Pump-sizing software tool for small-scale solar-powered irrigation systems in water-scarce conditions: a case study in Uttar Pradesh

by

Christina Sung

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Signature redacted

Signature of Author: ....
Department of Mechanical Engineering

Signature redacted

Certified by: ....
Daniel D. Frey
Professor of Mechanical Engineering
Thesis Supervisor

Signature redacted

Certified by: ....
Rohit Karnik
Associate Professor of Mechanical Engineering

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ABSTRACT

Two small-scale well-irrigation systems in rural Uttar Pradesh which had previously operated via diesel pumps have been modified to operate via solar pumps. The regions where the irrigation systems are located are currently experiencing drought, and the well of one of the systems runs dry during irrigation. It is hypothesized that the 3HP solar pumps installed in the systems are larger than necessary, and are overdrawing from the water supply. A pump-sizing software tool was developed in Excel Spreadsheets to model and analyze the two specific systems, as well as to aid in future pump-sizing for long-term water sustainability for similar types of irrigation systems operating in water-scarce conditions. It was determined that the 3HP pumps installed in the irrigation systems are not unreasonably large for the crop water demands, and that under drought conditions, it was inevitable that continued irrigation at the two sites studied would eventually lead to well depletion and is thus unsustainable. Focusing on pump-sizing for these types of irrigation systems in water-scarce conditions may not be as effective for water sustainability as adjusting the irrigation systems and methods at the sites.

Thesis Supervisor: Daniel D. Frey

Title: Professor of Mechanical Engineering

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1. Introduction

In rural Uttar Pradesh just outside of Jhansi, a non-governmental organization has been facilitating the implementation of solar-powered pumps for small-scale irrigation systems. These irrigation systems had previously operated via diesel-powered or grid-powered pumps. Solar-powered pumps have many advantages over diesel-powered, grid-powered, or other kinds of pumps. They have a potential to mitigate air pollution and the release of greenhouse gas emissions, they allow for more productivity than manually-powered systems such as those that use hand-pumps or treadles, and they use solar energy which does not cost anything and may also be more readily available or reliable, especially in rural areas where farmers have limited access to grid power.

The solar-powered pumps that have been purchased and installed have all been of the same size. Also, many farmers visually inspect the flow rate that their pump provides during irrigation as an indication of how well the pump is performing, and it is commonly believed that the larger the pump – and thus the more water it is capable of pumping in a given amount of time – the better it is.

However, in the reality, the needs and conditions of each farm are unique. Depending on the irrigation needs of a farm, the pump size for each farm can be optimized. There is a minimum pump size required to meet the irrigation needs of the crops. Purchasing smaller pumps can lower project costs. In addition, the conditions on a farm can be considered as well to mitigate the risk of overdrawing from the natural water supply. Overdrawing occurs when the water supply, such as a well, does not have sufficient time to replenish from natural processes. Overdrawing can damage pumps as well as exacerbate water scarcity by damaging the local water table. This leads to ineffective irrigation, and is also unsustainable due to cost for pump replacement and water usage.

Currently, some of the irrigation systems in Uttar Pradesh that have been installed with solar pumps are operating under water-scarce conditions. In some cases, farmers have to run a pump until the well is completely dry. They do this multiple times a day in order to provide as much water as they can for their crops via irrigation, each time having to wait for the well to recharge before running the pump again. It is hypothesized that the pumps that were installed are too large and are thus overdrawing from the water supply and damaging the local water tables.

To examine this hypothesis, a model of a well irrigation system that irrigates crops via flood irrigation was constructed. Available information and data from two different irrigation sites in Uttar Pradesh, collected by the MIT Comprehensive Initiative for Technology Evaluation, were used to analyze the systems. A software tool was created in Excel Spreadsheets to aid with the analysis. The tool takes inputs from the user about site-specific water supply and demand as well as irrigation system parameters, and recommends the appropriate range for the size of the solar pump. In addition, the tool was designed for easy access and use by project implementers, for purposes of aiding with future pump implementation.

