0.75 ppm. Finally, while one could use water with Sulfate levels below 50 ppm, they should add supplemental Sulfate to the crops because it is essential for plant growth (University of Massachusetts Amherst, 2015).

3. Project Design

3.1 Functional Requirements

When designing an irrigation system, many factors must be considered. Two major components of any complex system are its functional requirements and design parameters, both of which need to be determined early on in the design process. In terms of irrigation, Flats Mentor Farm will have to consider the farmers' needs. The amount of water farmers need and the types of crops they grow may change from season to season, so a versatile system that meets these needs will best fit their farm. A modular approach will also be more usable by the rest of the farm. One way to begin the process of creating a system is through Axiomatic Design (Suh, 2001).

3.1.1 Axiomatic Design

To determine the functional requirements of the irrigation system, an axiomatic design matrix was created. This matrix compares the functional requirements to the design parameters to determine the best design to meet World Farmers' needs (Suh, 2001).

The MQP team began by listing the first level functional requirements (FRs) and their design parameters (DPs). This process resulted in the first level matrix in Equation 14.

- FR_1 = transport water from river to plots
- DP_1 = piping and emitters
- FR_2 = power pump
- DP_2 = generator

$$\begin{bmatrix} FR_1 \\ FR_2 \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_1 \\ DP_2 \end{bmatrix}$$

Equation 14

Then, the process of decomposing them into the second level functional requirements and design parameters began.

Second Level Functional Requirements:

- FR_{11} = transport clean water
- FR_{12} = transport enough water at specific times
- FR_{21} = efficiently supply power
- FR_{22} = provide low-cost energy

Second Level Design Parameters:

- DP_{11} = filtration system attached to pump
- DP_{12} = user controller interface to turn on/off pump when needed
- DP_{21} = sufficient horsepower
- DP_{22} = low-cost, fuel-efficient generator able to run at full load most of the time

The decomposition of FR_1 and FR_2 resulted in decoupled matrices (Equations 15 and 16).

$$\begin{bmatrix} FR_{11} \\ FR_{12} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \end{bmatrix}$$

Equation 15

$$\begin{bmatrix} FR_{21} \\ FR_{22} \end{bmatrix} = \begin{bmatrix} X & 0 \\ 0 & X \end{bmatrix} \begin{bmatrix} DP_{21} \\ DP_{22} \end{bmatrix}$$

Equation 16

The final axiomatic design matrix features all second level functional requirements and design parameters (Equation 17).

$$\begin{bmatrix} FR_{11} \\ FR_{12} \\ FR_{21} \\ FR_{22} \end{bmatrix} = \begin{bmatrix} X & 0 & 0 & 0 \\ 0 & X & 0 & 0 \\ 0 & 0 & X & 0 \\ 0 & 0 & 0 & X \end{bmatrix} \begin{bmatrix} DP_{11} \\ DP_{12} \\ DP_{21} \\ DP_{22} \end{bmatrix}$$

Equation 17

Using Equation 15, the MQP team would use a pump with a user controller interface to turn the pump on and off and control the speeds. It would have a filtration system to transport clean water from the river to the crops. Equation 16 indicates the need for a powerful and efficient power source. While more costly in the long run, a diesel generator would effectively supply the necessary power to run the pump. World Farmers has a high-power pump that functions using a diesel generator. It is not feasible to convert the system to solar power without purchasing all new materials, so instead the system was designed using the pre-existing pump and diesel generator because they met the functional requirements.

3.2 Optimization

To optimize the irrigation system, the MQP team decided to work on saving water by creating a linear equation to model the total profit in MATLAB. There are three components of the linear model used to optimize the irrigation system. The total area of the farm segment in concern is roughly 28,328 square meters, or 304,920 square feet.

One way to avoid this loss is by applying linear programming to maximize the profit generated from the crop (or crops) while minimizing water used for irrigation to satisfy the crops' water needs without compromising the other plots on the farm. In this optimization, the total profit for the crop was optimized.

Nationally, the cost of irrigation for water when pumping from an onsite water source is about $15 per acre, or $15/43560 square feet. (Agricultural Resources, n.d) Additionally, depending on how deep the water needs to go when being irrigated, the cost to pump water from the nearby river is estimated to be $0.08/mm. (OECD, 2010) This means the total cost for the water is about $1.20/(mm*acre).

The three main crops being looked at are collard greens, amaranth, and kale. There should only be one kale plant per square foot, and kale seeds sell for roughly $3.65 per 1,000 seeds. (Harris Seeds, n.d) Therefore, the production price for kale is $0.00365 per square foot. A good yield for kale per acre based on results from New England is roughly 2000 pounds (University of Vermont, n.d), and fresh kale sells for $2.88 per pound based on data collected from Massachusetts in 2016. This means that the gain for kale is $5760 per acre. Similarly, there should only be one collard green per square foot, and collard seeds sell for roughly $4.75 per 100 seeds. (Johnny's Selected Seeds, n.d) Therefore, the production price for collard greens is $0.0475 per square foot. A good yield for collard greens per acre based on results from New England is roughly 2000 pounds (University of Vermont, n.d), and the collard greens sell for about $2.63 per pound. This means that the gain for collard greens is $5260 per acre. Amaranth seeds cost roughly $4.00 per acre, and it sells for roughly $0.40 per pound. The yield for amaranth per acre is 800 pounds, so that means when planted in this farm's area, there will be a gain of $320 per acre (Iowa State, n.d).

The first is the decision variables, which are the components of the model that can be edited to come up with the optimal solution of the model. Production cost is determined by human labor, cost of planting, and seed cost. One of these decision variables is the amount of area taken up by a crop. The MQP team can ask about the crops grown around the farm, and then choose how they are distributed throughout the area to maximize profit. However, the farm wants a minimum of 10000 square feet worth of each crop. One of the most important decision variables to look at is the crop water requirements (CWR) are defined as the amount of water needed to meet the water consumed by the crop through evapotranspiration. The crop water requirements for kale are between 12.5 mm to 30 mm. (Gardening Know How, 2019). The crop water requirements for collard greens are similarly also between 25 mm to 30 mm. (Bonnie Plants, n.d) Finally, the crop water requirements for amaranth are between 5 mm to 15 mm. (West Coast Seeds, 2021)

The objective function is what is needed to do to minimize the cost of irrigating the crop. This will be optimized by adjusting the above decision variables as well as the constants that affect them. Equation 18 is the objective function, where A_c is the area of the crop being looked at, P_c is the production cost of the crop being looked at, W_c is the irrigation cost of the crop, S_c is the sale price, and CWR is the crop water requirement:

$$CropProfit = (S_c * A_c) - (A_c * P_c) - (W_c * A_c * CWR) \tag{18}$$

The constraints are what the objective function is subjected to and affect how much the decision variables can be changed. One of the constraints is that the total amount of water used in one year must not surpass the amount available from the water source, V. Another one of the constraints is that the area for the crop must not be larger than the total area for the farm, TA. Additionally, the farm wants at least 10000 square feet worth of each crop being looked at. The final set of constraints is the CWR, which must be set between a minimum value and a maximum value for each crop. For this, it is always best that the CWR is as low as possible. Equations 19, 20, and 21 represent this.

$$A(i) \leq TA \tag{19}$$

$$CWR(i) \times A(i) \leq V \tag{20}$$

$$A_c(i) \geq 10000 \tag{21}$$

		Collard Greens	Amaranth	Kale	
	Units				
Production Cost	$/sqft	0.0475	9.18274E-05	0.00365	
Yield	$/sqft	0.120752984	0.007346189	0.132231	
Crop Water Requirement:	mm	25	5	12.5	
Area	sqft	10000	10000	284920	
Min CWR	mm	25	5	12.5	
Max CWR	mm	30	30	15	
Irrigation Cost	$	6.887052342	1.377410468	98.11295	
Area Cost	$	475	0.918273646	1039.958	
Gain	$	1207.529844	73.46189164	37675.37	
Profit	$	725.6427916	71.16620753	36537.3	
Total Area (sqft)	Available Area (sqft)	Minimum Area (sqft)	Total Profit ($)		Irrigation ($/sqft*mm)
304920	304920	10000	37334.10995		2.75482E-05

Table 1: Optimal crop and irrigation distribution

Overall, it seems that for the greatest optimization (Table 1), the crop that should be prioritized the most is Kale. This crop cost the least to produce compared to its selling price, and thus it has the highest margin of profit of all the crops. Additionally, it doesn't cost much to irrigate, and it has a large year round availability.

The MQP team also thought up several options for further optimization of the cost of the system when it is being constructed. One option for reducing the design cost is decreasing the diameter of the red layflat. Brookdale Fruit Farm's updated design includes 4" red layflat, but the MQP team suggested using either 2" or 3" instead. The 4" red layflat costs $796 per roll, whereas the 3" costs $600 and the 2" costs $300. There were concerns about the pressure being increased by reducing the layflat diameter. The pressure can be tested using the prototype, which could prove the viability of reducing the diameter. Replacing the 4” layflat with 3” would decrease the design price by $392 or 7.21%, whereas using the 2” would reduce it by $992 or 19.99%.

Another option the MQP team considered was reducing the number of sprinklers, necessitating an increased distance between each sprinkler. However, World Farmers rejected this alteration because it reduced the already limited land area irrigated by the system. Reducing the number of sprinklers would require more money spent on other watering systems to compensate for the reduced irrigation.

3.3 Required Irrigation Rate

To find the irrigation rate required for crops, the team used Equation 22. They first found the historic evapotranspiration (ET) value, which is the amount of water needed by irrigation. An online calculator from Rain Master Control Systems was used, where the maximum value was 0.15 inches per day during the summer (“Historic ET By Zip Code,” 2012). This value was multiplied by the plant factor (PF), which considers the amount of water that different plants need. Because each family farm has varying crop species and counts, the average water intake value of 0.5 was used. The result was then multiplied by the area in square ft. The size was estimated to be 4 acres, which equals 174,240 square ft. To get the values into gallons, this was multiplied by the factor 0.62. This was then divided by the irrigation efficiency, which was assumed to be 0.75. Drip irrigation systems generally have a 90% efficiency, so the calculation will go with IE = 0.90 (“How Much Water”, n.d.).

$$\frac{ET*PF*SF*0.62}{IE} = \frac{(0.15)(0.5)(174240)(0.62)}{0.75} = 10,802.88\ GPD \tag{22}$$

This value is far below the 300,000 gallons per day (GPD) required for a permit. While this value is an overestimate that does not consider the amount of land used in each season, it still lies far below 300,000 GPD, so World Farmers does not need a permit to pump water from the Nashua River.

3.4 Pump Requirements

The centrifugal pump available at Flats Mentor Farm will be utilized to transfer water from the Nashua River to the farm plots. Currently, farmers pump water from an on-site well to several tanks; the pump will be moved to transport water from the Nashua River to the farm area. Those at the farm have previously operated this pump from the river to transfer water to a 4-inch hydrant closer to the farm plots of interest. Using a foot valve on the suction hose of the pump to filter debris from the river, the pump can successfully supply water to each of the hydrants. A foot valve is a one-way valve at a pipe's inlet that has a mesh filter attached to remove debris. The goal of the project is to design an irrigation system on the farm using the existing pump. First, the project group must confirm the pump capabilities to irrigate the 4 acres of farmland. Using pump characteristic curves provided by the pump manufacturer, Rainbow Irrigation Company, allows for graphical analysis of the pump's capabilities. Self-producing characteristic curves of a pump from raw data would risk damaging the pump.

The pressure head and volumetric flow rate compose a pump performance curve, or H-Q curve, which illustrates that as head decreases, the flow increases (Figure 9).

