Village Source to Environment

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Detailed Task List

Design a distributed storage system for a village water supply

Design of distribution system

- Review last semester's projects [Completed by Diana]
- Compile best strategies from previous projects into one comprehensive design [Completed by Diana]
- Revise capstone calculations to incorporate tubing [Completed by Sarah]
- Optimize design for cost efficiency and equity [Completed by Rachel]
- Optimize for convenience [Ongoing; Rachel]
- Incorporate solar code into distribution code [Completed by Diana]
- Change flow equations to reflect turbulent flow [Completed by Rachel]
- Incorporate well pump [Completed by Rachel]
- Optimize algorithm for varying tier/length [Completed by Sarah]

Design photovoltaic and pump system

- Obtain hourly solar insolation data for India [Completed by Nick]
- Obtain accurate cost and efficiency data for solar panels and pumps [Completed by Diana]
- Design algorithm to determine how often the solar pumps will not receive enough power [Completed by Diana]
- Design algorithm for solar power generated at a given location [Completed by Nick]

- Sizing PV array for pumps, optimized for cost and designed to accommodate future growth [Completed by 5/09; Diana]
- Change optimal angle for solar panels [Completed by Nick]
- Incorporate read data into solar calculations and incorporate pump efficiency as a function of panel power [Completed by Diana]
- Include pump efficiency curves and ensure they reflect desired head and flow rate [Completed by Diana]
- Comprehensive system diagram [Completed by Nick]

Individual roles

Team Coordinator: Diana

- Responsible for facilitating Team meetings and keeping track of progress over the course of the semester to ensure that goals are completed in a timely manner. Point person for communication between the team and advisers, as well as between the team and the AguaClara leadership team.

Literature Coordinator: Rachel

- Responsible for compiling all relevant information gathered from literature sources and ensuring all material is properly cited.

Report Proofreader: Sarah

- Responsible for checking reports for proper spelling and grammar.

Team Glue: Nick

- Responsible for ensuring team unity and productivity.

Introduction

The newly formed Village Source to Environment Team combines the design of a distribution storage plan and wastewater treatment system for rural villages in India. Current distribution infrastructure consists of an elevated tank that fills and dispenses twice daily, each time supplying half the village's water needs. This method is inefficient and inconvenient, since villagers can only obtain water when the tank dispenses and must carry it half a kilometer to their homes. This system also makes it impossible to ensure that each family receives their designated share of water. Furthermore, due to limited access to water, villages improvise unsanitary household storage. They obtain all water for washing, drinking and cooking from these open containers, meaning the entire source can be contaminated any time they use it. Our proposed distribution system will pump water directly into villagers' homes, replacing the elevated storage tank with smaller household tanks. Each tank will connect to a sink for sanitary use on demand. Additionally, the sink's drain will allow us to eventually integrate a wastewater treatment or irrigation system. Small villages with limited resources often lack sanitary solutions for handling greywater and blackwater; we hope future teams will investigate strategies for treating wastewater for irrigation.

Our work builds upon capstone design projects from the Fall 2013 CEE 4540 class that focused on a distribution system for the village of Gufu, India. We revised the distribution design and planned to add household storage tanks, however the distribution system design took the majority of our focus this semester. This new team was formed to facilitate AguaClara's expansion to India. The local infrastructure, community sizes, and therefore required flow rates, differ significantly from those in Honduras. As a result, the team must take a very different approach to the problem. The Village Source to Environment Team has laid the foundation for distribution design this semester.

Parameter Definitions

Literature Review

Gufu Village

While the team ultimately plans to design a template applicable to any small village, we based our design on Gufu Village, seen in Figure 1 below. An electric pump powered by solar panels lifts water from a well located just outside the village. The water will be treated by an AguaClara Low Flow Stacked Rapid Sand filter (LFSRSF) and piped to each household. We assume a total population of 240 people, 5 people per household, and per capita demand of 100 liters per day.

The 2canzzzz' Capstone Design

The design for this project is based primarily on The 2canzzzz' capstone design project for CEE 4540 in Fall 2013. There were several recurring ideas that this group, and others who focused on the village distribution system, used that will be maintained in the ongoing design. Some of these ideas include:

- Use of a dimensionless parameter, Π_Q, shown in Equation 1 below. Π_Q represents equity in flow between houses in the village, and in The 2canzzzz' design was forced to be no greater than 0.1. Therefore, all household flows are within 10% of each other.

$$\Pi_Q = \frac{Q_{max} - Q_{Min}}{Q_{Avg}} \tag{1}$$

The equation can be rewritten in terms of head loss using an orifice, as seen in Equation 2.

Variable	Definition
g	Gravitational constant
ν	Kinematic viscosity constant for water
Π_Q	Unit-less parameter that represents equity of flow throughout the system. Set equal to 20% to ensure that all flows are within 20% of each other.
Π_{VC}	Unit-less parameter that describes minor losses through an orifice
$A_{Orifice}$	Area of the orifice
h_{LE}	Head loss due to major losses. Maximum, minimum, and average major losses are given with subscripts
h_{Equity}	Head required to maintain equity throughout the distribution system
$Q_{TargetHouse}$	Flow rate for each house throughout the system. Maximum, minimum, and average flow rates are given with subscripts
$Q_{TargetTotal}$	Total flow rate through the transmission line, i.e. flow rate that the pump must be able to handle
Q_{Capita}	Desired per capita flow rate of 100 L/day
N_{People}	Village population, estimated to be 240 for our model
D_{Tubing}	Diameter of the tubing
Q_{Tubing}	Real flow rate through the tubing at each house, given each house's accrued head loss
$h_{f.tubing}$	Requisite head loss through tubing to maintain equity. Maximum, minimum, and average tubing head losses are given with subscripts
$\Pi_{RatioAvgMin}$	Ratio of the average flow rate to the minimum flow rate through the tubing. Equals 1.1 for a $\Pi_Q$of 20%
h_p	Head provided by pump
h_L	Head losses (excluding minor losses)
L_{Tubing}	Length of tubing necessary to dissipate the average head for each house in the system, given the flow rate and equity requirements for each iteration of the code
$L_{Additional}$	Length of additional tubing required for a given house to achieve equitable head loss
$Min_{DTubing}$	Minimum diameter possible for tubing
$\Pi_{RatioMaxAvg}$	Ratio of maximum flow rate to average flow rate through the tubing. Equals 1.1 for a $\Pi_Q$of 20%
f_{factor}	Friction factor used to estimate head loss through turbulent tubing
A_{Tubing}	Area of the tubing given a diameter for each iteration of code
D_{Tubing}	Diameter of tubing chosen for any given iteration of the code
$\Delta h_{f.dist}$	Difference between minimum major losses through pipes in the distribution system and maximum major losses through pipes.
α	Constant employed in tubing head loss calculations

Table 1: Distribution Parameter Definitions

Variable	Definition
$\Pi_{SunHours}$	Percentage of each day for which there is sufficient sunlight to operate the PV pump. For the Gufu Village, this is assumed to be 33% (8 hours/24 hours).
N_{JD}	Number of Julian day, ranging from 1 to 365. One day was chosen for the 15th of each month (i.e. January 15 is the 15th Julian day)
D_{δ}	Declination angle relative to the equator
H_d	Diffuse component of daily insolation sum, thermal energy per square meter
$\overline{H}$	Global daily insolation sum, thermal energy per square meter
K_T	Monthly average clearness index
R_r	Ratio of total insolation on a tilted surface to that on an equivalent horizontal surface
R_{Bbeta}	Ratio of beam insolation on a tilted surface to that on an equivalent horizontal surface
S_M	Optimum PV tilt angle for a month, measured from the horizontal
ρ_{Ref}	Reflection coefficient, with 1 being the least reflective
H_t	Monthly average total daily insolation on a tilted surface, thermal energy per square meter
β	Solar cell temperature coefficient of PV efficiency, 1/degree C
η_r	Solar cell efficiency at rating conditions
η	Overall panel efficiency
T_A	Monthly average air temperature
T_M	Mean monthly ambient air temperature
T_C	Monthly average cell temperature
$\beta_{tiltsim}$	Optimal angle for solar panels
ρ	Density of water
ϵ	Pump Efficiency