2. Agriculture, Irrigation, and Water Supply

2.1 Irrigation in Agriculture[1]

Agriculture involves the science and practice of cultivating soil for producing crops. Plants require water for survival and growth, and through their root systems, they intake water from the surrounding soil. The water demands of crops are met through various natural processes, including rainfall and capillary rise from the groundwater table. However, in many cases, the crop water demands exceed the amount of water that these natural processes are able to provide, and thus, irrigation is important. Irrigation is used in agriculture to apply water, at the proper time and in the proper manner, to the soil in order to meet crop water demands. Through irrigation, farmers are able to increase crop productivity, as they can grow crops in areas and seasons that do not naturally allow for crop production.

2.2 Using Groundwater for Irrigation[1-3]

Water on the earth is available as surface water (eg. in rivers, ponds, and lakes), groundwater (eg. in wells and springs), and rainwater in the atmosphere. Through the hydrologic cycle, water circulates through the earth as natural processes move water to and from these different sources of water.

Groundwater is commonly used to supply water for irrigation systems. Groundwater is water that is present below the surface of the earth, in void spaces in soil and also in the fractures of rock formations. Below a certain depth underground, the ground is saturated with water. This saturated zone is called the aquifer. Above this zone, the ground is unsaturated. The water table marks the separation between the saturated and unsaturated zone.

Most groundwater comes from precipitation. Rainwater enters the soil and diffuses downward into the earth until it reaches impermeable rock or confining unit, as shown in Figure 1 below. The process of groundwater supply being replenished by precipitation is known as groundwater recharge. Groundwater recharge occurs usually only during the rainy season for tropical climates, or during the winter in temperate climates.

To extract groundwater for irrigation, wells are dug into the ground, and pumps are used to move the water out of the well to the desired location. Continuous overdrawing from a well can lower and damage the local water table. Overdrawing occurs when the rate at which water is removed from the well is higher than the rate at which water recharges into the well. Under water-scarce conditions such as droughts, which are prolonged periods of abnormally low rainfall, groundwater recharge and thus well recharge rates are low, and thus it is easy to overdraw from the water supply.

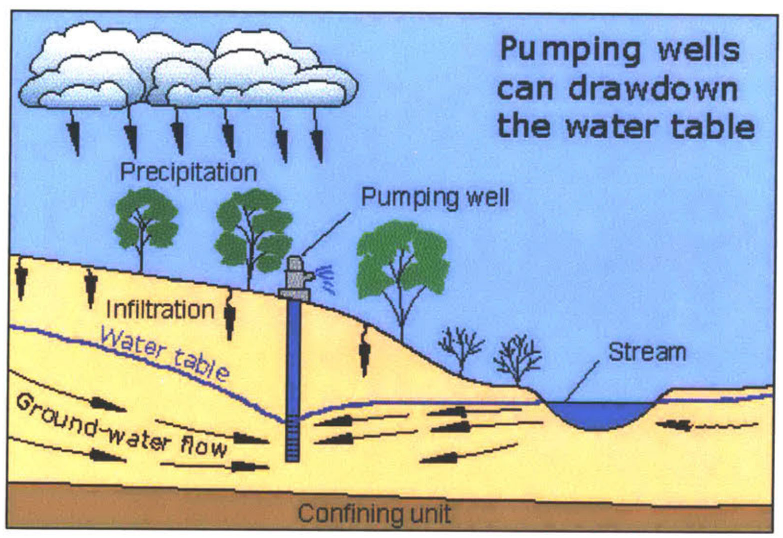

Figure 1. Pumping groundwater from wells[3]

3. Pump Sizing Method

In general, to select a pump a system, one needs to know the required head and volumetric flow rate, which determine the horsepower rating needed for the pump. For centrifugal pumps, the pump impeller size is important as well, as it determines the characteristic pump curve. Pump efficiency and net positive suction head are also important for pump selection. Impeller size, pump efficiency, and net positive suction head are important to consider for energy efficiency.[4] For water sustainability analysis, the pump sizing method used in this tool only considers required head and volumetric flow rate.

