Specific Power Requirements for a Aquifer Pump for Farmers in Massachusetts

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QR Code Linked to Sources

Project Introduction & Background

Access to sustainable water resources is critical for the success of farms, particularly in regions like Massachusetts where agricultural practices face unique environmental and regulatory obstacles. For smaller and medium sized farms (~66 acres), this presents the challenge of navigating the intersection between water need and energy costs. Due to a lack of accessible municipal water sources, many Massachusetts farms depend on underground sources of water, such as wells and aquifers. However, there are strict regulations around the amount of water one is allowed to extract, putting pressure on farmers to avoid overconsumption (3). Because of this limitation, farmers often use irrigation techniques that optimize water usage, particularly drip irrigation. Drip irrigation regulates the amount of water being delivered to crops while minimizing the amount of excess water used, which can result in environmental runoff (1).

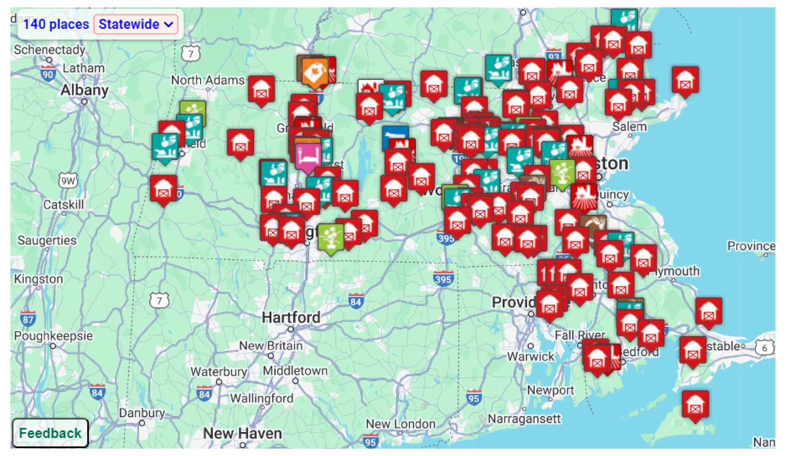


Fig 1: Map of farms with sweet corn in Massachusetts (2)

Pumps go up in price the more powerful they are, so in order for farmers to spend as efficiently as possible, they need to know how much power they actually need for their drip irrigation systems to function. For our project, we took on the challenge of identifying the amount of power needed to water a scalable sweet corn drip irrigation system.

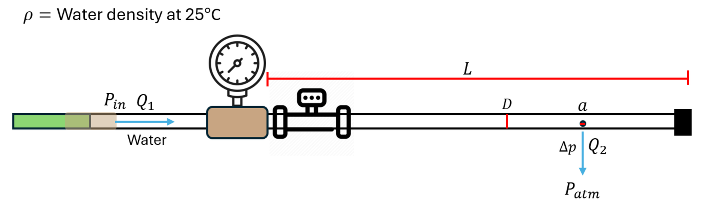
Darcy-Weisbach and Bernoulli Model Parameters

To specify a pump, we first need to determine how much power is needed for our hypothetical drip-irrigation system. We decided to use a scaled-down model with one drip hole so that we could experimentally validate our model.

Model Assumptions:

- Friction is the primary loss of energy in the system; all else is negligible
- Perfectly horizontal and vertical pipe orientations
- Incompressible fluid (constat density of water within pipe)
- Steady-state flow under a turbulent regime
- Uniform cross-sectional area along the pipe
- Constant surface roughness, smooth pipe
- Constant temperature

ρ = Water density at 25°C



$$J_{total} = J_v + J_h \qquad J_v = \frac{Q_1(P_{in} + \rho g h)}{\eta} \qquad J_h = \frac{Q_1(P_{in})}{\eta}$$

Eq 1: Power Equations

The total power needed for our system can be split into a vertical (J_v) and a horizontal (J_h) component. Because we are only planning on physically validating the horizontal component of the model, we will focus on the horizontal component (J_h) of this equation.