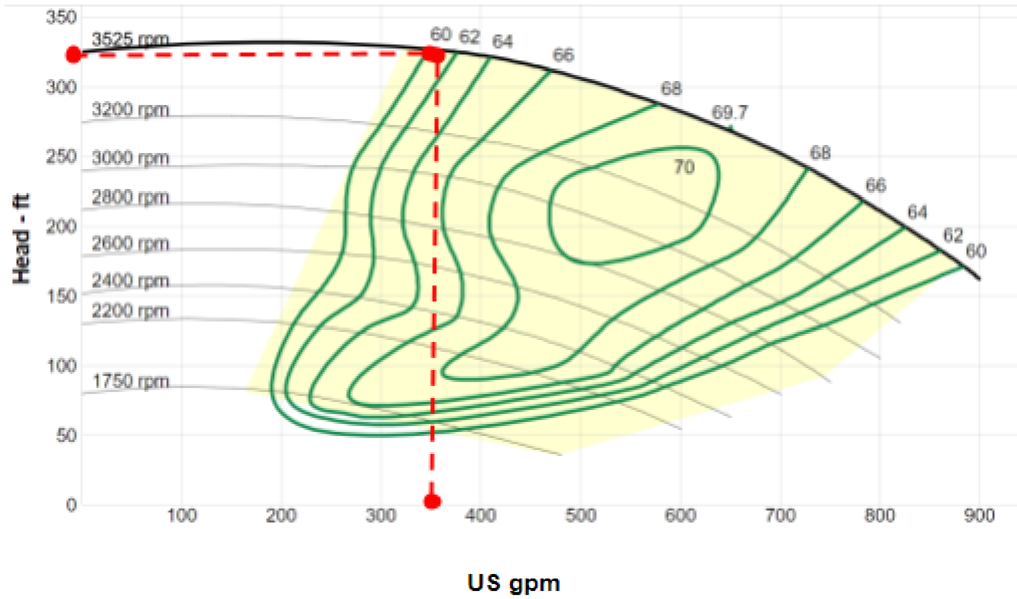


Figure 9: Head flow rate characteristic curve.

At a given head and flow rate, the pump would achieve a specific efficiency. Figure 9 also shows that this specific pump model has a peak efficiency of 69.7%, at which it has a volumetric flow rate of 650 GPM and head of 268 ft. Ideally, the pump should work at peak efficiency to minimize the amount of fuel the pump requires. These measures are the optimal head and flow rate at which the pump should ideally operate. The efficiency of the pump should exceed 60% efficiency. With the characteristic data relating power and flow rate below, one can find the amount of power necessary to operate the pump at optimal efficiency.

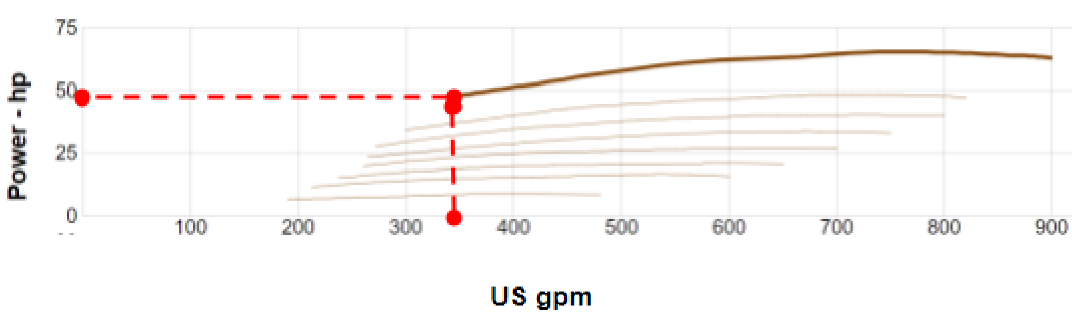


Figure 10: Power flow rate characteristic curve.

Figure 10 illustrates that this pump requires an input power of 63.2hp to operate at 650 GPM and optimal efficiency. The efficiency, head, flow rate, and power values depend on the pump impeller speed (3525 rpm) and its dimensions. The pumped fluid is assumed to be pure water at 68℉.

To confirm that this pump model meets this project's needs, it was vital to determine the necessary head and flow rate to irrigate the farm. The pump must overcome the pressure head loss between the pump and the farm area. The pressure head must also overpower any head losses throughout the system, including losses due to friction of the pipe material and bends in the system. The actual flow rate used to water a farm will depend on its size and the irrigation method utilized. Using Equation 24, the flow rate of water for a 4 acre farm was estimated to be around 10,803 GPD ("How Much Water," n.d.), assuming utilization of a sprinkler irrigation system. Alternatively, the desired flow rate could be estimated from the number of crops planted at the farm and daily watering needs of each plant. However, the number of crops per farm plot and the types of crops vary widely.

The pump at the farm is able to reach a maximum rotational speed of 3525 rpm and an estimated maximum flow rate of 900 GPM. Converting the head to pressure shows that the minimum pressure is 78 psi and the maximum is 142 psi at 3525 rpm. However, the pump does not need to operate at 3525 rpm, and it should be decreased. It is recommended that the pump operate near the middle of the pump capabilities between 2200-2500 rpm, 200-400 GPM, and 130-150 ft (300-347 psi). Reducing the pump rotational speed would decrease the output pressure, which can be adjusted manually via a throttle on the pump engine.

3.5 Piping Requirements

The material of the pipe would be required to withstand a minimal 35 psi compression above ground and a minimal 100 psi fluid pressure (the max psi of the current pump is 100 psi). The pipe should also be UV resistant. The material could be PVC, aluminum, layflat, or FlexNet. The piping will also require hose connectors, known as camlocks.

Stress is considered the ratio of force over area, and it greatly affects the piping system. In order to build the piping system, the physical properties that the piping will undergo must be put into consideration. To do this, Barlow's formula (Equation 23) must be used to calculate the relationship between the internal pressure (P), the allowable stress (σ), the thickness of the piping (t), and the diameter of the pipe (D).

$$P = \frac{2*\sigma*t}{D_{pipe}} \tag{23}$$

Because of the drop in internal pressure over the length of the pipe, that means that the allowaStress is considered the ratio of force over area, and it greatly affects the piping system. In order to build the piping system, the physical properties that the piping will undergo must be put into consideration. (Little P.Eng, n.d) One of the main types of stress is normal stress, which acts in a direction normal to the face of the crystal structure of the material, and may be either tensile or compressive in nature. One of them is hoop stress, which is applied in directions orthogonal to the axial direction and happens because of internal pressure. Another is longitudinal stress, which is when the normal stress acts parallel to the longitudinal axis of the pipe. (Little P.Eng, n.d) Bending stress is zero at the neutral axis of a pipe, and thus occurs because of the bends within the piping layout, with it increasing at a linear rate proportionally to the distance from the neutral axis. Another type of stress that must be taken into consideration in the team's design is the stress derived from thermal expansion, which happens as a result of changes in temperature. (Engineering Toolbox, n.d)

The first type is the hoop stress, where the liquid travelling through the pipe will push against the inside, meaning a pipe material that is strong enough to withstand it must be chosen. The way that different properties of pipe are considered can be found by using Equation 24, which is used to calculate the relationship between the internal pressure (P), the allowable stress (σ) caused by the pressure, the thickness of the piping (t), and the diameter of the pipe (D).

$$\sigma = \frac{P*D_{pipe}}{2*t} \quad (24)$$

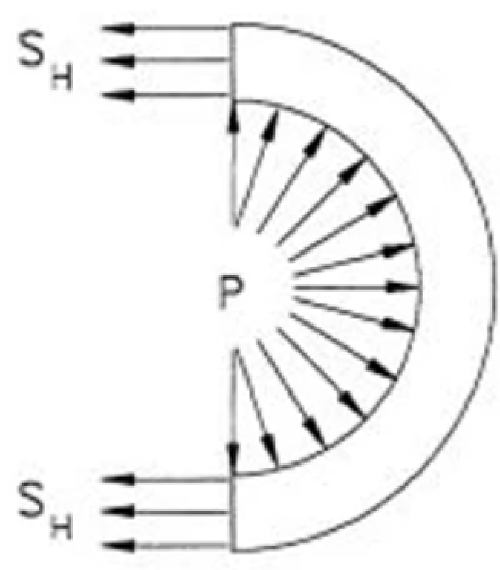


Figure 11: Hoop Stress due to internal pressure (Little P.Eng, n.d)

Because of the drop in internal pressure over the length of the pipe, that means that the hoop stress will decrease as the internal pressure decreases. Figure 11 shows how hoop stress, represented S_H, is created by the internal pressure pushing against the interior of the pipe.

Longitudinal stress often occurs due to the internal pressure of the material travelling through the pipe. Since our team's system does not contain an internal axial force acting on the cross-section other than the internal pressure from the liquid. When this occurs, it can be calculated using Equation 25, where (P) is the internal pressure, (D_{pipe}) is the diameter of the pipe, and (t) is the thickness of the pipe:

$$\sigma = \frac{P*D_{pipe}}{4*t} \tag{25}$$

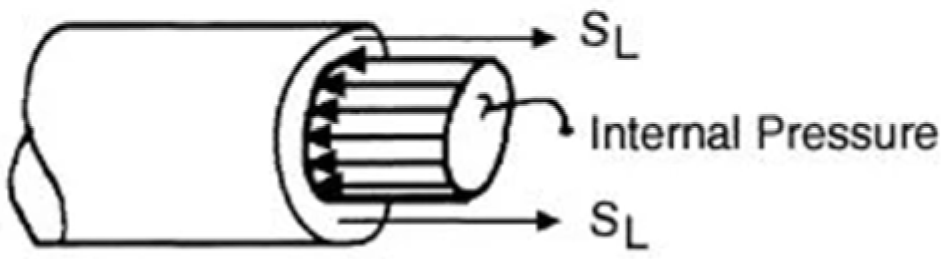


Figure 12: Longitudinal Stress due to internal pressure (Little P.Eng, n.d)

Similarly to the Hoop stress, because of the drop in internal pressure over the length of the pipe, that means that the allowable stress will decrease as the internal pressure decreases. Figure 12 shows how the internal pressure moving in one direction leads to a parallel longitudinal stress S_L in the opposite direction.

Additionally, whenever there is a fitting on the pipe, such as a bend or T intersection, then that will lead to a variation on the longitudinal stress in the material because of the compression and tension forces that result from the internal pressure. This bending stress is defined by the Equation 26, where (I) is the moment of inertia in Equation 27, (M) is the bending moment, which is calculated by multiplying a force by the distance between that point of interest and the force, and (c) is the distance from the neutral axis. (c) can't be greater than the radius of the pipe. Additionally, when finding the moment of inertia, (D) is the Diameter, and (t) is the thickness of the material.

$$\sigma = \frac{M*c}{I} \tag{26}$$

$$I = \frac{pi((D+t)^4 - D^4)}{64} \tag{27}$$

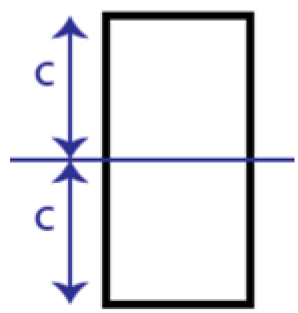


Figure 13: Bending Stress due to bends in pipe design (ReviewCivilPE, n.d)

Figure 13 shows how compressive force that results from the internal pressure results in bending stress. Additionally, to find the bending moment, it is important to multiply this force by the length of the bend, which in the team's system is never greater than six inches.

Also, thermal stresses must be considered as well since the temperature can vary greatly between a cool spring morning and a hot summer afternoon, which can lead to material changing size. This change in size can be determined in Equation 28 by finding the material's linear thermal expansion coefficient (α), and multiplying it by the change in temperature (dt) and original length (L). Additionally, to find the stress derived from the thermal expansion, use the elastic modulus (E):

$$dL = \alpha * L * dt \tag{28}$$

$$\sigma = E * \alpha * dt \tag{29}$$

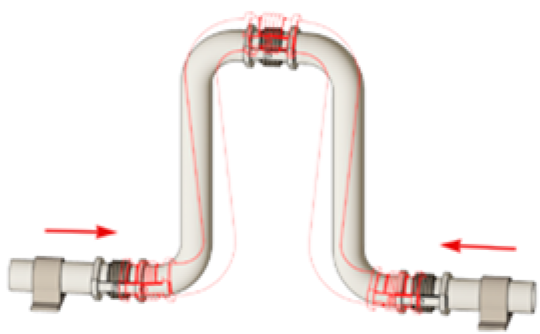


Figure 14: Thermal expansion due to change in temperature (The Process Piping, n.d.)