Table 2: Solar Parameter Definitions

Figure 1: Map of Gufu Village in India

$$\Pi_Q = \frac{\left[\Pi_{VC} A_{Orifice} \sqrt{2g\left(h_{Equity} - h_{LEMinimum}\right)} - \Pi_{VC} A_{Orifice} \sqrt{2g\left(h_{Equity} - h_{LEMaximum}\right)}\right]}{\Pi_{VC} A_{Orifice} \sqrt{2g\left(h_{Equity} - h_{LEAverage}\right)}} \tag{2}$$

Since every house has the same size orifice, we can reduce the equation and solve for equity, as reflected in Equation 3.

$$F_{hEq}(h_{Equity}) = (\sqrt{h_{Equity} - h_{LEMinimum}} - \sqrt{h_{Equity} - h_{LEMaximum}}) - \Pi_Q \sqrt{h_{Equity} - h_{LEAverage}} \tag{3}$$

- Use of different tiers of pipe that carry water from a main transmission pipe, originating at the well and ending in the center of the village, to each household.
- Iterating pipe diameter for each tier based on each tier's flow rate. Options will be narrowed down based on which pipe diameters maintain equity, and a final selection will be made by optimizing for cost.
- Use of a distribution system with one central pipe and a series of smaller pipes that branch outward from the central pipe, as shown in Figure 2.
- Separate designs for the transmission line (based on PV/PVC tradeoff) and for the distribution system (based on an initial guess as to the economic value of equity).

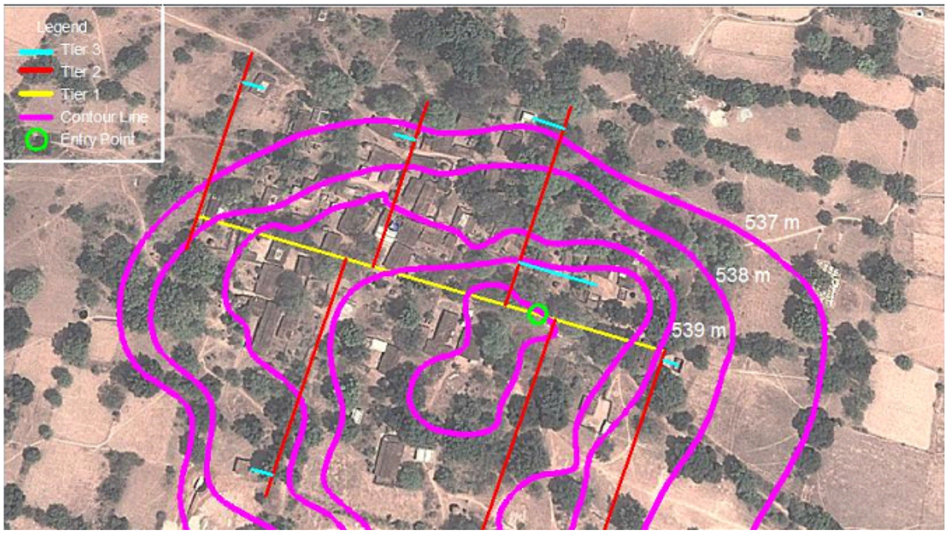

Figure 2: Distribution Layout

One significant difference between The 2canzzzz' design and the design that we will implement is our use of small diameter tubing to restrict the flow to each house. In The 2canzzzz' design, an orifice was used to control this flow and to maintain adequate pressure throughout the distribution system; however, we will utilize tubing as the head loss element. Tubing will be more readily available than small orifices and will be less prone to clogging because it will have a larger diameter than the orifices. It will also allow easy alteration of each household's flow rate by simply increasing or decreasing the length of the tubing for each house. Additionally, it will allow for easier monitoring of each house's flow rate, as the tubing will be placed in a small box at street level where flow meters can be installed.

Another significant difference between The 2canzzzz' design and ours is that our design accounts for weather variability during the year. This variability is key in determining the real performance of solar PV panels that power the entire system. This weather variability will be discussed later in this document.

Although our code is primarily modeled after The 2canzzzz' design, a few concepts were borrowed from another group who worked on distribution system design for CEE 4550 in Fall 2013. The use of tubing to restrict the flow rate to each house instead of an orifice was initially proposed by Mathcadre.

Additional resources

Design of Potable Water Supply Systems in Rural Honduras [3], a report published by Nathan Reents in fulfillment of his Masters thesis, details the design of a gravity-powered distribution system in rural Honduras. This system design is only slightly applicable to our design, as the flat topography of our site prohibits the use of gravity, so our design is driven entirely by pressure. However, Reents' design could be used in the future if the topography of the region in question changes. This system was designed using an Excel spreadsheet initially developed by the Peace Corps. Break-tanks were used to maintain a static head of less than 100 m and dynamic pressure greater than 0 m at all points throughout the system. This was controlled in order to eliminate the need for high-strength PVC pipes.

Methods

Distribution

We began by modifying The 2canzzzz' report to incorporate tubing into the distribution system. In the revised design, seen in Figure 5, all three tiers of PVC pipe will remain, with tubing placed into each house's segment of tier three pipe. We selected three tiers of tubing and the system layout suggested by The 2canzzzz', as this layout was most effective at minimizing elevation differences between houses throughout the system and minimizing the quantity of tubing, and thus cost, required. Ultimately the distribution system layout must be customized for each village to account for topography and placement of houses, and a method for optimizing the number of tiers must be determined.

Our code is based primarily on an energy analysis that tracks the head throughout the system and determines the head available at each house, shown as Δh in Figure 3 of a Hydraulic gradient line (HGL). There is a submerged well pump that provides enough head to bring water up from the well and push it through the LFSRSF. Because these submerged pumps are already in place for most villages, calculations were not included for the well pumps. However, future iterations of the code should include this submerged pump. The pump located at the AguaClara LFSRSF "plant" provides a certain head (hp) that increases the energy in the system by hp (seen by the rise in the HGL at the plant). During the transportation of water from the LFSRSF to the village, energy is lost due to major losses in the pipe and because the elevation of the village is higher than that of the pump. This is reflected in the downward slope of the HGL. The line h_{eq} measures the total available head when water enters the distribution system in the village. The major losses after this point are determined by the diameters and flows of all of the relevant pipes leading up to each house. In The 2canzzzz' design, the head available at the orifice at each house is then converted to kinetic energy as water flows through the orifice and into the distribution tank. Because this available head drives the flow through the orifice, they found this available head at each house and then found the respective flow for each house.