The pump sizing method can be divided into two parts. The first part determines the lower bound – the smallest pump needed to fulfill irrigation requirements. The second part determines the upper bound – the largest pump that can be used without depleting the well and thus overdrawing from the water supply.

3.1 Smallest Pump Required

The first part of the pump sizing method determines the smallest pump that an irrigation system needs to fulfill the crop water demand in a given amount of time. The pump needs to be able to deliver the correct volume of water V_{crop} that a field of crops needs per day. For a simple solar-powered irrigation system, the total irrigation time per day, t_{crop} is restricted by the available hours of sunlight in a day. Generally, there is a maximum of 8 hours of available sunlight per day, though this depends on the location and season of the irrigation site. From these two parameters, $\dot{V}_{crop}$, the volumetric flow rate required to meet the crop water demand can be determined.

Other parameters in this model are related to piping system specifics: pipe diameter, pipe length, and vertical distance that the water needs to be raised, which is from the water surface below the well to the highest point in the area to be irrigated. This vertical distance is also known as the static head. For simplicity, it is assumed that all of the piping is of the same diameter. The static head is also approximated as a fixed constant during a period of irrigation. A diagram representing the irrigation system is shown in the figure on the next page.

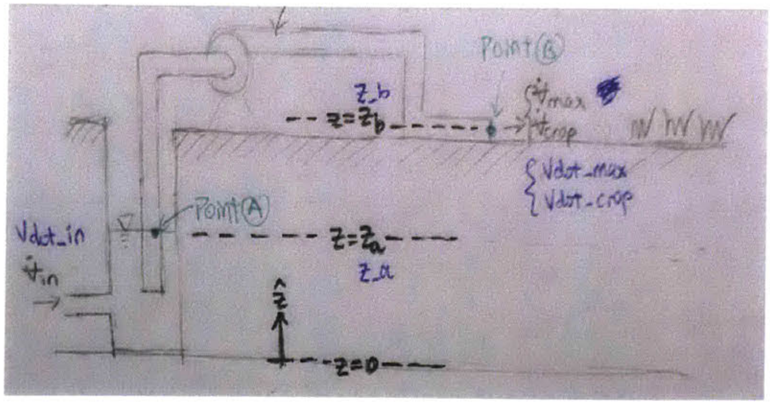

Figure 2. Irrigation System Diagram

Applying the First Law to a control volume of fluid from Point A to Point B and converting to units of meters, the head that the pump needs to be able to provide is

$$h_{pump} = \left(\frac{P}{\rho g} + \alpha\frac{v^2}{2g} + z\right)_B - \left(\frac{P}{\rho g} + \alpha\frac{v^2}{2g} + z\right)_A + \sum f\frac{L}{D}\frac{v^2}{2g} + \sum K\frac{v^2}{2g}$$

where P is the pressure at a point, ρ is the density of the liquid being pumped, g is the gravitational acceleration, α is the kinetic energy coefficient which depends on the type of flow – laminar or turbulent – through the pipes, v is the velocity of the liquid at a point, the difference between z_B and z_A is the static head, $\sum f\frac{L}{D}\frac{v^2}{2g}$ is the major head loss term due to friction in the piping system, and $\sum K\frac{v^2}{2g}$ is the minor head loss term due to components such as fittings and valves in the piping system. To find the smallest pump required to meet irrigation requirements for small-scale irrigation systems, the major head losses, minor head losses, and kinetic energy difference can be assumed to be negligible compared to the potential energy difference, or static head term. Thus, h_{pump} for determining the smallest pump needed can be approximated by the static head term alone, giving

$$h_{pump} \approx z_B - z_A$$

The minimum pump power output required to meet the required volumetric flow rate determined by the crop water demand and irrigation time per day is

$$\dot{W}_{pump,min} = \rho g \dot{V}_{crop} h_{pump}$$

3.2 Largest Pump for Avoiding Depletion

The second part of the pump sizing method determines the largest pump that can be used without overdrawing from the water supply. The water supply is modeled as a well, which recharges via natural processes. The model also assumes that changes in the water level in the well are negligible compared to the initial static head.