However, supports can be used to restrict the pipes movement from thermal expansion and help take some of the stress that would normally affect the bends. Figure 14 shows how the thermal expansion within the pipes can lead to the shape being changed, but also shows how the supports can mitigate it.

3.6 Cavitation and Net Positive Suction Head (NPSH)

In irrigation piping, a phenomenon known as *cavitation* can occur. Low-pressure areas below the water's vapor pressure can cause small bubbles of water vapor to form and collapse, sending shockwaves through the system damaging parts such as pump impellers or valves.

A piping system's potential for cavitation is based on the Net Positive Suction Head (NPSH), measured in head-feet. The NPSH is the difference between suction pressure and vapor pressure at the pump's suction nozzle. Cavitation is calculated from required and available NPSH: NPSHr and NPSHa, respectively. (Pumps & Systems, 2016). If NPSHa is greater than NPSHr, cavitation will not occur. Required NPSH is specified in pump performance curves; Flats Mentor Farm's pump curve is shown below in Figure 15:

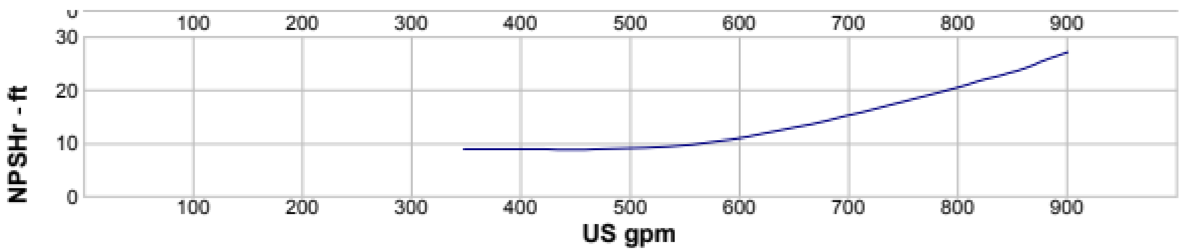


Figure 15: FMF Rainbow pump curve (US GPM vs. NPSHr in ft.)

Required NPSH for the FMF pump ranges from approximately 9-28 psi, meaning that NPSHa must exceed 28 psi to ensure pump function without cavitation. The available NPSH of the system can be calculated using Equation 30:

$$NPSHa = A - V + S - F \quad (30)$$

In the above equation to calculate NPSHa, (A) is absolute pressure on the water supply surface, (V) is vapor pressure of the pumped water, (S) is static head, and (F) is friction head. Assuming atmospheric absolute pressure, 293.15 K water temperature, 12 ft maximum static head, and knowing that 1 KPa = 2.9883 feet-head:

$$NPSHa = 33.7985 - 0.08031 + 12 - 14.2190 = 30.78 \text{ (ft. head)}$$

$$30.78 > 28\ (ft.\ head) \rightarrow NPSHa > NPSHr$$

In the proposed FMF irrigation system, the available NPSH is greater than the required NPSH. Additionally, since Equation 30 was calculated using the absolute minimum NPSHa and maximum NPSHr value, cavitation is highly unlikely to occur.

4. Project Approach

4.1 Design Iterations

Those at Flats Mentor Farm initially requested the project group to pump water from the river to the existing tanks at the farm. In order to utilize the tanks, they would need to be lifted about 81 feet to allow gravity to transfer the fluid. Alternatively, each tank or tank group would need a pump to irrigate the farm via a sprinkler system. Figure 16 shows an illustration of the tank group locations with Flats Mentor Farm's initial design suggestions.

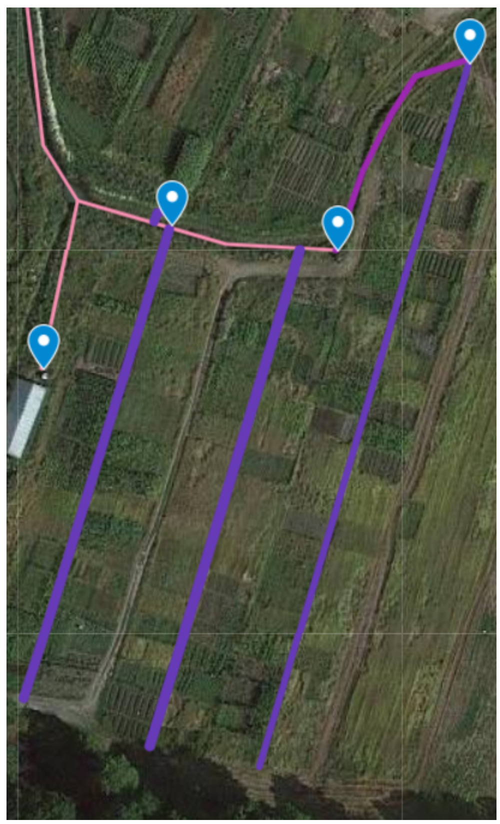


Figure 16: Flats Mentor Farm Suggested Irrigation System Using Tanks

World Farmers and the MQP team concluded that relying on holding tanks was not an efficient system; they would need to purchase several pumps for each tank group, increasing the total cost. Also, the pump that the farm currently has available is powerful enough to transfer water to the far east side farm plots with the proper piping configuration. The farmers and staff would not need to operate the pump as frequently to refill the tanks. Instead, one pump from the Nashua River will directly irrigate the farm through a sprinkler system without the use of tanks.

4.1.1 The MQP Team's First Design

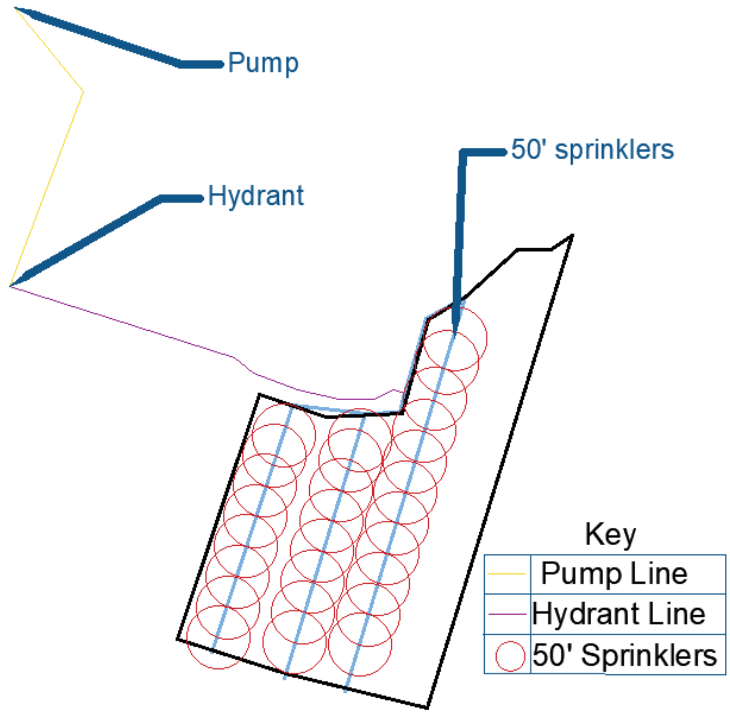


Figure 17: Original design with 24 50-foot radius sprinklers represented by red circles. The yellow line is the 6" diameter underground aluminum pipe connecting the pump to the hydrant and the purple line is the 1-¼" 26 SDR PVC connecting the hydrant to the sprinkler system. The blue lines have the sprinklers attached and go in between every other section.

Based on both existing constraints provided by World Farmers and relevant variables determined in the project's design phase, an irrigation system was designed (Figure 17). The limitations and relevant variables include piping specifications, spray radii of sprinklers, and required operational pressure. Through the consideration of these variables and constraints, a preliminary irrigation system design was developed.

In this design, several materials met the piping qualifications, but 1-¼" 26 SDR PVC was chosen as the material because it was the most cost-efficient of the initially researched materials. The piping maximum pressure rating, 160 psi, would fall within the limitations of the existing Rainbow Irrigation Systems pump.

The area of interest includes 130 plots that are 25' by 50' (Figure 1). Piping would run parallel to different sections, or rows of plots, within the area. It was concluded that a sprinkler irrigation system would meet the needs of the farm because of its low-maintenance, wide coverage, and ease of installation. Since the plots are 25-ft wide, the sprinklers would go in between sections M and N, O and P, and Q and R. The sprinklers would have a 50-foot radius and would be placed every 50 ft along the PVC line. The sprinklers would need to operate at 71.1 psi to meet their maximum radius of 59 ft. This system was found to be the most efficient in terms of cost as it reduces the number of sprinklers required to reach every plot (Figure 15). Despite this, it was found some issues in the approach as the sprinklers' coverage would fail to reach some plots' corners.

The existing pump on the farm operates at a range of pressures which falls within the pressure requirements for both the piping (maximum of 160 psi) and Irrigation King's ¾" Brass Impact 59-foot radius sprinklers (maximum radius achieved at 71.1 psi).

With these considerations, a decision was made. The MQP team's first design featured 1-¼" 26 SDR PVC pipes, ¾" Brass Impact 59-foot radius sprinklers, and used the existing pump which would meet the pressure requirements for operation of the system.

4.1.2 Brookdale Fruit Farm's First Design

Along with the project group's first design, World Farmers contacted its irrigation equipment supplier, Brookdale Fruit Farm, to develop its irrigation system design. The first

Brookdale design introduces different piping materials: layflat main line (Figure 22) attached to FlexNet laterals with elevated sprinklers attached to every 4th hole (or every 24 ft) (Appendix C), secured with a Type DP camlock and an end cap. FlexNet is highly durable, leak-proof, lighter and more flexible than conventional piping materials, and can be laid down and rolled up more easily than a layflat line.

Camlocks are aluminum fittings that are used to secure piping together and minimize any leaks within the system (Appendix C). Camlocks that are barbed at one end are designed to fit into flexible piping, such as FlexNet and layflat, while other camlocks are designed with a male thread to connect to a female threaded fitting such as PVC tees and other aluminum fittings. These camlocks are able to couple to each other by a male-female latching design — female camlocks latch onto the male indented camlocks. It is recommended to apply teflon tape or liquid to the threads to better secure the camlocks with attaching fittings.

However, FlexNet introduces difficulties due to its 36 psi max and higher cost per unit length. Its 36 psi maximum requires twice as many lines (seven instead of three laterals at the widest point) as the MQP team's original design (Figure 17), which doubles the cost of the already expensive piping. Brookdale's irrigation system design was itemized and quoted at $10,417, far exceeding the project operating budget (Appendix D). World Farmers rejected the initial Brookdale proposal for this reason, but FlexNet and camlocks would remain in later designs.

4.1.3 Brookdale Fruit Farm's Updated Design

Brookdale Fruit Farm's original design was severely over budget.

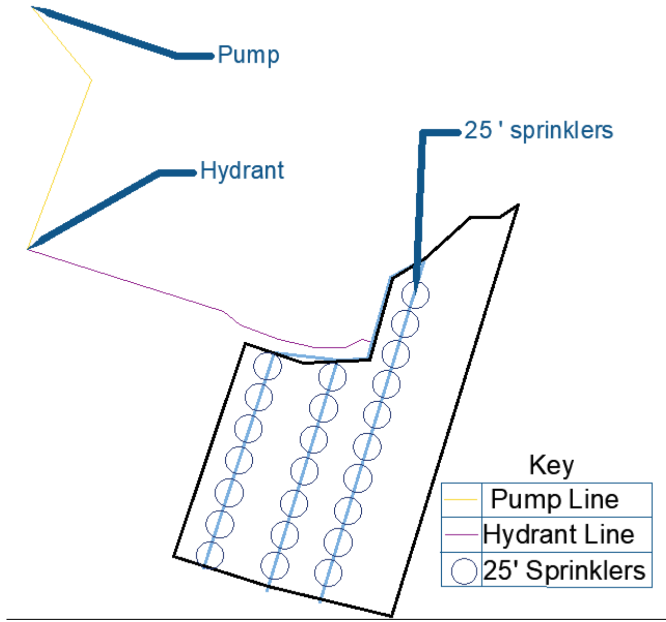


Figure 18: Brookdale Fruit Farm's redesign

The MQP team collaborated with Brookdale Fruit Farm to scale down their original design. They removed several lines so that it emulated the MQP team's first design with Brookdale Fruit Farm's supplies. The redesign was much cheaper than the original design since it used six rolls of FlexNet instead of the previously used 14 (Figure 18). The updated design has all the features that FMF wanted from the original design: a layflat line attached to FlexNet intervals with sprinklers attached every 24 ft secured with camlocks. It also reduced the number of rows of FlexNet from 14 to Y and the number of sprinkler assemblies from 225 to 75.