Instead of an orifice restricting flow at the household level, flow is restricted by a coil of tubing located at the street level. Tier 3 pipe carries water from the Tier 2 pipe to this tubing box and from the tubing box to each house,

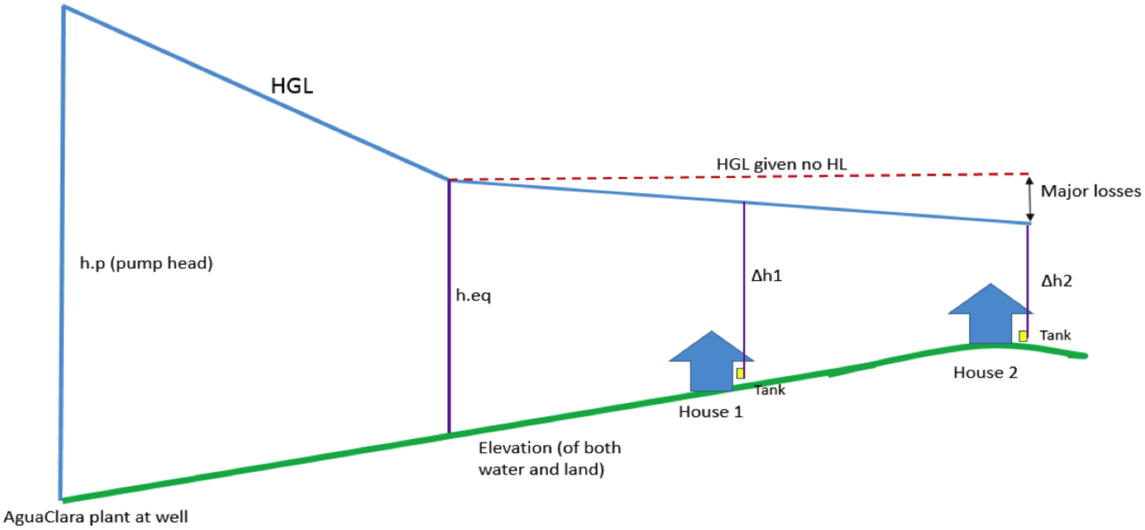

Figure 3: Hydraulic gradient line (HGL) following energy throughout the entire distribution system.

where it discharges directly into a household storage tank equipped with a float valve. The coil of tubing improves equity among the houses by increasing head loss to all houses. Figure 4 shows a simplified energy gradient line (EGL) from the house closest to the transmission line to the house furthest from the line. This diagram neglects elevation differences between houses and changes in rate of head loss for each diameter of pipe and instead plots head loss as a linear trend. A more in-depth EGL that accounts for differences in pipe diameter is shown in Figure 6. $\Delta h_{f.dist}$ represents the difference in major losses between the closest house and farthest house. The closest house to the transmission line will experience the least amount of head loss from pipes leading up to it and will consequently receive the highest flow. Since this house has the highest flow rate it will also have the highest head losses through tubing, $h_{f.tubing.max}$, assuming that all head is dissipated through the tubing before entering the house. $h_{f.tubing.min}$ represents the head losses through the tubing for the house furthest from the transmission line, which would experience the most head loss from pipe length and receive the minimum flow. Equity is centered around a target flow rate, ensuring all houses receive a flow within 20% of the target. The target flow rate per house is 1500 L/day per house, calculated using Equation 4 which uses the desired flow rate per capita of 100 L/day, 5 people per house, and the percentage of the day that the pump is in operation based on a viable amount of sunlight. The target flow rate for the entire village (i.e. the flow rate that the pump must be able to supply) is calculated by multiplying this target flow rate per house by the number of houses (48 houses) in the village.

$$Q_{TargetHouse} = \frac{Q_{capita} * N_{PeoplePerHouse}}{\Pi_{SunHours}} \tag{4}$$

$$Q_{TargetTotal} = Q_{TargetHouse} * N_{Houses}$$

We began the process by demonstrating that the flow through the tubing could be turbulent under certain conditions. Since we already assumed that the remainder of the flow through our system (i.e. through the pipes) was turbulent, this simplified the design. Turbulent flow will also dissipate more head through the tubing, decreasing the amount of tubing required at each house. However, although this turbulent assumption will hold for some of the tubing diameter and flow rate combinations, future designs should account for the variability in flow regime and model the rest of the system accordingly.

We found the Reynolds number for the smallest tubing diameter we are considering given available adapters and pipe sizes, 0.25 in, and maximum flow through the system, as these conditions will result in the highest Reynolds number. As shown in Equation 5 below, we multiplied the target flow by $\Pi_{RatioMaxAvg}$, since this represents the maximum flow under the 20% equity constraint, and 1.5 to account for variability in solar power, which will result in variable flow. We found a Reynolds number of 5,744, which is well within the turbulent range.

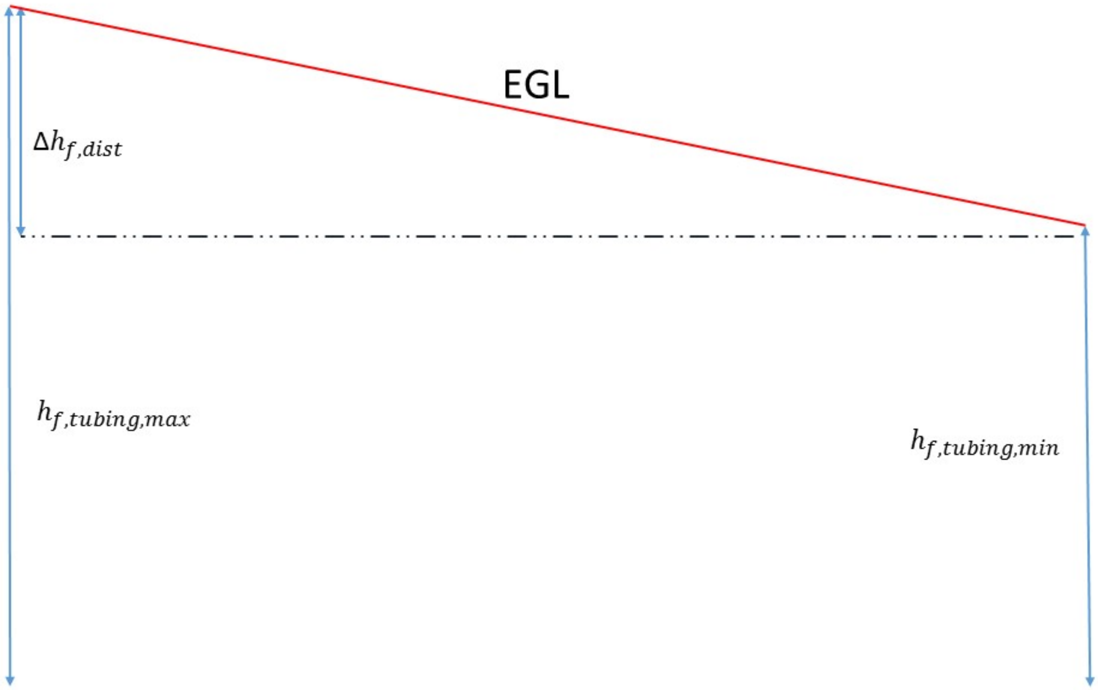

Figure 4: Simplified EGL
Simplified EGL illustrating the difference in head loss experienced by the house closest to the transmission line and the house furthest from the line.