Our equations were developed using a combination of Bernoulli's principles and the Darcy-Weisbach equation. Before applying Bernoulli's principle, we first created an equation for inlet Pressure (P_{in}) using the changes in pressure within the system:

$$P_{in} = P_{atm} + \frac{1}{2}\rho\left(v_2 - v_1\right)^2 + \Delta p$$

Eq 2: Inlet Pressure Equation

The second term in Eq 2 represents the change in pressure due to a change in water velocity throughout the pipe. This term is derived from Bernoulli's equation and is used to relate the inlet pressure (P_{in}) to the inlet flow rate (Q_1), drip hole flow rate (Q_2), the pipe diameter (D), the drip hole diameter (a), and the length of the pipe (L).

The third term is derived from the Darcy-Weisbach equation and represents the head loss of the pipe: the amount of pressure our system would need to overcome the friction between the pipe and the flowing water.

$$\Delta p = f_D \frac{8Q_1^2 \rho L}{\pi^2 D^5} \qquad f_D = \frac{0.3164}{Re^{0.25}}$$

Eq 3: Darcy-Weisbach Term

$$P_{in} = P_{atm} + \frac{1}{2}\rho\left(\frac{16Q_2^2}{\pi^2 a^4} - \frac{16Q_1^2}{\pi^2 D^4}\right) + \frac{8f_D L\rho Q_1^2}{\pi^2 D^5}$$

Eq 4: Expanded Inlet Pressure Equation

To compare our experimentally gathered data to our theoretical model, we can re-arrange our final equation to solve for the volumetric flow rate of water out of the drip hole.

$$Q_2 = \sqrt{\frac{\pi^2 a^4}{16}\left(\frac{2\left(P_{in} - P_{atm} - \frac{8f_D L\rho Q_1^2}{\pi^2 D^5}\right)}{\rho} + \frac{16Q_1^2}{\pi^2 D^4}\right)}$$

Eq 5: Re-arranged Expanded Equation

Preparing Experiment & Data Gathering

Fig 2: Physical Test Model

Procedure:

1. Set up system with correct drip hole PVC end
2. Turn on the hose; measure the flow rate. We kept the hose at the same pressure each trial.
3. Use a graduated cylinder to collect water. Simultaneously start a timer as you put the graduated cylinder under the steady-state flow from the drip hole.
4. Hold the graduated cylinder under the drip hole flow for 9 different durations (~1 second apart).
5. Once you reach a new time, simultaneously stop the timer and remove the graduated cylinder.
6. Record the time on the stopwatch and the volume of water in the graduated cylinder.
7. Repeat steps 3-6 until you have 9 data points for different lengths of time.
8. Turn off the water flow into the pipe. Switch the current .T PVC pipe to one with a new drip hole size.
9. Repeat steps 1-8 until you have data for all of your drip hole . sizes.

Figure 2 shows the physical model we used to gather data. We used a 3/4in garden hose in-line with a pressure gauge (P_{in}), an Arduino-powered flow meter (Q_1), and a 2ft length (L) of 1/2in PVC (D) with different drip hole sizes (a). To measure the water flow out of the drip hole (Q_2) we used a 200mL graduated cylinder and a timer. Our model's variables are defined below.

D = 1/2in , L = 24in, P_{in} = ~10psi
a = 9/64in, 1/8in, 7/64in, 3/32in, 5/64in

Metrics & Experimental Results

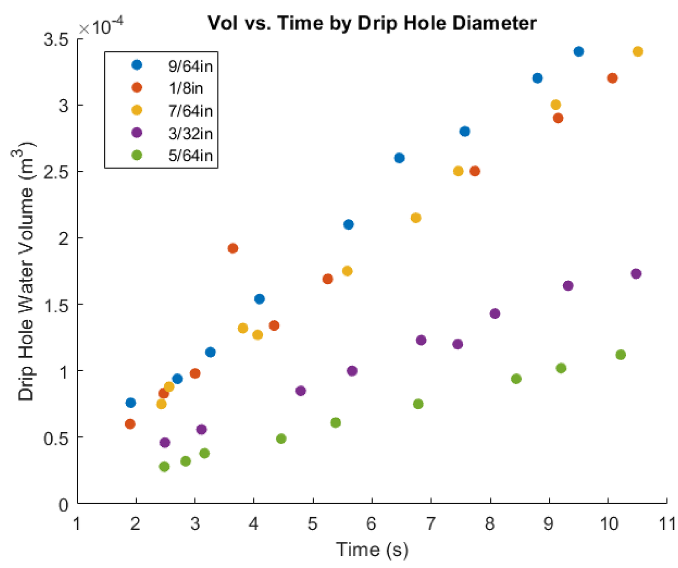


Fig 3: Volume vs. Time (Measured)