Quantity	Unit	Item	Unit Price	Total
6	rolls	2" x 328' flexnet with 6' holes	$295.00	$1,770.00
75	assembly	Green meganets with tubes and stakes	$12.00	$900.00
4	each	4"x4" x 2" threaded tee	$21.00	$84.00
4	each	2" x 3" nipples	$3.50	$14.00
4	each	2" threaded ball valves	$12.00	$48.00
4	each	1.5" pressure regulator at 35 PSI	$30.00	$120.00
8	each	2" x 1.5" threaded bushing	$2.75	$22.00
4	each	2" camlock B	$9.00	$36.00
4	each	2" camlock E	$4.50	$18.00
12	each	2" camlock C	$8.00	$96.00
12	each	2" camlock E	$4.50	$54.00
4	each	2" camlock DP	$4.00	$16.00
10	each	2" couplers	$1.55	$15.50
15	bags	2" clamps	$6.50	$97.50
1	can	liquid teflon	$14.00	$14.00
				$0.00
7	bags	flexnet plugs	$12.50	$87.50
				$0.00
				$0.00
8	each	4" female adapters	$5.50	$44.00
4	each	4" camlock B	$18.50	$74.00
4	each	4" camlock F	$15.00	$60.00
8	each	4" camlock C	$22.00	$176.00
8	each	4" camlock E	$14.00	$112.00
1	assembly	4" hook and latch x camlock adapter	$65.00	$65.00
				$0.00
2	rolls	4" X 300' red layflat	$796.00	$1,592.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
				$0.00
			Total	$5,515.50

Table 2: Updated cost after reducing the number of sprinklers and lines.

Decreasing the FlexNet lines scaled down the quantities for each of the other items on the original quote, reducing the final cost from $10,417 to $5,515 (Table 2).

4.2 Failure Analysis

When performing a failure analysis with the aluminum pipe, the team concluded that assuming the initial operating pressure of the pipe is 110 psi, that the diameter of the pipe is 6.07” and the thickness of the pipe is 0.28”, then by using the Barlow’s formula, it was found that the hoop stress will be 1192.32 psi at most. Additionally, the longitudinal stress will be 596.16 psi because of the internal pressure without counting any bends.

One important component to calculate is the force of the pressure, which is equal to the pressure times the area. Using the diameter, the cross-sectional area of the piping is 29.03 $inches^2$. Thus, the force would be 110*29.03 = 3193.3 lbs. For the bending stress, the team found that the moment of inertia was 13.17, and assuming the length of the bends in the pipe is 6 inches, that means that the bending moment is 3193.3*6 = 19159.8 lb*in. By using the bending stress equation, the team found that the total bending stress will be 1454.81 psi.

Finally, because the change in temperature of the liquid traveling through the piping is not noticeable, the thermal expansion is based on the outside temperature. For example, if the temperature outside is 20 F during a cold spring night but warms up to 80 F during the hot summer day, then that means that the pipe will expand by 4.68 inches over a length of 500 feet since the aluminum linear thermal expansion coefficient is $13*10^{-6}$. (Engineering Toolbox, n.d) Additionally, since the elastic modulus is 10^6 psi (AmesWeb, n.d), the stress happens because of the thermal expansion is 780 psi.

Overall, the greatest possible stress that could be exerted on the piping is 4020.29 psi, and since the allowable stress of aluminum piping is 24000 psi, this means that the aluminum piping will not fail because of the internal stress. (Wagner Companies, n.d)

When performing a failure analysis with the polypropylene FlexNet, the team concluded that assuming the initial operating pressure of the FlexNet is 35 psi, that the diameter of is 2.09" and the thickness is 0.103", then by using the Barlow's formula, it was found that the hoop stress will be 1219.17 psi at most. Additionally, the longitudinal stress will be 609.58 psi because of the internal pressure without counting any bends.

One important component to calculate is the force of the pressure, which is equal to the pressure times the area. Using the diameter, the cross-sectional area of the FlexNet is 3.43 inches^2. Thus, the force would be 35*3.43 = 120.05 lbs. For the bending stress, the team found that the moment of inertia was 0.318, and assuming the length of the bends in the FlexNet is 6 inches, that means that the bending moment is 120.05*6 = 720.3 lb*in. By using the bending stress equation, the team found that the total bending stress will be 2265.09 psi.

Finally, if the change in temperature is 60 C, then that means that the FlexNet will expand by 34.56 inches over a length of 1200 feet since the thermal expansion coefficient for polypropylene is $40*10^{-6}$. (Engineering Toolbox, n.d) Additionally, since the elastic modulus is 1.9^5 psi (AmesWeb, n.d), the stress that happens because of the thermal expansion is 456 psi. Overall, the greatest possible stress that could be exerted on the FlexNet is 4549.84 psi, and since the allowable stress of polypropylene FlexNet is 6526.7 psi, that means that the team's prototype design will not fail because of the internal stress of the FlexNet. (Wagner Companies, n.d)

When performing a failure analysis with the PVC layflat, the team concluded that assuming the initial operating pressure of the layflat is 137 psi, that the diameter is 4.13" and the thickness is 0.067", then by using the Barlow's formula, it was found that the hoop stress will be 1078.73 psi at most. Additionally, the longitudinal stress will be 539.37 psi because of the internal pressure without counting any potential bends.

One important component to calculate is the force of the pressure, which is equal to the pressure times the area. Using the diameter, the cross-sectional area of the layflat is 13.4 in^2. Thus, the force would be 137*13.4 = 1835.8 lbs. For the bending stress, the team found that the moment of inertia was 1.76, and assuming the length of the layflat is 6 inches during bending, that means that the bending moment is 1835.8*6 = 11014.8 lb*in. By using the bending stress equation, the team found that the total bending stress will be 6258.41 psi.

Finally, if the change in temperature is 60 C, then that means that the layflat will expand by 11.73 inches over a length of 543.33 feet since the thermal expansion coefficient for PVC is $30*10^{-6}$. (Engineering Toolbox, n.d) Additionally, since the elastic modulus for PVC is 4^5 psi (AmesWeb, n.d), the stress that happens because of the thermal expansion is 720 psi.

Overall, the greatest possible stress that could be exerted on the layflat is 8596.51 psi, and since the allowable stress of PVC layflat is 7542.96 psi, that means that the team's prototype design may fail because of the internal stress of the layflat depending on how much the pressure has dropped by the time the liquid reaches the bends. (Vinidex, n.d)

4.3 Design Calculations

The design will require piping from the hydrants to the farm plots. The piping will be required to sustain a minimal pressure and flow rate to the sprinklers. To calculate the pressure loss in the pipe, the Darcy-Weisbach Major Head Loss Equation (Equation 10) was used. This equation calculates the major head losses along a given length of pipe for an incompressible fluid. For an estimated pipe length of 2,362 ft, which was the longest pipe distance in the first proposed design, it was calculated that the total pressure drop would be 270 ft or 624 psi. This means that for the sprinklers to operate at the minimum required pressure, the pump would need to be run at least 2.60 ft or 6 psi above the minimum pressure of the sprinklers (the minimum working pressure of the Meganet sprinkler obtained from experimental data of the prototype.

Variables	Suction Hose	Aluminum Pipe	Layflat Line	FlexNet Line
hL, major = Head loss (psi)	0.14	5.91	100.71	186.73
hL, major = Head loss (ft of fluid)	0.33	13.64	232.64	431.33
f = Darcy friction factor (unitless)	0.013911122	0.013911122	0.013016590	0.014991089
L = Pipe length (ft)	12.00	500.00	1200.00	543.33
D = Inside pipe diameter (ft)	0.5000	0.5000	0.3333	0.1667
v = Fluid velocity (ft/sec)	7.95	7.95	17.88	23.8410
g = Gravitational constant (32.2 ft/sec^2)	32.20	32.20	32.20	32.20
d = Inside pipe diameter (in)	6.00	6.00	4.00	2.00
Q = Volumetric flow rate (gal/min)	700.00	700.00	700.00	233.33
A - Cross-sectional area (ft^2)	0.196	0.196	0.087	0.022
r - Radius (ft)	0.250	0.250	0.167	0.083
ρ = Fluid density (lb/ft^3)	62.32	62.32	62.32	62.32
μ = Fluid viscosity (cP)	0.9946	0.9946	0.9946	0.9946
Re = Reynolds number (unitless)	370331.76	370331.76	555497.65	370331.76
ε or k = Pipe absolute roughness (in)	0.000039	0.000039	0.000039	0.000197
ξ = minor loss coefficients	0.20	1.50	4.30	0.15
minor loss (ft)	0.20	1.47	21.35	1.32
total major losses (psi)	106.76			
total major losses (ft)	246.61			
total minor losses (psi)	9.96			
total minor losses (ft)	23.02			
TOTAL SYSTEM HEAD LOSS (psi)	116.72			
TOTAL SYSTEM HEAD LOSS (ft)	269.63			

Table 3: Total system head loss using piping system spreadsheet.

The MQP team calculated the head loss for each line separately before adding them to get the major losses and minor losses (Table 3). The total head loss was calculated from the pump suction hose to the FlexNet lines to be about 270 feet, which we then added to the minimum working pressure of the Meganet Sprinkler, 6 psi or 14 ft, and we get a total system head loss of

276 ft. Since pressure regulators are to be installed directly before the FlexNet lines, we did not include the FlexNet head loss in the total system head loss. However, each 2” FlexNet line will experience its own head losses depending on the number of sprinklers attached to it and lengths of the FlexNet lines. If a higher pressure, or smaller head loss, is needed through the FlexNet lines, the team recommends using 4” diameter FlexNet lines, which is the same diameter as the layflat lines.

The data for the pump head loss at different flow points came from the manufacturer, and is used to find the head loss curve by plotting each point. Additionally, by using equation 5, the head loss of the system can be calculated. These data points are shown in Table 4:

Flow (GPM)	Pump Head Loss (ft)	System Head Loss (ft)
864	181	361.7816514
720	244	268.7761468
576	288	192.6807339
432	318	133.4954128
288	327	91.22018349
0	325	57.4

Table 4: Data points for the head loss of the pump and the system

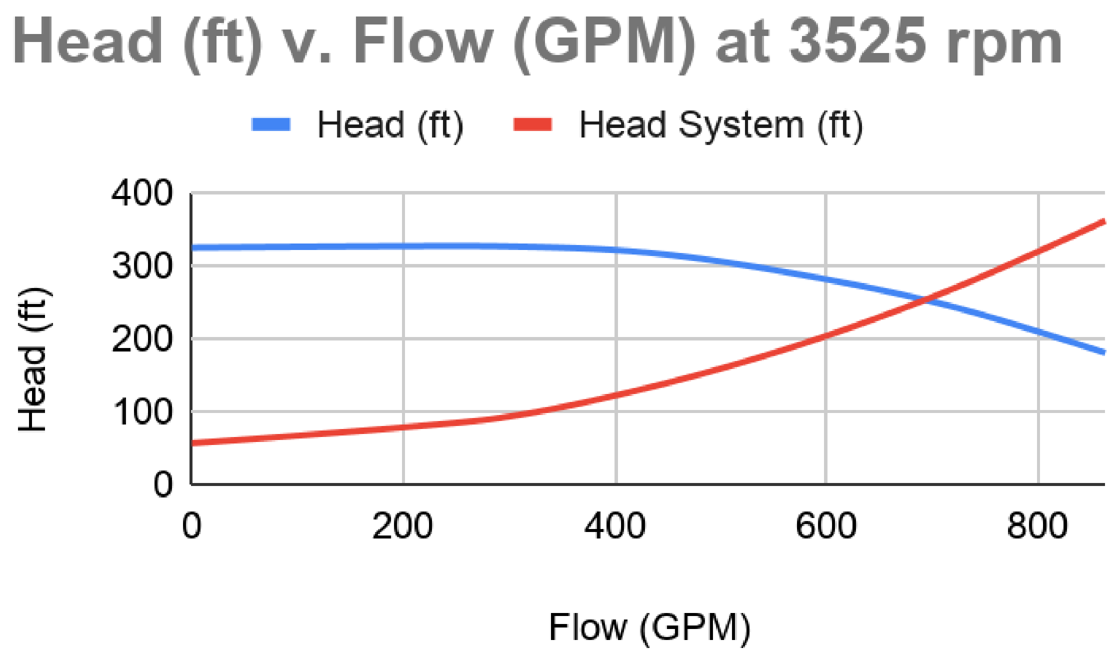


Figure 19: Operating Point Pump and System Characteristic Curve

To find the head loss data points for the system that were used to create Figure 19, Equation 5 was used, where $\Delta Z$is the initial head loss, g is the gravitational constant, Q is the head loss of the pump, and K is the head loss constant derived from head loss of the pipe parts. It is printed again below. In this case, K was assumed to be 0.008. The data points derived from the equation were plotted with a line connecting them.

$$\Delta Z + \frac{KQ^2}{2g} = h_L \qquad (5)$$

The operating point is the point where the system head loss and the pump head loss are equal, and it is the optimal point to run the system. These curves were gathered from the manufacturer of the pump. From Figure 19, the operating point lies around 150 feet with a flow of about 700 GPM. The farm may need a more powerful pump than what they have currently, but an experimental test using their current pump is required to ascertain this suggestion. This is the point where both the system and the pump operate, meaning the pump that should be chosen has 3525 rpm.