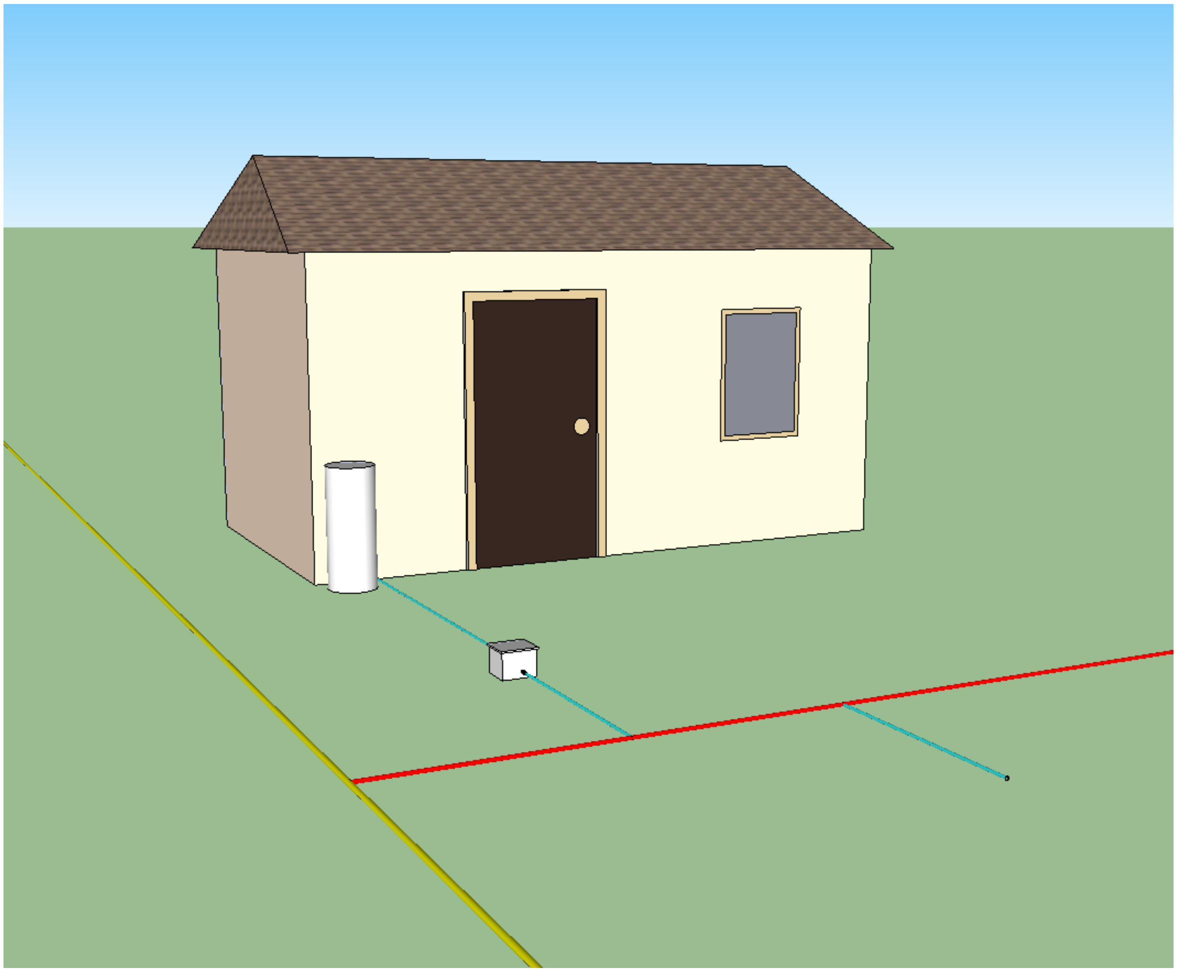

Figure 5: Distribution Illustration
Illustration of the three-tier distribution system. Tier 1 (yellow) is connected to the main transmission line and Tier 3 (blue) opens into a storage tank in each house. Tubing is placed into a small box located in each house's length of tier three pipe.

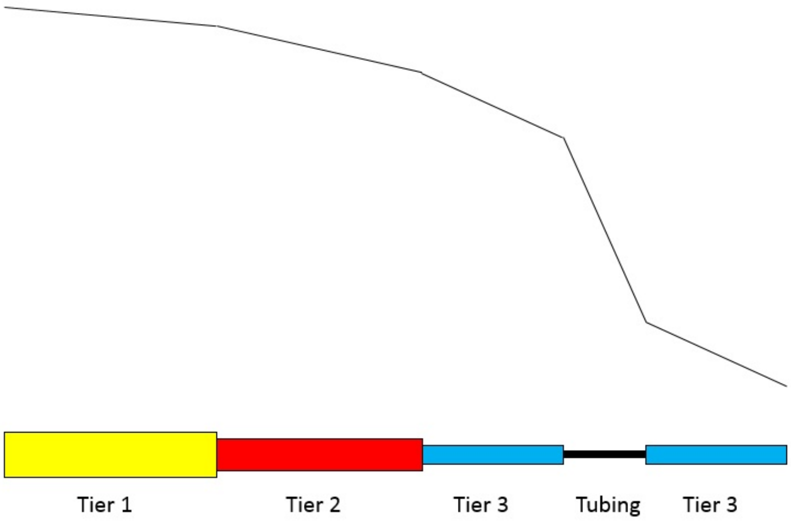

Figure 6: EGL
Representative EGL for one house that reflects changes in head loss given different pipe and tubing diameters.

$$Re = \Pi_{RatioMaxAvg} * 1.5 * \frac{Q_{TargetHouse}}{\frac{\pi}{4}\nu Min_{DTubing}} = 5,744 \tag{5}$$

Since tubing replaced orifices as the head loss element, we had to revise our Π_Q equation to reflect this change. Assuming flow is always turbulent, we calculated the friction factor using the Swamee-Jain equation (6). We used our maximum flow rate (not accounting for solar-induced flow variations), minimum diameter of tubing, and the roughness coefficient for PVC pipe and tubing as inputs. The resulting friction factor of 0.06 represents the minimum possible friction factor. Using the minimum friction factor will result in the minimum estimated head loss, which equates to a conservative design.

$$f_{factor} = \frac{0.25}{\left(\log\left(\frac{\varepsilon}{3.7Min_{DTubing}} + \frac{5.74}{Re_{Pipe}(Q_{Max}, Min_{DTubing}, \nu)^{0.9}}\right)^2\right)} \tag{6}$$

We used the EGL shown in Figure 4 to determine relationships between head loss through tubing and head loss through the distribution system, as shown below. The first two equations were gleaned directly from the EGL diagram.

$$h_{f.tubing.max} = \Delta h_{f.dist} + h_{f.tubing.min}$$

$$\Delta h_{f.dist} = h_{LEMax} - h_{LEMin}$$

Since flow through the tubing is assumed to be turbulent, Equation 7 below for head loss through tubing is related to turbulent flow through the tubing. It uses the diameter for the tubing for each iteration and assumes a fraction factor as calculated in Equation 6. Each of these parameters represent the flow rate, diameter, and length chosen for each specific iteration of the code. They are used as general terms here.

$$h_{f.tubing} = f_{factor}\left(\frac{L_{Tubing}}{D_{Tubing}}\right)\frac{\left(\frac{Q_{Tubing}}{A_{Tubing}}\right)^2}{2g} \tag{7}$$

All constants from Equation 7 were compiled into one constant, α, shown in Equation 8.

$$\alpha = \frac{f_{factor}L_{Tubing}}{2gD_{Tubing}A^2_{Tubing}} \tag{8}$$

We then solved for the maximum, minimum, and average tubing flow rates in terms of their respective head losses.

$$\Pi_{RatioAvgMin} = \frac{Q_{Avg}}{Q_{Min}} = 1.1 \tag{9}$$

$$Q_{Max} = \sqrt{\frac{h_{f.tubing.max}}{\alpha}} = \sqrt{\frac{\Delta h_{f.dist} + h_{f.tubing.min}}{\alpha}}$$

$$Q_{Min} = \sqrt{\frac{h_{f.tubing.avg}}{\alpha}} = \Pi_{RatioAvgMin}\sqrt{\frac{h_{f.tubing.min}}{\alpha}}$$