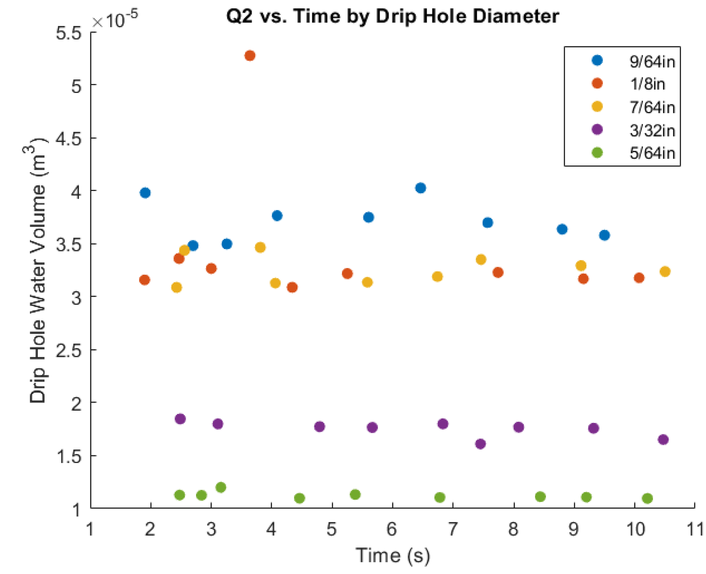


Fig 4: Drip Flow Rate vs. Time (Measured)

Before using our data to validate our model, we wanted to take a closer look at it to make sure that it fit our expectations.

Because we were not measuring the drip hole flow rate directly, but rather the volume of water flowing out over time, we wanted to make sure that our calculated flow rates made sense. The first plot shows the volume vs. time,

which, as expected, maintains a linear relationship, with the exception of an outlier in the 1/8in drip hole data. As expected, the flow rate vs. time plot was also constant, which made sense as we were keeping pressure constant throughout trials. While the pressure within the system differed slightly from trial to trial, it was overall pretty similar, so the increase in mean flow rate as the drip hole diameter increased made sense.

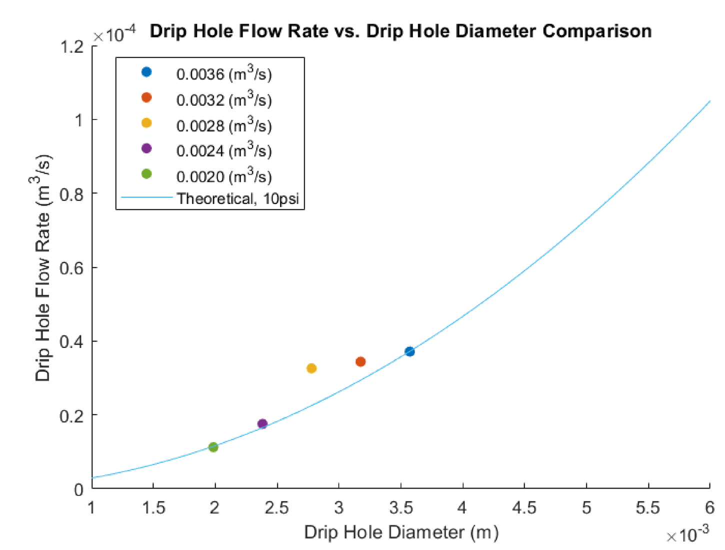


Fig 5: Drip Flow Rate vs. Drip Diameter

Figure 5 shows a comparison between our theoretical model and the experimentally-gathered data. The theoretical line was generated using an inlet pressure value of 10psi, which was pretty close to the pressure in the pipe.