The well recovery rate, $\dot{V}_{in}$, is the rate at which a well recharges to its full capacity. It can be measured on a farm and is typically measured over a period of 24 hours. In the current model, we desire for the well to be able to fully recharge within a 24-hour period. Thus, the volume of water V_{in} that enters into the well – and subsequently the rest of the irrigation system – in a single 24-hour period is

$$V_{in} = \dot{V}_{in} * 24\ hours$$

The volume of water V_{out} that is pumped out of the irrigation system and delivered to the crops in a single 24-hour period is

$$V_{out} = \dot{V}_{max} t_{crop}$$

where $\dot{V}_{max}$ is the maximum volumetric flow rate allowed through the irrigation system without overdrawing from the well.

The initial volume of water in the well at the start time of an irrigation period, $t = 0$ and the final volume of water in the well at the end time of an irrigation period, $t = 24\ hours$ are related by the following equation

$$V_{intial} = V_{final} + (V_{out} - V_{in})$$

Since it is desired for $V_{intial} = V_{final}$, it follows that V_{out} must be equal to V_{in} to satisfy this requirement. Setting the equations for V_{in} and V_{out} equal to one another and solving for $\dot{V}_{max}$, we obtain

$$\dot{V}_{max} = V_{in}/t_{crop}$$

Similar to how the required power output for the smallest pump was obtained, $\dot{W}_{pump,max}$ can be obtained, which is the power output of the largest pump that can be used in the irrigation system without depleting the well in a 24-hour period.

$$\dot{W}_{pump,max} = \rho g \dot{V}_{max} h_{pump}$$

4. Pump Sizing Analysis Using a Spreadsheet Tool

A spreadsheet tool for pump sizing was made in Excel. Data and estimates from available information from two irrigation sites in Uttar Pradesh were inputted into the tool to determine the smallest size pump needed as well as the largest size pump allowed for each of the sites.

4.1 Spreadsheet Tool Design

The main design criteria for the software tool were accessibility and ease of use. Target users are project implementers, who may not have the time to look into the specifics of correctly sizing pumps, especially due to the fast-paced nature of NGO-facilitated projects. The spreadsheet was selected as a platform of the tool, as spreadsheet software is widely available for everyday use, and more available compared to other software that may only be available through institutions such as universities. It can also be used offline, which is beneficial for places where there is limited Internet access.

To make the tool as easy to use as possible, we wanted to minimize the inputs required from the user. Furthermore, we wanted to make sure each of the inputs themselves would not be difficult to obtain. Currently, seven inputs are required from the user: total amount of water per day, desired total irrigation time per day, irrigation pipe diameter, irrigation pipe length, height of water in well, height to water delivery point, and well recharge rate. The two outputs are the minimum pump size needed and the maximum pump size allowed.