We solved Q_{Avg} in terms of $h_{f.tubing.min}$ to minimize the number of variables in our calculations. Because we know that Q_{Avg} should be no more than 10% greater than the minimum, we multiplied the Q_{Min} head loss term by $\Pi_{RatioAvgMin}$ to put the Q_{Avg} term in terms of $h_{f.tubing.min}$. From this equation, we could solve for our new Π_Q equation, illustrated in Equation 10 below.

$$\Pi_Q = \frac{\sqrt{\frac{\Delta h_{f.dist}+h_{f.tubing.min}}{\alpha}} - \sqrt{\frac{h_{f.tubing.min}}{\alpha}}}{\Pi_{RatioAvgMin}\sqrt{\frac{h_{f.tubing.min}}{\alpha}}} = \frac{\sqrt{\Delta h_{f.dist} + h_{f.tubing.min}} - \sqrt{h_{f.tubing.min}}}{\Pi_{RatioAvgMin}\sqrt{h_{f.tubing.min}}} \tag{10}$$

We rearranged this equation and found roots of the following function, Equation 11 (i.e. the values of $h_{f.tubing.min}$ that satisfy the equation). $h_{f.tubing.min}$ was equated to the requisite head loss, $h_{f.tubing}$, through the tubing at each house.

$$F_{h.f.tubing}(h_{f.tubing.min}) = \Big(\sqrt{h_{LEMax} - h_{LEMin} + h_{f.tubing.min}} - \sqrt{h_{f.tubing.min}} - \Pi_Q * \Pi_{RatioAvgMin}\sqrt{h_{f.tu} \tag{11}$$

We also derived an equation to determine the length of tubing necessary to dissipate the average head for each house in the system, illustrated in Equation 12. This equation is found by rearranging the equation for turbulent head loss.

$$L_{Tubing} = \frac{g * h_{f.tubing}^2 \left(\frac{\pi D_{Tubing}^2}{4}\right)^2 * D_{Tubing}}{f * Q_{Tubing}^2} \tag{12}$$

Once the base length of tubing was found for each iteration of code, the elevation of each house was used to determine the length of tubing required to normalize the head losses across the houses, given the fact that they each have different elevations. The following equation, 13, was used to determine how much tubing needed to be added or subtracted for each house. For houses at a lower elevation than that of the transmission pipe when it enters the village (E_{In}), this additional length will be added to the average length of tubing required, as these houses have more potential energy due to the elevation drop and consequently need more head loss through the tubing to equalize flow. Equation 13 shown below takes the absolute value of the difference in elevation, so the value of $L_{Additional}$ is always positive. For houses at a higher elevation than that of the transmission pipe when it enters the village, this additional length will be subtracted from the average length of tubing required, as these houses have less potential energy due to the elevation drop and consequently need more head loss through the tubing to equalize flow.

$$L_{Additional} = \frac{g * |Elevation_{House} - Elevation_{In}|^2 * \left(\frac{\pi D_{Tubing}^2}{4}\right)^2 * D_{Tubing}}{f * Q_{Tier3}^2} \tag{13}$$

In previous iterations of the code, a check was conducted using the set length of tubing to ensure that each of the household flow rates remained within the equity limits, even with the adjustments to the system (i.e. addition of tubing length). This check was removed in this iteration in the interest of finishing our code; however it should be reinstated in the future.

Solar

Since our system relies on solar pumps to deliver water to each house, we developed an algorithm to calculate the amount of solar power generated at a given location each year. The algorithm requires the following site-specific inputs: latitude, longitude, clearness index values, monthly average temperatures, and monthly average solar insolation values. In an effort to find accurate weather data for Jharkhand, we used procedures for estimating various parameters for major cities in India outlined in *Estimation of global radiation using clearness index model for sizing photovoltaic system* [1], a paper by Umanand Ravinder Kumar at the Indian Institute of Science, Bangalore. In the report, the monthly average daily solar insolation values ($\overline{H}$) and the monthly average clearness index values (K_T) for Kolkata were calculated for a year. We used these values in our calculations, given Kolkata's close proximity to Gufu.

Our algorithm includes several steps summarized below. These equations were found in the textbook *Energy Systems Engineering: Evaluation and Implementation* by Vanek, Albright, and Angenent.

The declination angle, calculated in Equation 14, is the angle at which sunlight hits the surface of the earth, and depends on the Julian day and latitude. This is used to find out how many hours of sunlight a given location receives each day, which determines how much energy is received.

$$D_\delta = 23.45 \sin\left[360\frac{(284 + N_{JD})}{365}\frac{\pi}{180}\right] \tag{14}$$

The daily solar insolation, from Equation 15, is the the amount of solar power that hits the earth each day and is found using the clearness index and the monthly daily average global insolation.

$$H_d = \overrightarrow{\left[\overline{H}\left(1.39 - 4.03K_T + 5.53K_T^2 - 3.11K_T^3\right)\right]} \tag{15}$$

The solar insolation ratio, in Equation 16, relates the amount of sun power that hits a horizontal surface to the amount that hits a tilted surface. This ratio is later used in Equation 17.

S_M is the optimum panel tilt angle that will yield the most energy. Each month has an average optimum tilt. We decided to tilt the panels at the optimum angle for August, as this month receives the least amount of sunlight on average and we want to optimize the system for the month that receives the least sunlight.

$$R_r = \overrightarrow{\left[\left(1 - \frac{H_d}{\overline{H}}\right) R_{Bbeta}\right]} + \overrightarrow{\left[\frac{H_d}{2\overline{H}}\right](1 + \cos(S_M))} + \frac{\overrightarrow{[\rho_{Ref}(1 - \cos(S_M))]}}{2} \tag{16}$$

$$H_t = \overrightarrow{(\overline{H} * R_r)} \tag{17}$$

Next, using characteristics of the solar panels such as the temperature coefficient and the heat loss coefficient, we were able to find the total solar panel efficiency using Equation 18. We then calculated the monthly average power generated per square meter of solar panel, using Equation 19.

$$\eta = \eta_r\left[(1 - \beta(T_C - T_A) - \beta(T_A - T_M) - \beta(T_M - T_F)\right] \tag{18}$$