While the data we gathered is pretty close to our theoretical model, we would need to gather more iterations of data at different pressures and lengths of time before being confident that it is reasonably applicable to scoping agricultural pumps.

However, despite the need for further validation, we believe that the model is pretty reasonable. In the 'Determining Power Specifications' section we determine that the power needed for 1-acre of sweet corn is 1.9HP horizontally and 3.8HP overall. These values are comparable to values we calculated from literature (3-4HP per acre of sweet corn) (6, 7).

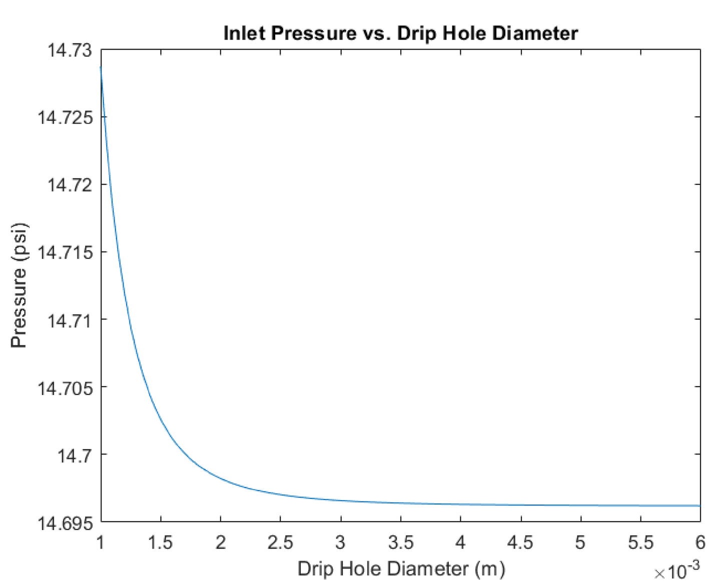


Fig 6: Inlet pressure vs. Drip Hole Diameter

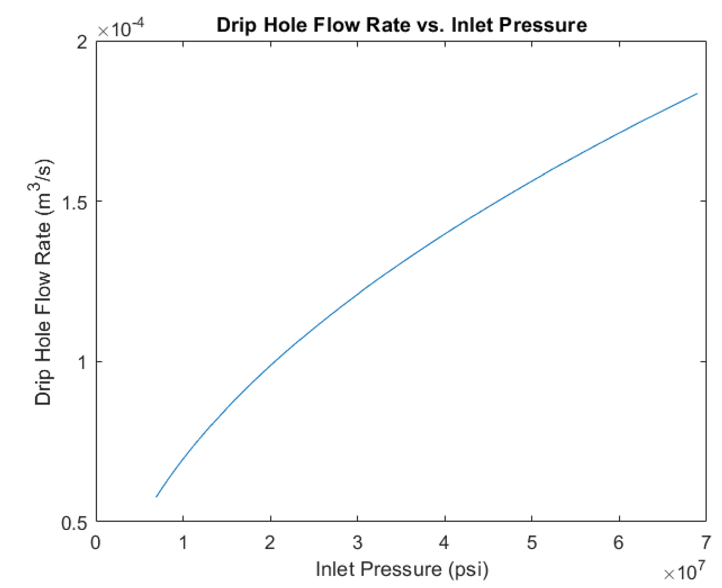


Fig 7: Drip Hole Flow Rate vs. Inlet Pressure

Figures 6 and 7 show the relationship between key variables in our theoretical model. Figure 6 shows the relationship between inlet pressure and drip hole diameter, where Q2 is kept at a constant rate of 0.0083333 gallons per minute, which aligns with the flow rate for sweet corn.

Figure 7 shows the relationship between drip hole flow rate and inlet pressure. Because we were unable to accurately measure changes in pressure, we were unable to validate these models, but they show a good representation of how pressure and drip hole diameter would impact drip hole flow rate.

Reflection on Measurement & Uncertainties

While we were able to successfully gather data with our experimental system, we encountered challenges that likely impacted the quality of our data. Most notably, we had continuous issues with our pressure gauge. We measured that we were sending in about ~10-15psi of water into the system, but the actual gauge was unreliable, meaning that we cannot confidently validate our model with pressure.