5. Mini Guide for Farmers

Upon consulting with a local vendor of irrigation supplies, Brookdale Fruit Farms, World Farmers concluded that the first design found in section 4.1.1 was outdated. Most commercial and private farms moved away from the use of 50-foot radius sprinklers with aluminum lines to a system using FlexNet, detailed in section 4.2. However, Jessy Gill, Worcester Polytechnic Institute's correspondent at World Farmers, approved the MQP team's original design and requested to formulate it into a mini guide that allowed farmed to create a smaller scale design.

The mini guide's purpose is to explain how the farmers could implement the original design into their plots. While World Farmers would not supply them with the means to do so, they could purchase the equipment themselves to create the irrigation system. A step-by-step guide to installing the system was provided, with product recommendations and a guide to tank sizing. It was also detailed how to convert the design into one suitable for drip irrigation. The mini guide is available in Appendix B.

6. Prototype

6.1 Prototype Design

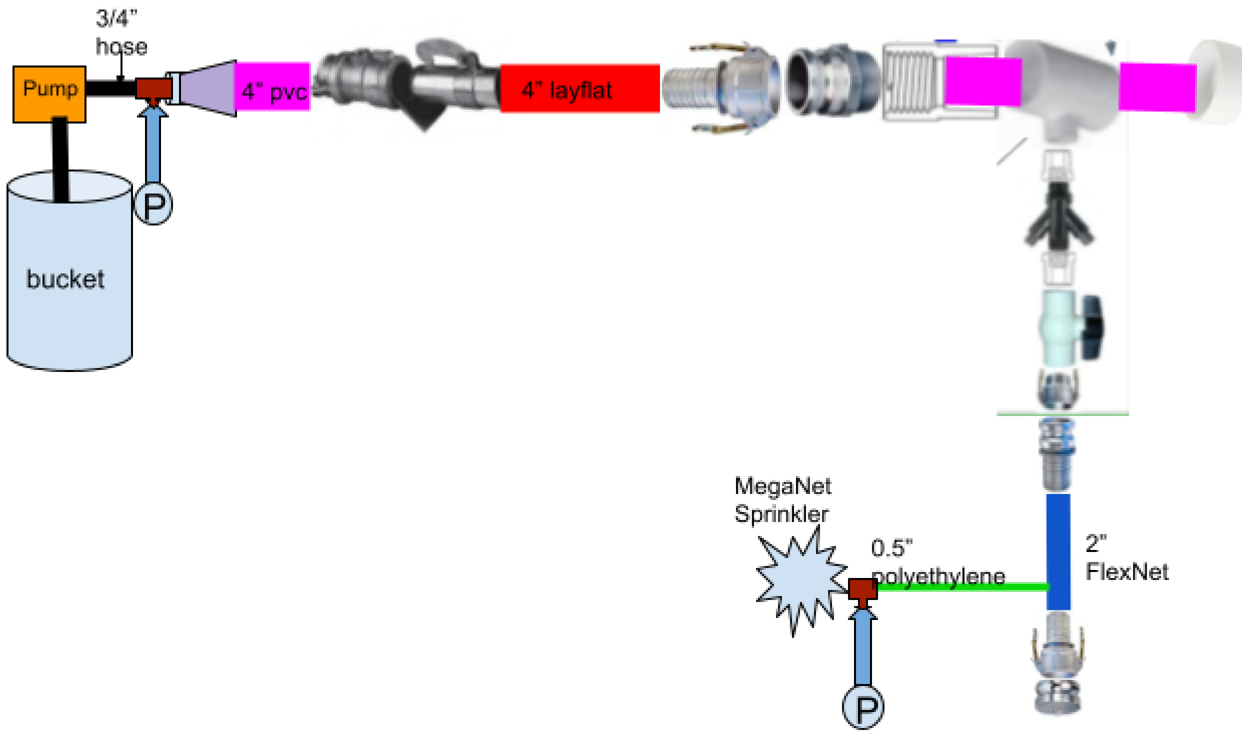


Figure 20: Prototype Design

The prototype design (Figure 20) is a scaled-down version of the actual system that will be implemented on the farm. It takes up approximately 25' x 25' and will replicate the water provided to one family farm (25' x 50'). The system begins with water being drawn out from a tank by a pump connected by a hose. The pump has a ¾" inlet and outlet, and it connects to a ¾" hose, a PVC reducer, a hook-latch, and then to the 4" layflat. After 25' of layflat, the system encounters a 90 degree bend. It uses a 4" camlock C, 4" camlock F, a thread-slip coupler, and a threaded tee with a cap on the 4" outlet. The 2" outlet that creates the bend has a threaded bushing, a pressure regulator, and another threaded bushing attached. It then goes into a PVC valve, which has a 2” camlock B and a 2” camlock E. From there, it connects to a 25’ segment of FlexNet. The end has a 2” camlock C and a 2” camlock DP. Attached 3’ from the end is a MegaNet sprinkler assembly. The pressure gauges are represented by P in Figure 20.

6.2 Prototype Tests

6.2.1 MegaNet Water Output

In order to best understand how long crops will need to be watered with the MegaNet sprinklers, it is necessary to know the MegaNet’s volumetric output of water over a given area. With this information, the farm can determine the crop which needs the least watering and determine how long it takes to water that crop. The farm can then set the sprinklers to stay on for that length of time to avoid overwatering any of the crops. To test how much water is sprinkled onto a given area, a 5 inch diameter measuring cup with a 4.5 cup volume would be placed within the range of the sprinkler of the prototype (Figure 20). The sprinkler would be turned on and timed with a timer app. Once the measuring cup filled, the timer would be stopped and the sprinkler turned off. With the full measuring cup, dividing the volume by the amount of time elapsed will give the volumetric output over the area encompassed by the cup.

6.2.2 Design Efficacy

For the prototype design to work most effectively, the system must not have any leaks in the piping material or at the connections. Also, the pressure regulator must reduce the pressure to 35 psi to produce a volumetric flow rate of 1.54 GPM. The team checked if there were any leaks in the design and the pressure before and after the pressure regulator to determine the design’s effectiveness.

6.2.3 Pressure Loss Over Entire System

In order to determine the pressure loss over the entire system, two pressure gauges were used. One was placed after the pump and the other before the sprinkler. From the Darcy-Weisbach equation (Equation 10), the head loss in one line was estimated to be 9.16 feet, or 3.96 psi. The measurement of each gauge was checked on video. The group compared the experimental pressure loss to the theoretical one.

6.2.4 Total Flow Rate Following the Sprinkler

With readings from the pressure gauges, Equation 31 was used to calculate flow rate. In this equation q is flow rate (ft^3/s), A_C is the area ratio, P_1 and P_2 (psi), ρ is the fluid density ($slug/ft^3$), D_2 is the nozzle inner diameter (ft), D_1 is the upstream and downstream pipe diameter (ft), and d is the diameter ratio (Frank, 2017).

$$Q = A_c\left(\frac{\pi}{4}\right){D_2}^2\left[\frac{2(P_1-P_2)}{\rho(1-d^4)}\right]^{1/2} \tag{31}$$

7. Results

7.1 Prototype Tests

7.1.1 MegaNet Water Output

The team's original intention was to test the water output of the MegaNet sprinkler. Despite the team's intentions, this was not possible. Unforeseen shortcomings of the built prototype made measuring this impractical. The level of water loss was too high due to the large quantity of leaks in the prototype. While this information would be useful for the farm to know, its absence does not impact the integrity of the design.

7.1.2 Design Efficiency

One measure of design efficiency is having minimal leaks within the materials and at the connections. After constructing the prototype, the MQP team encountered many leaks at each of the connections. By reinforcing them with double clamps and liquid Teflon, the leaks reduced. However, the team did not have enough time for the liquid Teflon to cure completely, and they did not have enough double clamps to secure each connection. The camlocks proved more secure than the PVC connections. Flats Mentor Farm will use aluminum piping instead of PVC, so they may not encounter this same issue. Also, they will be able to use the hook-latch part since it will be welded onto their aluminum pipes. This part will create a tighter connection between the aluminum and layflat piping.

Pressure did not reach 35 psi at the end of the system; the project group could not confirm the effectiveness of the pressure regulator. However, we believe that it will be effective when used in the real system because it did react, and it was newly bought. The output pressure of the pump was tested to be 61 PSIG. This value was obtained using a 0.5 hp non-submersible transfer pump and a pressure valve. For the first test a pressure gauge was adjusted onto a threaded tee attached directly to the pump outlet, then the hose valve was closed for a few seconds (Figure 21).

Figure 21: Pressure gauge attached to threaded tee on pump outlet;

For the second test, the pressure gauge was placed at the end of a 50-foot hose, directly on the outlet of the hose, blocking any water from escaping (Figure 22). Each test produced a pressure output of 61 PSIG.

Figure 22: Pressure gauge attached directly to hose outlet

This pump with an output pressure of 61 PSIG is estimated to have a volumetric flow rate of around 1525 GPH. As mentioned in section 7.1.1, the flow rate of the prototype could not be experimentally measured with accuracy due to the many leaks at connections and the system disassembling within seconds under pressure.

7.1.3 Pressure Loss Over the System

The team placed two pressure gages on the prototype: one on the hose at the pump outlet and the other on the FlexNet before the MegaNet. The initial pressure that the pump produced was measured to be 61 psi. This value is higher than the rated maximum pressure of 56 psi. The pressure before the MegaNet was about 6 psi, meaning the pressure loss over the system was 55 psi. Compared to the estimated pressure loss of 5.456 psi for 25 feet of FlexNet, 25 feet of layflat, and 10 feet of PVC, this pressure loss is much higher than predicted.

7.1.4 Total Flow Rate Following the Sprinkler

By solving the Darcy-Weisbach equation for volumetric flow rate, the team could calculate the total flow rate from the experimental pressure drop.

$$Q = \frac{\Delta P}{L} * \frac{\pi}{128} * \frac{D^4}{\mu} = \frac{55\ psi}{68*12\ in.} * \frac{\pi}{128} * \frac{(4\ in.)^4}{2.344\ lb.s/ft^2(1\ ft^2/144\ in.^2)} = 26.(\quad (32)$$

This calculation used the length of the FlexNet line in the prototype. Due to the leakages that the prototype experienced, the team could not measure the flow rate experimentally. It would distribute about 6.764 GPM, or about 9,738.829 GPD. This lies close to the estimated water needs for the farm, and Jessy Gill said that they refilled the tanks every other day. Seeing as the three tanks have a 3,310 gallon capacity, this flow rate still provides plenty of water to the farm.