$$ActualOutput = \overrightarrow{(H_t * \eta * deratingfactor)} \tag{19}$$

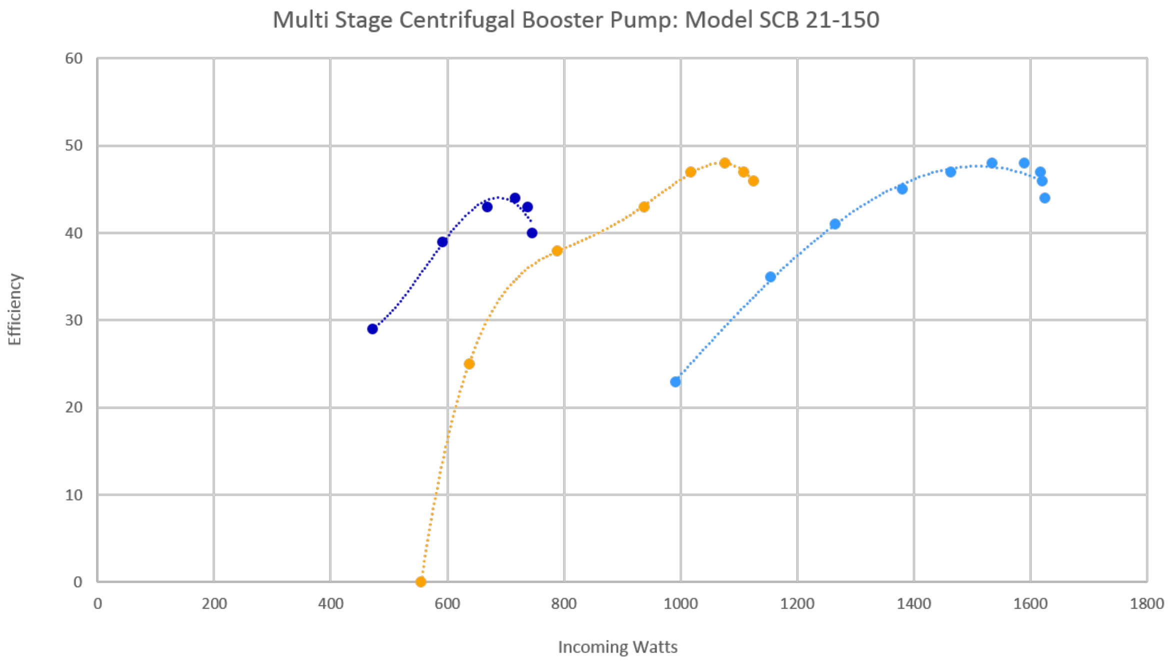

Figure 7: Fitting Efficiency Curves
These efficiency curves were fit to data points from Grundfos pump specifications. They were used to find the pump efficiency based on incoming panel wattage.

We used the lowest monthly actual power output as the design power for our algorithm. This ensures the system will successfully pump water as often as possible. This assumption does not incorporate any variability from the weather data; this is incorporated after the algorithm below has determined system parameters. We used the hourly actual power output data to determine the $\Pi_{SunHours}$ term used above to calculate the house target flow rate. This was done by taking a conservative estimate of the number of hours per day during which there is sufficient sunlight to power the pump.

We accounted for inefficiencies in the pump by fitting several curves to data points from Grundfos pump specifications [4]. This allowed us to create a function that defines efficiency based on incoming solar power. These curves can be seen in Figure 7. We then used the design power, the efficiency function, and the desired pump head from the previous section to select an optimum pump and number of solar panels.

Figure 3 shows the pump curves we input into our code. The optimal pump is then selected to ensure equity and minimize cost.

Pump Model	Pump Power (hp)	Pump Head Range (m)	Pump Cost (USD)
P3240	0.33	1.07 - 3.35	$797.95
P5040	0.33	3.35 - 3.96	$587.95
P3280	0.5	3.96 - 7.01	$585.95
P4080	0.75	7.01 - 8.84	$754.95
P5080	0.75	8.84 - 9.14	$724.95
P32160	0.75	9.14 - 14.33	$977.95
P40240	1.5	14.33 - 18.59	$1,383.95
P80240	3.0	18.59 - 23.99	$1,448.95

Table 3: Grundfos Pump Costs

Overall Algorithm

A diagram of our algorithm can be seen in Figure 8. This algorithm is designed to optimize two factors, cost and equity. Equity is forced during the first stages of the code (head loss through tubing required to ensure equity is found based on our equity constraint). Throughout the rest of the code, design parameters are chosen to maintain this equity and minimize cost. This primarily involves weighing solar cost against cost of PVC piping. Larger PVC pipes cost more, however they also have significantly less head loss and consequently require less initial pumping head (equating to fewer solar PV panels and a smaller pump). These two factors are varied in each iteration of code until a system with the lowest cost is found. This tradeoff between pump/PV and PVC is seen in both the overarching code, and the transmission section of the code nested within the main code.

The basic structure of our code is as follows:

1. Head loss per length values are found for all possible diameters for each tier, given the estimated average maximum flow that each tier will carry. Tier 3, which carries water to each house, will carry an average maximum flow of $Q_{TargetHouse}$. The estimated flows for the other tiers are found by summing the number of Tier 3 pipes that each tier services and multiplying that number by $Q_{TargetHouse}$.
    (a) This average maximum flow rate is then used to determine the maximum major losses (H_{LMax}) for this flow for all possible diameter sizes. An average H_L is then estimated for each possible pipe diameter to be 1/3 of this H_{LMax} for each tier. This rough estimate is used in this case because each tier loses energy as it carries water through the distribution system.
2. A threshold for maximum diameter is set based on the point where head loss values become negligible (i.e. the diameter of the Tier 1 pipe for which values for head loss per length are below 0.001). The Tier 1 pipe is used to set this limit because the Tier 1 pipe will always be carrying the most flow of all the tiers (and consequently will have the largest head loss).

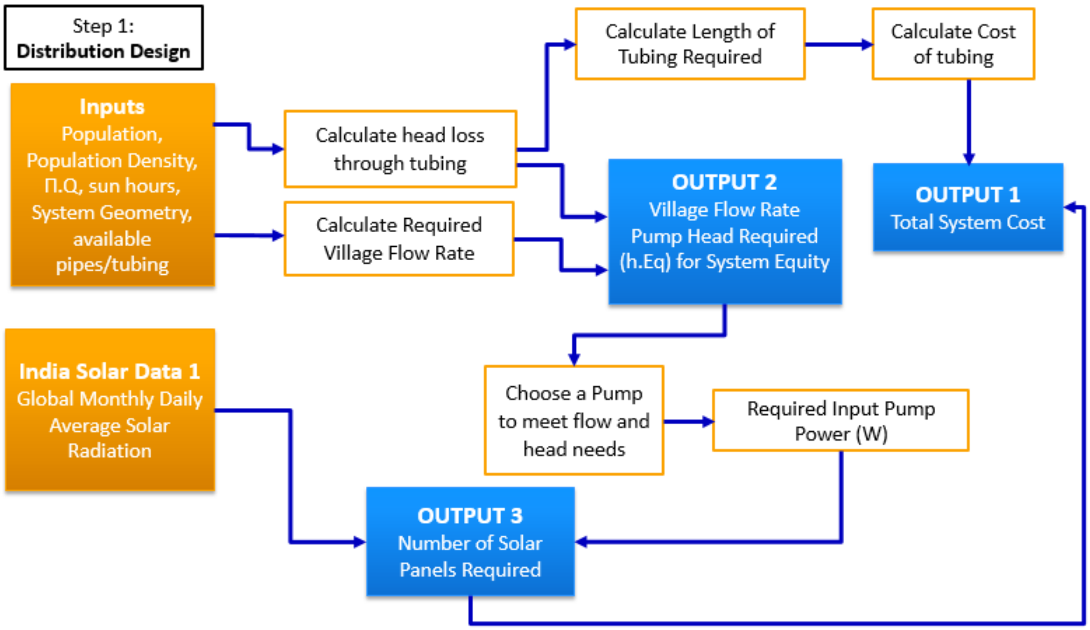

Figure 8: Algorithm Map Part 1
A diagram of the basic design algorithm steps.

3. Possible combinations of pipe size and tubing are determined by eliminating pipe combinations for which no connector exists and eliminating pipes that are above the aforementioned maximum diameter threshold. Tees are used to connect pipes to each other and adapters are used to connect pipes to tubing. Possible connections are compiled into a matrix that serves as an input to the main code.

4. Major losses throughout the distribution system are found for each house for each possible combination of pipes and tubing, using the head loss per length values found in step 1. Each house has a given length of pipe leading up to it; when the estimated head loss per length values for the given diameter chosen in the iteration are multiplied by the length of pipe leading up to each house, an estimate of the head loss for each house can be found.