The graduated cylinder used to measure the drip hole's water volume had a precision of ±20 mL, introducing potential error.

Similarly, inaccuracies likely arose in timekeeping and removing the beaker from the water.

Something that we noticed was that the drip flow rate was much stronger than we were hoping for; water flowed out in a stream rather than a drip. While we could have attempted to drip by opting for a lower inlet pressure, we would not have been able to get pressure data at all due to the rating of our pressure gauge.

Determining Power Specifications

To determine the power we would need for our hypothetical acre of sweet corn, we scaled up our theoretical model. For our math, we used a drip hole diameter of 3/32in. We assumed that the flow rate was linear for the entire length of each row (66ft). Additionally, when scaling up our model, we decided to space out our rows by 3 feet and our plants 1 foot with each other given a study provided by the University of New Hampshire. To make the area of land one acre, we had to create an area 660 ft wide by the 66ft depth we chose. The visual below depicts the model we scoped a pump for:

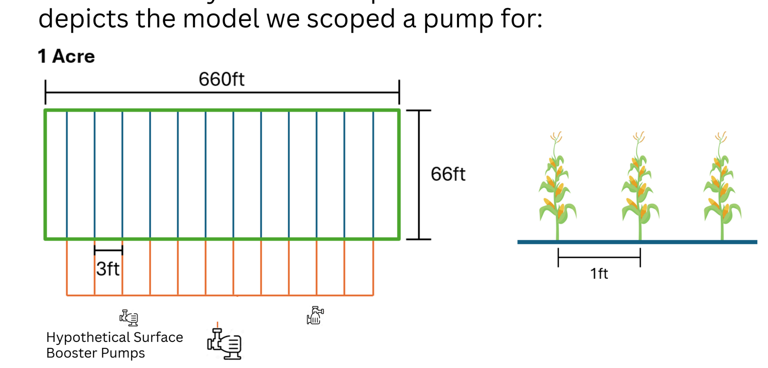


Fig 8: Model values of corn plants/acre

How Much and When to Water

The first component of the specific power of a pump is the volumetric flowrate. An the second is the pressure loss and displacement coulmn pressure for a vertical pipe. Recall our equations for power presented after the introduction:

Common Flow Parameters for DripLine per 100 ft						
Emitter Spacing	0.4 GPH Emitter		0.6 GPH Emitter		0.9 GPH Emitter	
Inches	GPH	GPM	GPH	GPM	GPH	GPM
12"	42	0.70	61	1.02	92	1.53

Table 1: Flow Parameters for Driplines (9)

In order to determine the maximum drip flow our system would be able to provide, we looked at the various growth stages of corn and the soil conditions in Massachusetts.

The greater Boston area has loamy terrain, meaning that water gets quickly soaked up and generally stays in the ground. Because of this, a smaller emitter is preferred.

We are also assuming that our system is able to transfer ~90-95% of the water to plants (rather than run-off).

More information on watering depth and soil saturation can be found in our resources QR code (4), (8).

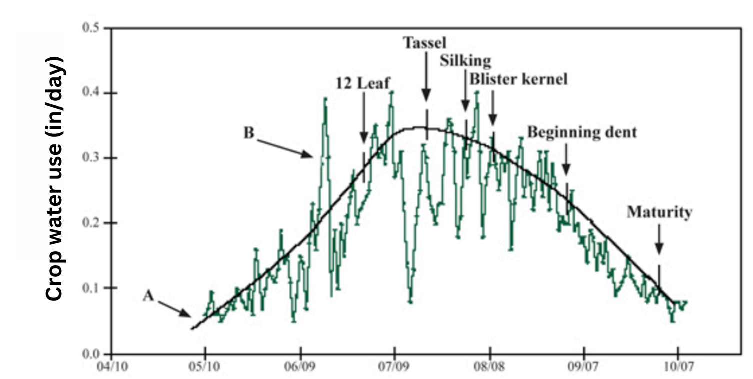


Fig 10: Corn water use throughout life cycle

When scoping our pump, we used the maximum value of water use per day as the emitter amount in order to simulate the maximum amount of power a farmer would need. Assuming an overall root depth of 18 inches, an active root zone of ~3 inches, and loamy soil, we approximated that it would take about 3 days for loamy soil to become fully saturated. It is important to note that we are operating under the assumption that there is no rain/other weather that could interfere with or significantly impact the drip irrigation pattern for corn.