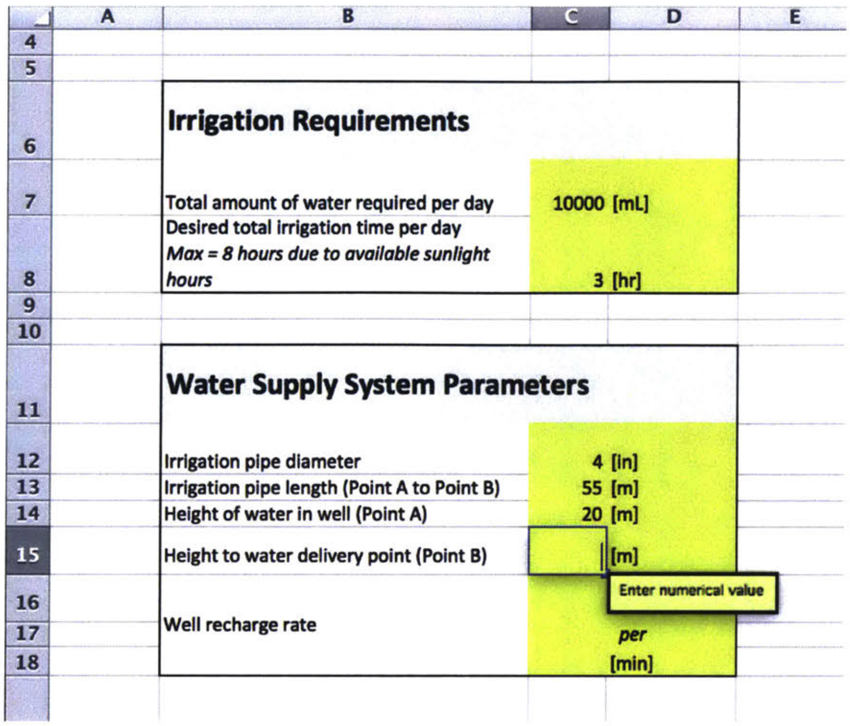

Figure 3a. Tool inputs: Crop water demand, water supply, and piping system parameters

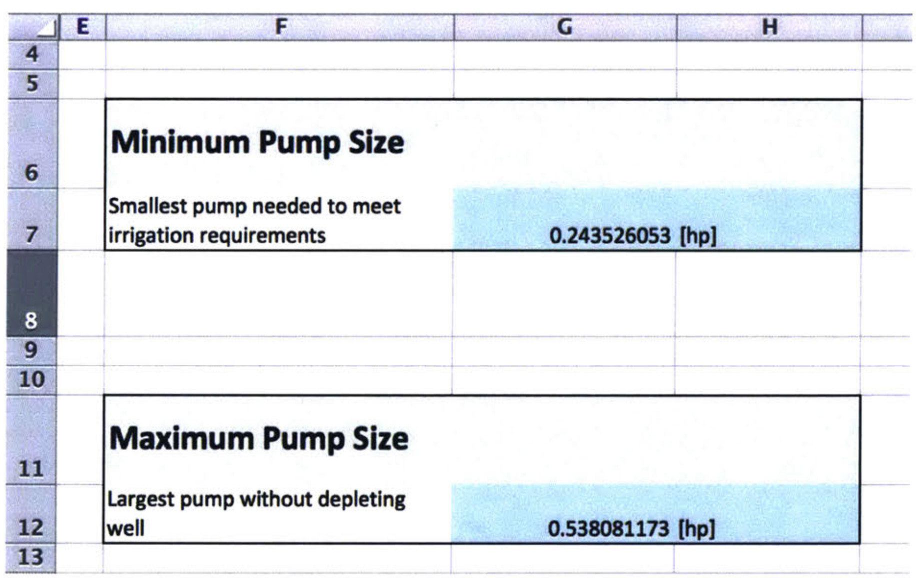

Figure 3b. Tool outputs: Minimum pump size and maximum pump size

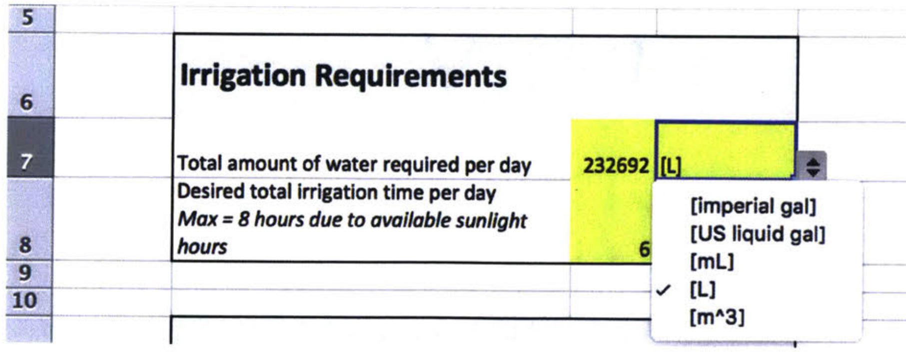

Figure 3c. Units selection

4.2 Case Study: Water Supply and Piping System Parameters

The irrigation system model used for pump sizing was based on the irrigation systems at two sites near Jhansi, in Uttar Pradesh. The locations are within kilometers of one another. Information from field visits made by the MIT Comprehensive Initiative for Technology Evaluation was used for these models.