5. The calculated head losses are used in conjunction with the head loss through tubing equation shown above to determine the average head loss required through the tubing to maintain equity. The entire explanation of this process can be found above.

6. This average head loss required through the tubing is then used to determine the average length of tubing required to dissipate this requisite head.

7. The additional length required for each house given the elevation variations within the village, $L_{additional}$, is then determined and added to or subtractedfrom the initial length of tubing to find the tubing length required for each house.

8. The head required to push water through the system and maintain equity is then found by adding the requisite head loss through the tubing to the maximum head loss throughout the distribution system. This “equity head” is essentially the amount of additional input head required to ensure that each house throughout the system receives equitable flow.

9. The following steps occur as their own mini iteration within the code. These steps determine the transmission line diameter and the corresponding pump and number of solar panels required for the diameter chosen. The code starts by setting the diameter of the transmission pipe equal to the diameter of the Tier 3 pipe from the current iteration. It then proceeds through the following steps for each increasing size of pipe diameter. Once these iterations are complete, the code picks the lowest cost option. One change to implement in the system would be to allow for a "sliding centrifugal pump." This means that the centrifugal pump could be located at any point along the length of the transmission line. The centrifugal pump would be required to pump water through the length of transmission pipe located after it, and a submerged pump located at the

well would be required to pump water up from the well and through the length of transmission pipe leading to the centrifugal pump.

   (a) A pump and number of solar panels are chosen based on the pump head required to ensure equity and the total flow rate for the system. A series of pumps, with their pumping head capacities and costs, are sorted through to find an adequate pump, given input values. An associated cost is then found for the PVC pipe chosen.
   (b) The solar wattage required to power the chosen pump is then found by using a series of pump efficiency curves that are shown above in Figure 7. Given this requisite solar power input, the number of PV panels required for the system is then chosen.
   (c) The cost of PVC, cost of the pump, and cost of PV panels are summed to find the total cost for this iteration of the code.

10. The cost of the distribution system can be found with equation 20, which uses the length and cost of each tier of pipe and the tees or adapters selected by the code.

11. The code outputs the optimal (minimum cost) solution, given the possible pipe, pump, and panel requirements

$$Cost_{tiers} = \begin{cases} L_{Tier1*}Cost_{Pipes\left(ind_{Ex_0}\right)} \\ L_{Tier2} * Cost_{Pipes\left(ind_{Ex_1}\right)} + \sum Nodes_{Tier1} * Tees_{ind_{Ex_1},ind_{Ex_2}} \\ \sum \overrightarrow{L_{Tiers}^{<2>}} * Cost_{Pipes\left(ind_{Ex_2}\right)} + \sum Nodes_{Tier2} * Tees_{ind_{Ex_1},ind_{Ex_2}} \\ L_{Tubing} * Cost_{Tubing\left(ind_{Ex_2}\right)} + \sum Nodes_{Tier2} Adapters_{ind_{Ex_2},ind_{Ex_3}} \end{cases} \tag{20}$$

12. A separate step from this code, discussed in detail in the “Variability Check” section of this document, takes this system design and weather data from India and determines how often our system provides adequate water to villagers.

Results and Analysis

This system is designed to ensure equitable flow, where all houses receive a flow within 10% of the average, which places stringent constraints on our system design. Maintaining this level of equity requires a costly system, mainly due to the relatively long length of tubing required at each house to ensure significant head is dissipated. The tubing size is limited by the availability of tubing adapters.

After running the distribution code, we determined the total cost of the village distribution system. The cost is shown in Table 4. The total cost of the village distribution system with our current input parameters is $27,220 and the full system design can be seen in Table 5.

Component	Cost (USD)
PVC Pipe	$6,953.00
PV Panels	$18,800.00
Pump	$1,384.00
Total	$27,140.00

Table 4: Cost Summary

Tubing Diameter (in)	0.25
Tier 3 Diameter (in)	0.5
Tier 2 Diameter (in)	0.75
Tier 1 Diameter (in)	2.0
Transmission Pipe Diameter (in)	2.0
Total Tubing Length (m)	540
Optimal Number of Solar Panels	11
Optimal Pump Power (hp)	1.5
Pump Head (m)	16.2
Equity Head (m)	1.9

Table 5: Optimal System Values

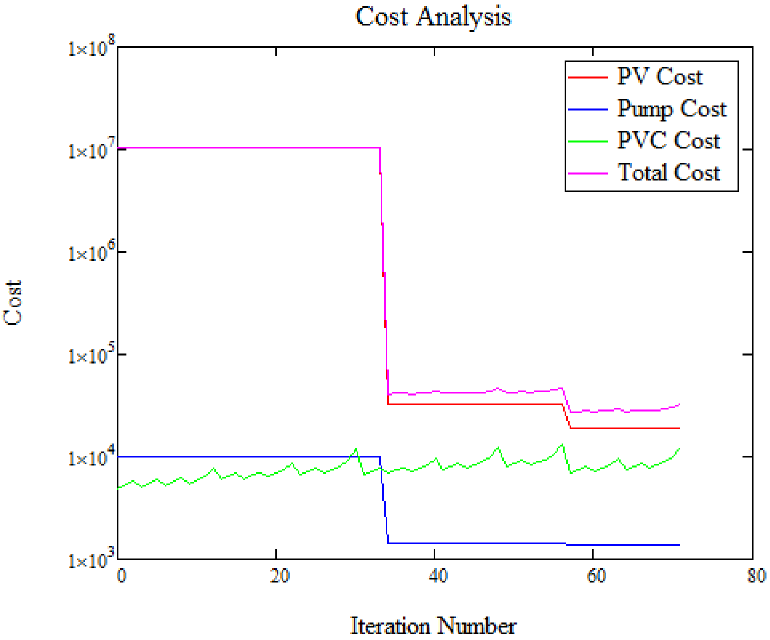

Figure 9: Cost Optimization Analysis
Illustration of how system cost varies with each iteration of pipe size.

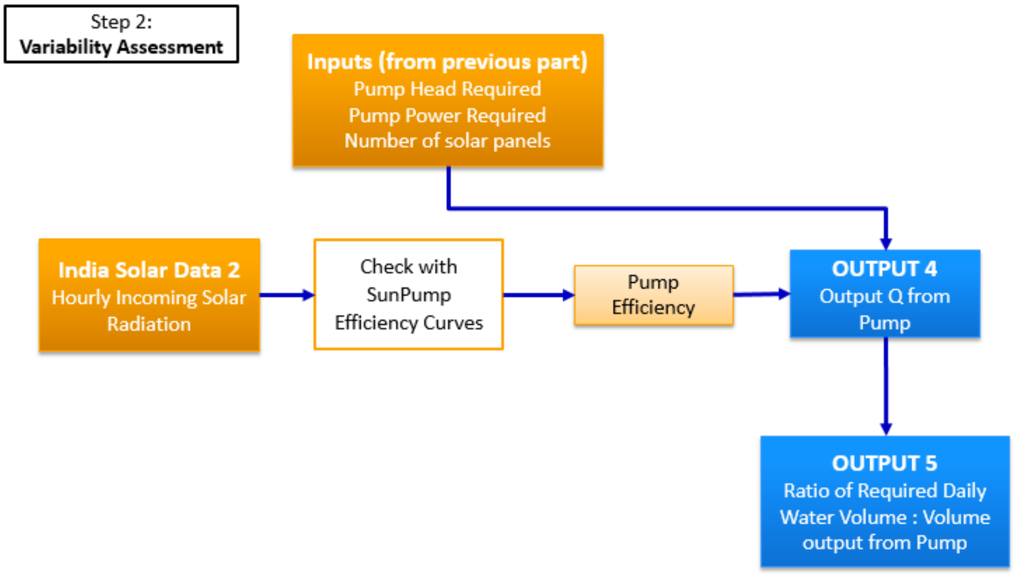

Figure 10: Algorithm Map Part 2
A diagram of the steps carried out in the variability check.