7.2 Prototype Recommendations

The group encountered several challenges while constructing and testing the prototype. One major issue was that many of the pipe connections were leaking, which impacted the pressure losses throughout the system. Teflon liquid was used to minimize leaks, however, this sealant required several hours to dry and the system was operating before the Teflon liquid could completely dry. Another reason for leakage was not having access to the proper equipment, such as wrenches to tighten the clamps, and compatible thread sizes. Due to high pressures, the piping connections would burst at one or more locations.

The pump had a far lower output pressure than the one used at Flats Mentor Farm. The testing pump had a 0.5 hp rating, meaning it would produce about 56 psi in the prototype. Also, the pump had a broken piece. It took several minutes to reach its maximum operating pressure, and the system often disassembled by the time it reached the correct rating. The team tried to alleviate this issue with a check valve, but the pump failed to operate with it attached. However, the pump's manual did suggest adding it to the system to increase the pressure output. By strengthening the connections and priming the pump, it reached approximately 6 psi before the MegaNet sprinkler. While this pressure was sufficient for the sprinkler to expel water horizontally, it was not enough for it to rotate in a stationary position. Its full operation would require a 20 to 30 psi pressure of water.

There are a number of recommendations the MQP team has based on the challenges faced during the prototyping phase. A substantial issue encountered was that the system couldn't hold the pressure generated by the pump. For this the team recommends a longer drying period for the liquid teflon which would likely account for the time constraints faced during construction of the prototype. Alternatively, FMF could use teflon tape or a combination of liquid and tape as a more immediate solution to this problem. The least problematic connections in the prototype were camlock to camlock connections. As such, these connections are recommended where possible. For cases where this connection type is not possible the best connection identified was one which uses a double ringed clamp. While only one double-ringed clamp was tested on the prototype, this was the only non-camlock to camlock connection that did not leak.

8. Broader Impact

8.1 Engineering Ethics

This MQP project abides by the Mechanical Engineering Code of Ethics in that the team used their knowledge to enhance the careers of the farmers employed by Flats Mentor Farm. Instead of manually watering their crops, they can focus on other farming tasks and work with the other programs that World Farmers provides as they assimilate to American culture. The team met with World Farmers regularly to ensure they met the client's needs in designing an efficient irrigation system for their farm (ASME, 2012).

The team performed extensive calculations to determine the theoretical efficacy of the design and to see if the system is safe to use. By placing most of the focus on the thermo-fluids aspects of the project, the MQP team could stay within their realm of competency and provide the most accurate information to their capabilities. The team collaborated with other farms to evaluate the system based on current irrigation trends, and they compromised with Brookdale Fruit Farms and Flats Mentor Farm to design a low-cost yet efficient system (ASME, 2012).

8.2 Societal and Global Impact

This MQP project could help the farmers at Flats Mentor Farms by reducing the time they spend watering their crops. Many of the farmers are senior citizens, so the stress of labor-intensive manual irrigation is detrimental to their health. Since they will spend less time on manual irrigation, the farmers could use the extra time to focus on other aspects of farming, engage in other programs that World Farmers offers, and reduce their stress.

Other non-profit agrarian organizations could implement a similar low-cost irrigation system to assist their farmers. While this design did not fully satisfy the farm's watering needs, it did supplement it. The mini guide could become a starting point to create affordable solar-powered irrigation systems that mitigate fuel costs while improving environmental sustainability measures. Since many of the farmers come from around the world, they could integrate the ideas from the implemented system and the mini guide into their work in other countries.

8.3 Environmental Impact

A sprinkler irrigation system offers more consistent rates of water consumption compared to manual irrigation. Measuring and controlling water usage is valuable for reducing the environmental impact of farming. Water use in manual irrigation methods is highly variable depending on the farmers' techniques, and usage cannot be tracked as easily as an irrigation system, where consumption can be calculated based on flow rate and changed by adjusting pump speed or closing valves.

However, the current configuration of the irrigation system uses a gasoline-powered pump to supply water. The gasoline pump produces fumes and greenhouse gases, which pollute the environment. This issue does not exist with manual irrigation methods. Although the current irrigation system configuration uses a pre-supplied gasoline pump to stay within budget, the gasoline pump could be easily replaced with a more environmentally friendly solar-powered model.

The team created a mini guide that discussed ways to create an independent solar-powered sprinkler irrigation system to complement the water provided by World Farmers. Flats Mentor Farm did consider utilizing a solar-powered pump, but they did not have the capital costs to purchase one. However, the farmers could purchase solar-powered pumps connected to small tanks to water their own crops to sustainably manage their plots.

8.4 Codes and Standards

For the prototype, Schedule 40 was used which has a maximum pressure of 200 PSI. This was more than adequate for the prototype's projected pressure of 35 PSI and actual pressure of 7 PSI. Additionally, Schedule 40 PVC can reach temperatures of up 140 F which was higher than the room temperature water that was used.

8.5 Economic Factors

Changing from a manual irrigation system to a gasoline pump-powered sprinkler irrigation system greatly increases farming efficiency. Manual irrigation has a high time and labor cost, but a low monetary cost. On the other hand, a sprinkler irrigation system has a higher capital cost, but it saves many hours of labor and improves the quality of life of the farmers. The farmers can use the time previously spent filling and transporting water buckets on other farming tasks, such as pulling weeds or fertilizing soil. Gains in free time may be so significant that farmers may have a shorter workday. These changes will lead to higher profits versus time spent farming.

9. Conclusion

World Farmers' Flats Mentor Farm requested the design of a sprinkler irrigation system for 4 acres of farmland using layflat lines, FlexNet lines, and MegaNet sprinklers. They wanted the MQP team to use the available 63 horsepower pump to reduce the total cost of the system. The pump can support a sprinkler irrigation system when operating at a speed of 3525 rpm and a flow rate of 400 GPM. The team collaborated with another farm to design an irrigation system that supplied water for about 4 acres of land. Calculations show that the head loss through the system is about 270 ft.

To simulate the sprinkler system, the MQP team designed and constructed a small-scale prototype using the requested materials, from which the team provided recommendations to FMF for the construction of the large-scale design. Through building the prototype, the team measured the minimum working pressure of the Meganet sprinkler to be 6 psi; however, at such low pressure, the sprinkler spins slowly. Due to the Coronavirus pandemic, the team was unable to build the large-scale prototype at the farm. Hands-on experience was gained through the construction and field-testing of the prototype.

9.1 What the MQP Team Learned

Over the course of this project, the MQP team learned the process of designing an irrigation system. The team researched different technical fields, such as various irrigation systems, fluid dynamics, energy sources, power sources, and water quality standards in Massachusetts. Through a social lens, the team learned the complexities of working with a diverse clientele who were inexperienced with mechanical design. Additionally, the team learned about prototyping and fixing unforeseen problems in real time.

9.2 What Could Be Done Differently

If the MQP team had a chance to restart the project, they would confirm the specifications of the equipment sooner. This was a challenge since those at FMF were uncertain of their preferred irrigation method and the capabilities of their specific pump, such as whether the pump had adjustable rotational speeds. When building the prototype, the team would set aside more time for the Teflon liquid sealant to dry, and try to plan out how to set up the prototype beforehand. The team would also better plan for testing of the prototype, as this would better allow for some tests that had to be abandoned due to time constraints.

Appendix A: Calculations

From the pump efficiency, e_p, and the power input, P_i, the power output of the pump, P_o, can be calculated using the following equation:

$$P_o = e_p P_i$$

$$P_o = 0.697(63.2hp)$$

$$P_o = 44.05hp$$

Power output can be calculated at peak efficiency using the specific weight of water (at a given temperature), the pump head, and the desired flow rate, as shown below.

$$P_o = \gamma Q h_p$$

$$P_o = 62.3lb/ft^3(1.45ft^3/s)(268ft)$$

$$P_o = 24180\ ft \cdot lb/s$$

$$P_o = 44.0hp$$

The mini guide shows pumps used at each tank location. The tanks pump output power required for Section M can be calculated as follows.

$$P_o = \gamma Q h_p$$

$$P_o = 62.3lb/ft^3(0.0147ft^3/s)(56.4ft)$$

$$P_o = 51.7ft \cdot lb/s$$

$$P_o = 0.0939hp$$

$$P_o \cong 70.0W$$

The input power that the tanks pump requires to operate can now be found using the following formula, assuming the pump is operating at 65% efficiency.

$P_i = e_p / P_o$

$P_i = 0.65/70.0W$

$P_i \cong 108W$

Setting the source head (tanks elevation), H_S, as the datum point (0 ft), the farm elevation, h_R, becomes -5. The pump pressure head comes from:

h_P = Pump Head;	$h_p = (h_R - h_S) + h_L$
h_S = Source Head;	$h_p = (-5 - 0) + 56.4$
h_R = Receiving Body Head;	$h_p = 51.4$ ft
h_L = Head Losses	

Alternatively, if the tank pumps from the bottom instead of the top, the difference in elevation ($h_R - h_S$) equals 0 ft, and the pump head equals the head losses of 56.4 ft.

Appendix B: A Farmer's Tank Irrigation Mini Guide

In consideration of those at World Farmers Flats Mentor Farm located in Massachusetts, the MQP group created this Mini Guide to assist farmers in developing their own sustainable irrigation system.

To use a given water holding tank, you will likely need to operate a pump with hoses or piping to transfer water. In place of a pump, you could use gravity and PVC piping to irrigate your land, which will be discussed in the final section of this guide. This guide lists essential steps and questions to help you design a tank-pump irrigation system that adequately suits your specific needs.

1. Estimate your watering needs

a. How many plants are you watering?

The amount of needed water can be found by counting the total number of crops and multiplying it by 0.6 gal (2 liters), the average amount of water a full-size plant needs in 1 day.

Ex: Say you have 12 crops on your plot. To calculate the amount of water needed, $12 * 0.6 = 7.2$ gallons per day, or 24 liters.

b. What is the size of your land?

For larger areas, multiply the length and width of your land, then divide it by 4 ft^2 (assuming plants are 2 ft apart). Multiply this value by 0.6 gallons (2 liters).

Ex: A plot of land that is 25 by 50 ft has an area of 1,250 square ft and an estimated 312 plants, which require 187 gallons (709 liters) of water daily.

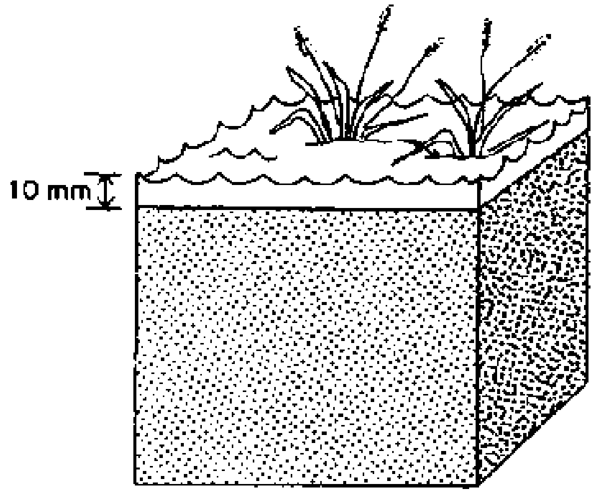


Figure A: 10 mm/day water volume per area (Crop Water Needs, n.d.)

2. Acquire the appropriate tank and measure its dimensions.

Common tank volumes include the following: 50, 100, 200, 500, 1000, 3000, and 5000 gallons. These water storage tanks are also referred to as Intermediate Bulk Containers (IBC). Your tank should hold enough water for at least 1 day of crop watering needs. A farm plot which requires 187 gallons of water per day should utilize a 200 gallon tank.

Take note of the height of your tank and the location of the water outlet on the tank. Some tanks have the outlet close to the bottom while others have an opening on the top.

Figure B: Various water tank sizes

Tank Recommendations:

- UV-resistant Polyethylene Tanks with both inlet and outlet
- Firm base or foundation to keep it from falling or bursting at the bottom
- A submersible pump should be placed a few inches from the bottom of the tank to avoid sludge entering the pump

NOTE: Check the diameter of the inlet and outlet carefully! Make sure they match your piping from the pump and the piping to the crops.