Both locations are prone to drought, and were facing a drought at the time of the field visits. The field visits were made in January, one of the months of least rainfall, even under non-drought conditions. The average annual rainfall is normally 955 mm, as shown in the climate graph below – however, in the last two years, the average annual rainfall been less than 200 mm.

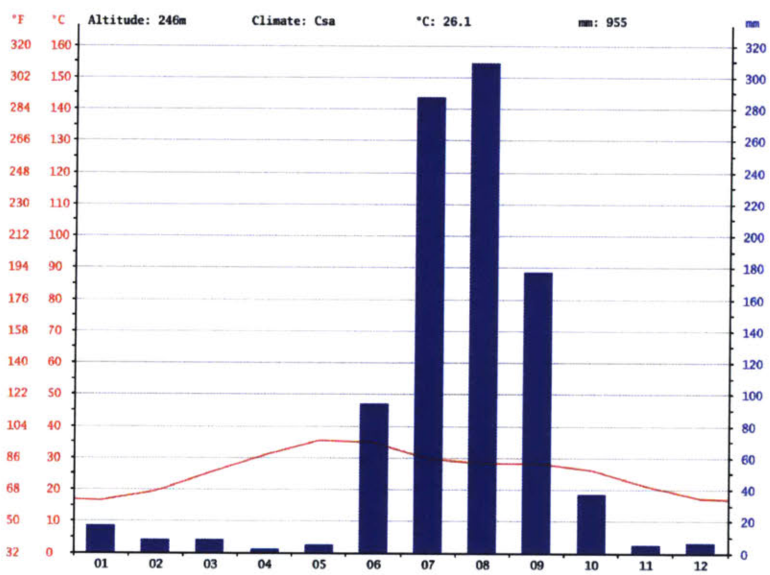

Figure 4. Climate graph for Jhansi, comprised of weather data collected from 1982 to 2012[5]

On the first site, Site A, the well depth is 20m, and the diameter is estimated from photos to be approximately 4m. The size of the plot of land is about 10 acres. Like other local farms, the farmers here use flood irrigation to grow wheat, groundnut, pulses (or lentils), depending on the season. The solar pump installed is a 3HP submersible AC pump. During the field visit in January, it was operated twice per day for 1 hour each time until the well is exhausted, for a total of 2 hours per day.

On the second site, Site B, the well depth is 20m, and the diameter is estimated from photos to be approximately 4m. Although the area is currently facing a drought, water is plentiful in the area. The size of the plot of land is about 10 acres. Same types of crops are grown here. Farmers here also grow vegetables and spices in their small kitchen garden. The solar pump installed here is also a 3HP submersible AC pump. It is currently operated 6 hours per day from 10am to 4pm, which are the available sunlight hours.

Figure 5a. Open well at Site A. Courtesy of CITE
Figure 5b. Open well at Site B. Courtesy of CITE

4.3 Case Study: Crop Water Demands[6]

The crop water demands for each of the two sites had not been determined quantitatively. Thus, to estimate the total amount of water required per day for the crops on the each farm, the Food and Agriculture Organization of the United Nations (FAO) was used.

The FAO crop water demand model is based on evapotranspiration, a process in which evaporation and transpiration occur simultaneously. During evaporation, liquid water turns into water vapor and is removed from the evaporating surface. Water evaporates from the soil surface. During transpiration, liquid water contained in plant tissues is vaporized and removed to the atmosphere. Most of the water taken up by a plant is lost by transpiration and only a small fraction of it is used within the plant. Factors that affect evapotranspiration include weather parameters, crop characteristics, management and environmental aspects.