Figure 9 shows how the cost of each component varies with each iteration of pipe sizes. The pump cost is a step function because there are a set number of pumps inputted. Because the number of solar panels is determined by the pump chosen, this causes the PV cost to be step function as well. The cost functions are ultimately limited by the availability of pipe sizes and adapters. This graph demonstrates the slight tradeoff between PVC and PV/pump costs; as the PVC costs increase, the PV/pump costs decrease.

Variability Check

Our design is based off average weather data but we wanted to see how our system would perform under realistic conditions. The steps we carried out to check this performance can be seen in Figure 10. We used hourly weather data to create a simulation to test our design. Using the information and studies provided by the National Renewable Energy Laboratory (NREL) of India [2], we obtained an Excel spreadsheet with daily hourly average horizontal global irradiance, temperature, and the day and hour in which the data was collected. The website claims to use the "The SUNY model [to produce] estimates of global and direct irradiance at hourly intervals on the 10-km grid for all of India, as shown on the India solar maps." We extracted the information into a matrix in Mathcad and wrote functions to convert the data into a more usable format. The date values were converted to Julian days, the hourly global insolation

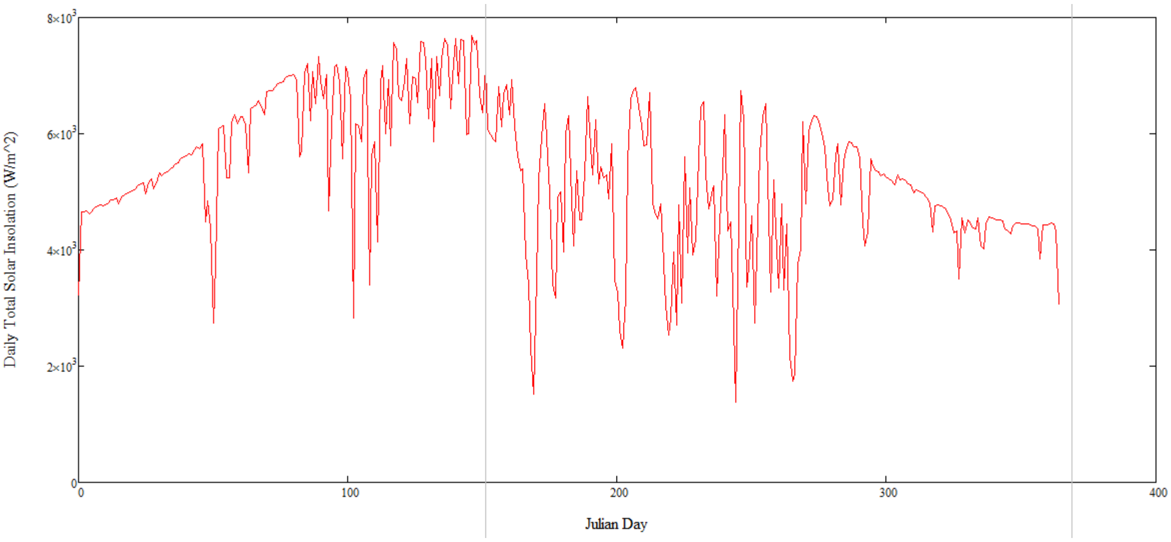

Figure 11: Daily Global Insolation
The daily global insolation varies significantly on a daily basis and throughout the year.

values were summed to get the total daily global insolation, and the hourly temperatures were averaged to get daily temperatures.

The daily global insolation values can be seen in Figure 11. Although the insolation is higher in the summer, there is also significantly more variability.

This real hourly data will be used to test the variability of our distribution system by determining how much water will be pumped on any given day. We converted the hourly global insolation values to insolation on a tilted surface values using Equation 16 and then found the hourly flow rate using Equation 21 and the chosen pump and the efficiency function described above.

$$Q = \frac{P\epsilon}{h\rho g} \tag{21}$$

Using the hourly flow rate, we calculated the total volume of water pumped each day and compared this value to the village's demand to quantify how many days sufficient water will be provided. The resulting ratio of water supplied to water required is shown in Figure 12. For each day the graph falls below a ratio of one, the village does not receive enough water. We also wrote a function that counts the number of consecutive days this occurs. With our final design, there are at most three days in a row without sufficient water supplied and this only occurred twice during the year. We believe this system would be feasible if it incorporated large enough household storage tanks that could hold a three-day supply of water for each family. These could be filled on days when a surplus of water is pumped and emptied when insufficient water is pumped.

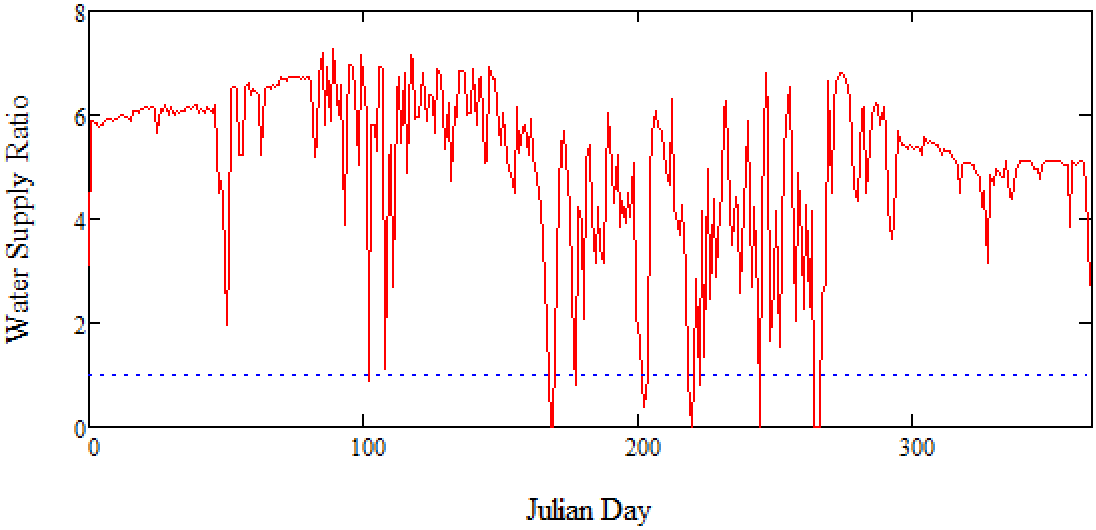

Figure 12: Water Ratio

Using this variability simulation, we can adjust our final design to meet the needs of the village.

Future Work

In future semesters, we hope to improve our code by accounting for flow type variability. We currently assume flow is turbulent, but this may not always be the case. We also want to find more accurate pump efficiencies. The current efficiency functions are from different pumps than those currently used in India. Finally, we would like to make our code more user-friendly by minimizing and simplifying the inputs.

Furthermore, the simulation could be improved with data from multiple years. Future teams should look into other data sources to improve the simulation's accuracy.

Other useful research areas include the sizing and implementation of a storage tank, the design of household infrastructure, and options for handling human waste.

References

[1] Umanand Ravinder Kumar. Estimation of global radiation using clearness index model for sizing photovoltaic system.

[2] NREL.

[3] Nathan Reents. Design of potable water supply systems in rural honduras Â . 2003.

[4] Sunpumps. Sunpumps pump curve.