3. Estimate the distance between your tank and farm and connect your pump and farm land with hose

The distance from your tank and farm land is approximately the length of your hose or piping. The further away your farm is from your tank, the more hose or piping you need and the more powerful the pump will need to be. The hose should be able to withstand the appropriate amount of pressure your pump discharges. For example, if your pump has a pressure output of 80 psi, it is essential that the hose is able to withstand such pressure. You can utilize a garden hose or layflat lines to transfer water. Below is a common layflat product used to transfer water for irrigation purposes.

Distributed by Brookdale Fruit Farm (Hollis, NH)

Heavy Duty Lay Flat

Heavy Duty water hose for main lines, water wheel travelers and discharge hose. Long lasting and rugged.
Sold in 300 foot rolls

Size	Max PSI	Part Number	Price
1.5"	150 PSI	LFR15	$230.00
2"	150 PSI	LFR20	$300.00
3"	150 PSI	LFR30	$600.00
4"	125 PSI	LFR40	$790.00

Figure C: Layflat Specifications

4. Choose your pump and power source

The pump you choose should be powerful enough to provide enough pressure at the outlet of your hose. The pressure required for a standard size garden hose (⅝ inches in diameter), is 30 psi (207 kPa). The longer your hose, the more pressure the pump must output to move water through the length of your hose. In order for a sprinkler system to work properly, the pump should output a minimum of 30 psi. This typically requires a pump that is 0.5 hp. Two common power sources for a small pump are AC electric power and solar power. To use AC power, simply plug the pump into a nearby wall outlet. For a solar-powered pump system, it is recommended that you purchase an all-inclusive kit that includes the solar panel, solar-powered pump, and cables, as shown below.

Distributed by Amazon

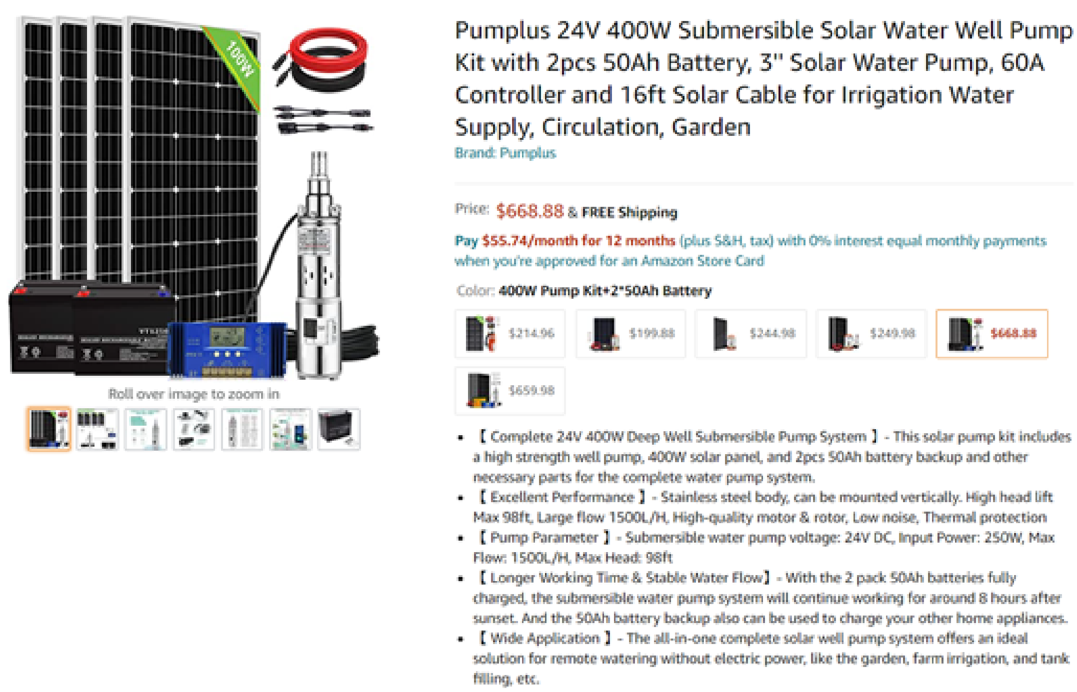


Figure D: Solar Powered Pump Kit

Benefits:

- Comes with solar panels, solar battery, and water pump
- Designed for irrigation
- 250 W would suit the 50-foot radius sprinklers
- Flow rate: 6.6 GPM (gallons per minute)

5. Choose your watering method

There are several ways to directly water your crops: you can manually water each plant with your garden hose, use sprinklers, or establish a drip irrigation system. This guide will focus primarily on the sprinkler system method. Two important factors to consider when choosing a sprinkler is the flow rate and radius of the water flow. The output volumetric flow of a sprinkler can range from 2-13 gallons per minute and its radius can range from 20-30 ft. Below are two comparable sprinklers sold by IrrigationKing that can efficiently water your crop area.

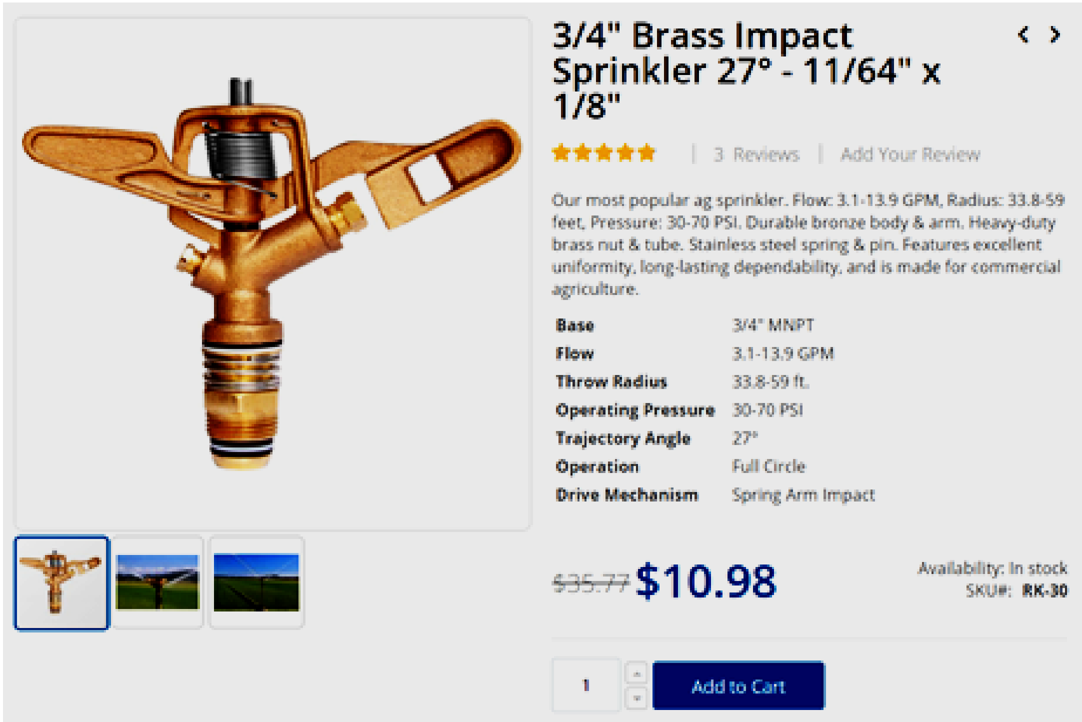


Figure E: Threaded Sprinkler with 59 ft Radius

Benefits:

- Up to 59 foot radius so it will cover the entirety of the plot
- Dual jets for more coverage
- Corrosion resistant
- Full circle rotation
- Using the 250 Watt pump kit would create a 50 foot radius

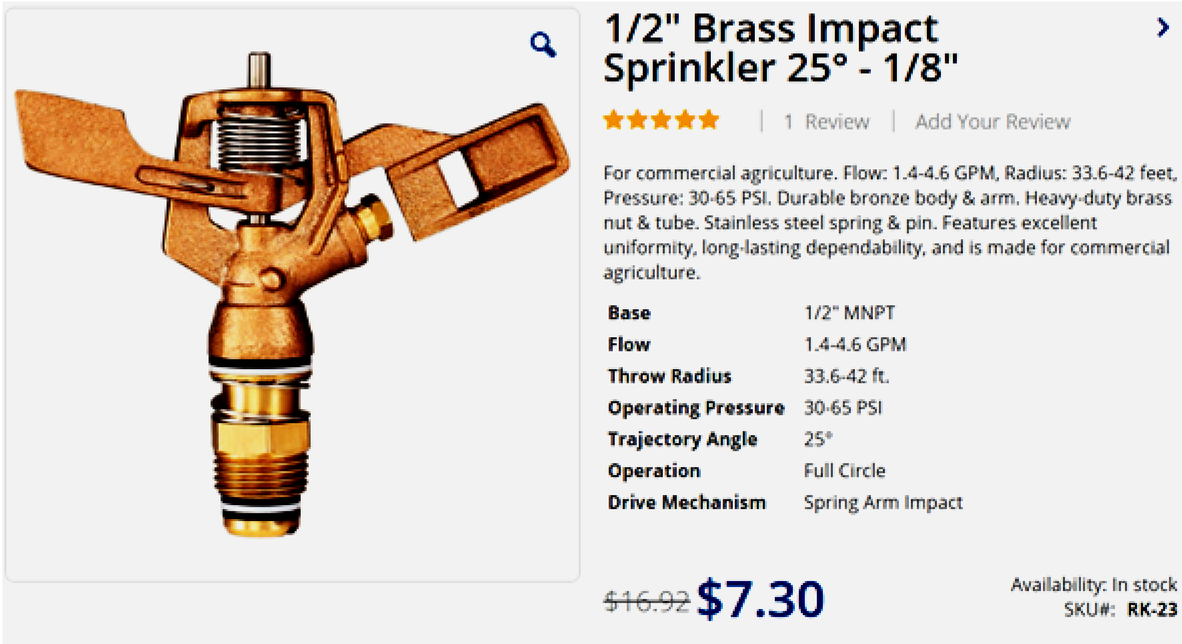


Figure F: Threaded Sprinkler with 42 ft Radius

Benefits:

- Corrosion resistant
- Single jet of water
- Designed for agriculture
- Using the 120 Watt pump would create a 40 foot radius

With the above information, you can determine the amount of time it would take your pump to irrigate your farm land given the following assumptions:

- 50 foot radius sprinklers
- Pump power of 250 Watts
- Flow rate = 6.6 GPM

Table 1: Time of Pump Operation

Tank Size	Time to Empty Tank

275 gallon tank	42 minutes
500 gallon tank	76 minutes
1000 gallon tank	152 minutes
1500 gallon tank	227 minutes

To determine the time to empty for your tank, divide the capacity in gallons by the pump's flow rate in gallons per minute (GPM). You can use an online calculator to convert the units (e.g. L/h) into GPM or whichever units you prefer.

10 Steps to Install Your System:

1. Place the pump by the tanks (or inside the tank if pump is submersible)
2. Attach the solar panels (and solar battery if applicable) as instructed by the pump manufacturer

NOTE: You may be able to connect the existing pump to your tank if permitted.

3. Connect the pump to the hydrant using piping
4. Use piping to connect the hydrant to each of the tanks and the tanks to each other. This piping system will transport water from the river to the hydrant to the tanks.
5. Turn off the pump **GRADUALLY** once the tanks have been filled to avoid overfilling them and prevent water hammer from occurring
6. Connect piping to the tank outlet that is long enough to reach the desired plot
7. Make sure the piping has holes the desired distance apart and attach sprinklers to the openings
8. Install a submersible solar-powered pump at the bottom of each tank as per the manufacturer's instructions
9. Turn the pump on for the duration you wish to water the crops or until the tank is nearly empty.

NOTE: Using the pump with unfiltered water risks damaging the pump.

10. To use a drip irrigation system, attach a “soaker hose” to the pump and extend it throughout your farm plot

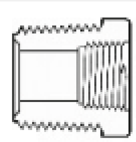
Appendix C: Components of the Irrigation System

FlexNet lines and MegaNet sprinklers.