To determine crop water demand, crop evapotranspiration under standard conditions were used. Standard conditions indicate disease-free, well-fertilized crops, grown in large fields, under optimum soil water conditions, and achieving full production under the given climatic conditions. While the conditions on the two sites were not standard, this allowed for simple estimates.

The FAO model uses the following parameters to determine crop water demands: crop type, growth stage, climatic zone, mean daily temperature, and monthly rainfall. To simulate the condition that would require most water via irrigation – in other words, the worst-case scenario – we used mid-season values for the growth stage parameter and 0 mm for the monthly rainfall parameter. For conditions specific to Jhansi, humid subtropical values were used for the climatic zone parameter, and upper bound values corresponding to 20 degrees Celsius were used for the mean daily temperature parameter.

Using this model, the range of crop water demands for entire fields of wheat, entire fields of groundnut, and entire fields of pulses/lentils was estimated to be 212,000 L/day to 233,000 L/day.

5. Results and Discussion

5.1 Analysis of Two Irrigation Systems in Uttar Pradesh

For a given crop water requirement of 212,000 L/day, a total irrigation time per day of 6 hours, pipe diameter of 4 inches, total pipe length of 30 meters, and a fixed static head of 3 meters, the smallest pump needed to meet the crop water requirement was determined to be 1.4HP. Varying the crop water requirement to 233,000 L/day and maintaining the other parameters, the smallest pump needed was determined to be 1.7HP. These results indicate that even under conditions that would require the largest amount of water provided via irrigation –

mid-season growth stage and no rainfall – the smallest pump needed to fulfill irrigation requirements is smaller than the 3HP pump currently installed on the two farms.

With a 3HP pump that each of the irrigation systems currently uses, it was found that the static head can be as large as 4.6 meters for a 212,000 L/day water requirement, and 16 meters for a 233,000 L/day water requirement, and still be able to deliver the required amount of water in 6 hours. Under continuous drought conditions, wells do not recharge and thus the static head, even if it is approximated at a fixed value within each 24-hour period, actually increases with each successive 24-hour period. Over continuous days of irrigation, as the static head approaches 20 meters – in other words, as the well nears full depletion – it was found that the minimum pump size of 3.6HP is needed to fulfill the 212,000 L/day requirement in 6 hours, and 4.1HP for the 232,000 L/day requirement. Thus, under non-ideal conditions in which the well does not fully recharge by the end of a day of irrigation – meaning that eventually, after some number of successive 24-hour periods of irrigation, the well will be depleted – the pump will have to operate at very high static heads, and a 3HP pump is not unreasonably large. In fact, it would be reasonable to have a 3HP pump installed in the system so that farmers can continue irrigating their crops even when the water level in the well is low.

No-rainfall conditions were used to model the systems in Jhansi, so 0 US liquid gpm was used as the input for the well recharge rate – in other words, the well does not recharge. Thus, it is inevitable that continued operation of any pump, regardless of size, over successive 24-hour periods would eventually cause the well to be fully depleted.

Even with a typical well recharge rate of 5 US liquid gallons per minute under non-water-scarce conditions, it was found that the largest pump that can be used without depleting the well over successive 24-hour periods is 0.05HP. Any pump larger than 0.05HP would not allow the water in the well to recover to its initial volume within one 24-hour period. Regardless of the initial volume of water in the well, continued operation of a pump oversized, in terms of water sustainability, over successive 24-hour periods would eventually cause the well to be fully depleted.

For a given crop water requirement of 212,000 L/day, the well recharge rate would need to be 39 US liquid gpm in order for the well to not be depleted over time. For a given 233,000 L/day, it would need to be 42 US liquid gpm. These are very high recharge rates and unrealistic for wells, suggesting that under continuous drought conditions, the two irrigation systems in

Jhansi cannot be operated daily to meet crop water requirements without eventually leading to well depletion.

From these results, it seems to be the case that other types of irrigation systems and practices may be more suited for these specific locations. Possible alternatives include more efficient irrigation systems which allow for more of the irrigated water to be applied to the plant roots so that less water is wasted via evaporation, including the use of storage tanks for harvesting water during seasons when water is more plentiful, and then releasing the storage water along with water drawn from the well for irrigation.