With these assumptions in mind, we settled on modeling 0.35inches of water per day per corn plant. From Table 1, we assumed the 0.9GPH emitter. Assuming that each corn plant has an radius of influence of r = 1ft , we concluded that we would need about 55 gallons of water per watering cycle if the corn was to be watered at the maximum flow rate. Given the soil and crop specifications listed in this section, we chose a ~5-7 day watering cycle. With all of this in mind, we predicted 61 hours of active drip irrigation throughout each watering cycle.

To know how much power we would need, we scaled our model from one drip hole to entire acre. The total flow per acre is calculated using the total number of corn plants per row, the total number of rows, and the distance between each row:

$$Q_{total} = Q_{drip} \times \#\, of\ plants\ per\ row$$

Eq 6: Scaled pipe flow rate

$$P_{flow} = \frac{1}{2}\rho\left(\frac{16Q_2^2}{\pi^2 a^4} - \frac{16Q_1^2}{\pi^2 D^4}\right) \times \#\, of\ plants\ per\ row$$

Eq 7: Scaled pipe flow pressure

$$P_{head\ loss} = \sum_{plant=1}^{\#\, plants\ per\ row}\left(f_D \frac{8Q_1^2\rho(1ft)}{\pi^2 D^5}\right)$$

Eq 8: Scaled Head Loss

Using the scaled-up pressure loses due to head loss and pipe pressure, we calculated the pressure we would need per row:

$$P_{per\ row} = P_{atm} + P_{headloss} + P_{flow}$$

Eq 9: Total Pressure per Row

We also calculated the head loss in the pipe traveling between the drip irrigation pipes:

$$P_{between\ rows} = \#\, rows\ per\ acre \times f_D \frac{8Q_1^2\rho(3ft)}{\pi^2 D^5}$$

Eq 10: Pressure from head loss between rows

To get the total pressure, we added the head loss between each row and the pressure loss within each row:

$$P_{per\ acre} = P_{between\ rows} + P_{per\ row} \times \#\, rows\ per\ acre$$

Eq 11: Total Pressure per acre

Using Eq 1, we calculated the following power requirement for our model:

$$J_h = 1393.4\text{HP per acre}$$
$$J_{total} = 2823.8\text{HP}$$

For the vertical component of power, we assumed a well depth of 200ft.

Thought Experiment

The 30/30 rule in drip irrigation shows that for about 30 gallons, drip lines should be shorter than 30 feet to keep the pressure loss about linear. Our system would also require additional booster pumps past a width of 12 feet given the head loss of submersible pumps offered in the market today. Right is an example of how the combined length of the laterals is similar to the central ways, helping maintain flow.

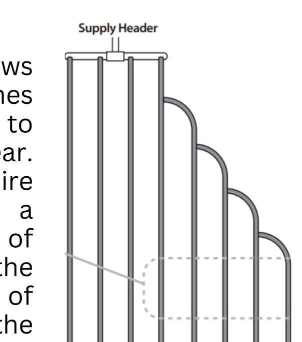


Fig 9: Drip Layout

After making this thought experiment, we realized that the layout wont change the power requirement as much as the pump configuration, so we decided to move on.

Concluding Remarks

Ultimately, here lies an exploration of pipe flow and how it can be applied to agriculture. However, as the saying goes: "All models are wrong, but some models are useful" stands true. We made a series of assumptions and oversimplifications when creating our model. Most notably, our scaled model does not follow common drip flow configurations and is difficult to scale due to pipe head loss limitations associated with the 30/30 rule. Figure 9 shows an example of a common configuration that accounts for the expected pressure losses.

On the subject of physical validation... as mentioned in our 'Reflection on Measurement & Uncertainties' section, our experimental data left much to be desired. In future iterations, we would gather more data and avoid having unreliable equipment.