1 ½" 2 tip
Regulator
PR-15…$30.00
GPM: 7-40
Regulation PSI
12, 15, 20, 25, 30,
35, 43, 50, 65

Pressure Regulator

Bushing
FPT x MPT

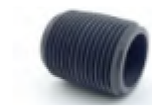


Threaded Bushing

Flexnet Plug

FlexNet Plug

Nipples- SCH80
MPT x MPT



Nipple

Threaded Ball Valve

Clamp on Hook Latch Set
Repair run over pipe
2 inch……$45.00
3 inch……$58.00
4 inch……$71.00

Hydrant Hook and Latch with Camlock Adaptor

Heavy Duty Lay Flat

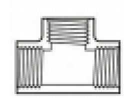
Heavy Duty water hose for main lines, water wheel travelers and discharge hose. Long lasting and rugged.

Sold in 300 foot rolls

Size	Max PSI	Part Number	Price
1.5"	150 PSI	LFR15	$230.00
2"	150 PSI	LFR20	$300.00
3"	150 PSI	LFR30	$600.00
4"	125 PSI	LFR40	$790.00

Layflat

Threaded Tee

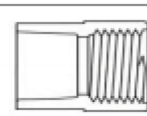


FPT x FPT x FPT

¾”.........405-007........$2.00
1”.........405-010.........$2.75
1 ½”......405-015........$4.00
2”.........405-020.........$5.00

Threaded Tee

Female Adaptor



Slip x Female

¾”........435-007........$0.65
1”.........435-010........$0.85
1 ½”......435-015........$1.00
2”......... 435-020.......$1.25
3”.........435-030........$4.50
4”.........435-040........$5.75
6”.........435-060........$21.00

Female Adaptor

Camlock A	Camlock B	Camlock C
Male x male pipe thread ¾"A……$3.50* 1"A…….$3.50* 1 ½"A…$3.75 2"A…….$4.50 3"A…….$7.50 4"A…….$12.00 	Female x male pipe thread ¾"B……$7.00* 1"B…….$7.00* 1 ½"B…$7.25 2"B…….$9.50 3"B…….$15.00 4"B…….$19.50 	Female x barb ¾"C…….$6.50* 1"C……..$6.50* 1 ½"C….$7.00 2"C……..$9.00* 3"C……..$14.75 4"C……..$22.25 
Camlock D	**Camlock E**	**Camlock F**
Female x female pipe thread ¾"D……$6.50* 1"D…….$6.50* 1 ½"D…$7.50 2"D…….$10.25 3"D…….$15.50 4"D…….$22.50 	Male x barb ¾"E…….$4.00* 1"E……..$4.00* 1 ½"E….$4.25 2"E……..$4.50* 3"E……..$9.50 4"E……..$14.00 	Male x male pipe thread ¾"F…….$4.00* 1"F……..$4.00* 1 ½"F….$4.25 2"F……..$5.50 3"F……..$10.25 4"F……..$15.25 
Camlock DP	**Camlock DC**	**Camlock Gaskets**
Male plug ¾"DP……..$4.00 1"DP……..$4.00 1 ½"DP….$4.25 2"DP……..$4.50 3"DP……..$7.50 4"DP……..$11.00 	Female plug ¾"DC……$6.50 1"DC…….$6.50 1 ½"DC…$6.75 2"DC…….$8.00 3"DC…….$12.50 4"DC…….$17.00 	¾" ..1"….$0.75 1 ½"……..$0.75 2"…………$1.00 3"…………$2.00 4"…………$2.00 6"…………$3.50 

Standard Camlock Types

Appendix D: Brookdale Fruit Farm Quote for First Design

		Quantity	Unit	Item	Unit Price	Total
1		16	rolls	2" x 328' flexnet with 6' holes	$295.00	$4,720.00
2		225	assembly	Green meganets with tubes and stakes	$12.00	$2,700.00
3		14	each	4"x4" x 2" threaded tee	$21.00	$294.00
4		14	each	2" x 3" nipples	$3.50	$49.00
5		14	each	2" threaded ball valves	$12.00	$168.00
6		14	each	1.5" pressure regulator at 35 PSI	$30.00	$420.00
7		28	each	2" x 1.5" threaded bushing	$2.75	$77.00
8		14	each	2" camlock B	$9.00	$126.00
9		14	each	2" camlock E	$4.50	$63.00
10		20	each	2" camlock C	$8.00	$160.00
11		20	each	2" camlock E	$4.50	$90.00
12		14	each	2" camlock DP	$4.00	$56.00
13		10	each	2" couplers	$1.55	$15.50
14		15	bags	2" clamps	$6.50	$97.50
15		1	can	liquid teflon	$14.00	$14.00
16						$0.00
17		14	bags	flexnet plugs	$12.50	$175.00
18						$0.00
19						$0.00
20		28	each	4" female adapters	$5.50	$154.00
21		14	each	4" camlock B	$18.50	$259.00
22		14	each	4" camlock F	$15.00	$210.00
23		14	each	4" camlock C	$22.00	$308.00
24		14	each	4" camlock E	$14.00	$196.00
25		1	assembly	4" hook and latch x camlock adapter	$65.00	$65.00
26						$0.00
27						$0.00
28						$0.00
29						$0.00
30						$0.00
31						$0.00
32						$0.00
33						$0.00
34						$0.00
35						$0.00
36						$0.00

Notes:

	Total	$10,417.00

Appendix E: How to Optimize

A linear optimization problem is a mathematical problem where the best input element from a set must be chosen in order to maximize or minimize an output. Linear optimization problems consist of three main parts, with the first one being an objective function which contains a quantity that is to be minimized or maximized. Additionally, optimization problems contain a series of unknown variables that affect the objective function. If **x** represents these unknown variables as a whole, then **f(x)** displays how the variable **x** affects the quantity that should be maximized or minimized. Finally, the optimization problems often feature constraints that restrict the values that can be assigned to the unknown variables. These constraints can vary from simple boundary conditions that determine the domain of each variable, or they can be more complex and tie multiple variables to each other. The goal of most optimization problems is to assign values to the unknown variables that fall within the constraints and use these variables to find the minimum or maximum value for the objective function. When working with linear optimization problems, some are considered constraint satisfaction problems, which do not define an explicit objective function, and instead, the objective is to find a solution that satisfies all of a set of multiple predefined constraints.

To solve a linear optimization problem, linear programming must be taken advantage of. When an optimization problem is described with mathematical symbols, functions, and relationships, the problem is called a mathematical program, and if the relationships are linear, then the problem is known as a linear programming problem. A linear programming problem involves finding a variable **x** to maximize the given linear function, where **x** ranges over all vectors satisfying a given system $\mathbf{Ax} \leq \mathbf{b}$ of linear inequalities. One of the most prominent ways of solving a linear programming problem is by using the simplex algorithm. The simplex algorithm operates on the canonical form, which involves maximizing the function cTx when it is subjected to the constraints **$Ax \leq b$** and **$x \geq 0$**. The c is in the form **c = (c1, … cn)**, and is the coefficient of the objective function. The **T** indicates the matrix transpose, which swaps the row and the column of the matrix. **A** is a **p x n** matrix that when multiplied by **x = (x1, … xn)**, leads to an inequality with **b = (b1, … bp)**. The feasible region is the set of all possible points, or x values, that fulfill the constraints of the linear programming problem. For a linear program that is in standard form, if the objective function has a maximum value on the feasible region, then that tells us that the maximum value lies at an extreme point. An extreme point is a point in a convex set which does not lie in any open line segment joining two points of the convex set, and it always lies within the feasible region. However, because there are so many extreme points in most linear problems, this is not that useful. In order to use the simplex algorithm, the problem must be converted to standard form.

One important aspect to standard form is that all inequalities should be transformed into equalities to make the problem easier to solve. Having an inequality between two equally sized vectors means that for every value within the first vector, the equivalent value in the second value in the second vector matches the stated inequality between the two. For example, if there are two equally sized vectors **r = (r1, … rn)** and **w = (w1, … wn)**, then if **$r \geq w$**, then that means **ri ≥wi** for **i = 1, …, n**. As an example, we want to maximize the objective function **z = x1 + 3x2 + 5x3**. The constraints of this problem are that **x1≥3**, **3x1 + x2 + 4x3 ≤ 4**, and **8x2 - 3x3≤ 9**. To transform a linear problem into standard form, for each variable with a lower bound other than 0, a new variable is introduced representing the difference between the variable and bound, which is used to remove the original variable using substitution. For example, since x¬1≥3, then a new variable y is introduced so that **y= x1 – 3**, and **x1 = y + 3**. This can be rewritten as **x1–y=3**. Now the second equation can be used to eliminate x1 from the linear program. Then, for each remaining inequality constraint, create a slack variable that changes the constraint into an equality constraint since it is easier to algebraically manipulate these equations. For example, if **3x1 + x2 + 4x3 ≤ 4** and **8x2 - 3x3≤ 9**, then replace these with **3x1 + x2 + 4x3 + s = 4** and **8x2 – 3x¬3 + v = 9**. In this case, the s values are considered the slack variables. Finally, eliminate each unrestrained variable from the linear equation by solving an equation where it appears and then eliminating it through substitution. After completing this, all the constraints have now been rewritten as equations, meaning that they are easier to manipulate and solve. Also, the constraint equations are written in canonical form. This means that each constraint equation contains one variable with a coefficient of 1 that does not appear in the other equations, in the form of the slack variable. These variables are called basic variables, while the other variables are considered nonbasic variables. The nonbasic variables are the ones that make up the original objective function. Now, everything can be put into a matrix:

$$\begin{array}{ccccccc} 1 * x1 & 0 * x2 & 0 * x3 & y & \square & \square & 3 \\ 3 * x1 & 1 * x2 & 4 * x3 & \square & s & \square & 4 \\ 0 * x1 & 8 * x2 & -3 * x3 & \square & \square & v & 9 \end{array}$$

While the objective function can be rewritten as:

z - x1 - 3x2 - 5x3 + 0y1 + 0s1 + 0s2 = 0

Now that the problem has been changed to canonical form, the nonbasic variables can be set to zero and the solution can be obtained from **y = 3**, **s = 4**, and **v = 9**. This solution corresponds to the nonbasic values being equal to zero, and the set of basic variables is said to constitute a basic feasible solution. To test whether this solution is optimal, see how high the nonbasic variables can increase without making any of the existing variables negative. For example, because x3 has the largest coefficient, it will be picked as the entering variable, meaning that it will enter the set of basic variables. Then, **y = 3**, **s = 4 – x2** and **v = 9 – 8x2**. Here it can be seen that values of **x2** greater than 9/8 will drive **s2** negative. That means the maximum possible value for **x2** is 9/8, and **s2** will be chosen as a leaving variable that becomes nonbasic since it is the first value that will become zero by increasing **x2**. The equation that the leaving variable appears in is called the pivot equation. To reconstruct canonical form with respect to the new set of basic variables, the equations must be rewritten so that the new basic variables each appear in just one equation with a coefficient of 1. That means that **x2** will have a coefficient of 1 in the third equation, and a coefficient of zero in the first two. To rewrite the equations in the matrix, perform elementary row operations such as multiplying a row by a constant. Doing this will not change the set of variables needed to satisfy an equation, but it will make it easier to add a multiple of one row to another, allowing for the elimination of certain variables.

To perform the simplex algorithm, first perform the necessary operations to get a basic feasible solution. Then test the current solution for accuracy by checking if all coefficients in the objective function are non-negative. If they are, then the solution is optimal, but if they are not, then choose an entering variable by identifying the smallest coefficient of the objective function. Then find the leaving variable by finding which basic variable becomes zero first when increasing the entering variable. The equation that contains the leaving variable is the pivot equation, while the coefficient of the entering variable within that equation is the pivot value. Finally, use elementary row operations to update the canonical equations by making the entering variable into a basic variable. After that, test the solution for optimality, and if it isn’t optimal, then repeat the above process until all the coefficients in the objective function are nonnegative.

Overall, using the simplex method is the easiest way of solving a linear optimization problem, as the linear solver in Excel is an implementation of the simplex method, and the simplex method constitutes virtually every successful commercial software package for optimization. (Rebonato, 2010)

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