5.2 Tool Limitations

Many of the tool limitations come from the modeling itself. The model used in the tool is currently based on irrigation systems that draw water specifically from wells. While the water supply parameter – currently there is only one parameter in the model, which is the well recharge rate – does not affect the result for the smallest pump recommended, it directly affects the result for the largest pump allowed.

Currently, the assumption made in the model is that within a 24-hour period of irrigation, when the pump is in operation, the water surface level does not change significantly with time compared to the vertical distance that pump must move the water. In other words, the model assumes a fixed static height. This assumption is valid only under certain conditions, such as if the water source is a large body of water – if the water source is a well, the cross sectional area would have to be significantly larger than the depth of water in the well in which the cross sectional area is – or if the vertical distance from the water surface level to the ground level of the crops is significantly larger than the depth of the water in the water source. For the specific sites in Uttar Pradesh that were analyzed, case study, the dimensions of the wells actually do not allow for valid application of this assumption. In the future, the model will be updated to include a variable static height.

In addition, it is important to consider the consistency of well recharge rate. The model takes as an input a single fixed well recharge rate. Under the extreme conditions of drought, such as in the cases that were analyzed, it is reasonable to assume 0 mm of rainfall, or a constant 0 US liquid gpm for well recharge rate, in order to find the maximum pump size without depleting the well. However, under normal (non-drought) conditions in which there is rainfall, the well recharge rate will not be 0 US liquid gpm and will have to be measured. Well recharge rates are typically measured over a period of 24-hours. Well recharge rates are heavily affected by rainfall patterns, which may vary from day to day and from season to season. Dry seasons will result in slower recovery rates, while wet seasons will result in faster recovery rates. While one could track the well recharge rate each day over a whole entire year or longer to find the lowest well recharge rate that occurs during the year, rainfall may differ from year to year as well. Erratic rainfall patterns would make it difficult to determine the largest pump that can be implemented in a system.

Finally, the pump-sizing model does not currently take into account pump specifications – supplied by pump manufacturers – which are important for properly selecting pumps for energy efficiency, which is considered separately from properly sizing pumps for water sustainability. In the future, this will be included in the tool to give a more comprehensive pump selection process.

From the results of the Uttar Pradesh case studies, it is clear that a limitation of the tool itself is that merely having two outputs – the minimum pump size needed to meet crop requirements, and the maximum pump size in order to not overdraw from a well – is not very useful for pumping sizing for irrigation systems similar to the ones at these two sites, if a region is facing drought. In cases of extensive drought, it is not possible to irrigate consistently without eventually depleting the well. The best that a pump could do for these irrigation systems would be to pump out the maximum water available from the well in a day. This is, however, unsustainable. As mentioned earlier, for these specific irrigation systems under drought conditions, it may be more productive for water sustainability efforts to make adjustments to the irrigation systems and practices themselves rather than trying to optimize the pump.

6. Conclusions and Future Work

Through analysis using a model built in a pump-sizing spreadsheet tool, it was determined that the 3HP pumps were not unreasonably large for the systems in which they were installed, given crop water demands. In fact, it would be reasonable to have a 3HP pump installed in the system so that farmers can continue irrigating their crops even when the water level in the well is low. However, it was also determined that under drought conditions, it was inevitable that continued irrigation at the two sites studied would eventually lead to well depletion and is thus unsustainable.

While the pump-sizing spreadsheet tool was also developed with the intention of aiding in pump selection for future solar pump implementations in similar irrigation systems as the ones analyzed, it is clear from the results of these case studies that this tool is currently ineffective for pump-sizing for long-term water sustainability in water-scarce environments.

In addition to the future work discussed in the tool limitations section, other future work may include looking into more efficient irrigation methods and incorporating them into the tool, providing comparisons between different irrigation systems and methods, which could aid users in decisions that they make for their irrigation systems and methods.

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