Campus Center for Appropriate Technology Rainwater Catchment and Solar Water Pump System Re-Design

Julia Anderson, Anh Bui, Grishma Raj Dahal, Chih-Wei Hsu

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EXECUTIVE SUMMARY

The design team partnered with the Campus Center for Appropriate Technology (CCAT) to create a more sustainable solution for the rainwater catchment & solar water pump system. CCAT uses this system to water their plants during the dry summer season, but the system runs out of the water early in the season, forcing CCAT to turn to city water. The goal of this project is to design and implement a redesign that enables CCAT's mission to meet its plant watering needs more effectively.

To pursue this goal, the existing system was assessed and changes were proposed in this document. The system consists of a catchment surface, a gutter, screen, first flush, overflow, two storage tanks located next to the tool shed, a solar panel, water sensor, pump, a top storage tank, and the piping and valves that connect the system components. When there is adequate insolation and the water levels allow, the solar pumping system pumps water 26 feet uphill to the top tank. The service provided by the current system is limited primarily by its storage capacity. In order to have enough water for the gardens on the southern side of the toolshed through summer, CCAT should take into consideration reduction methods proposed from the Demand design documents (Cervantes et al., 2019). By doing this, the daily water use could decrease to approximately 3.4 gallons per day (24 gallons per week), and the stored water from the system would last all summer. If CCAT is not able to implement these methods, or if they want to make the system more robust for future generations, we recommend installing a new 500 gallon tank (1892 liter) on the eastern hillside of CCAT that will replace the current 264 gallon (1000 liter) tank. The replaced 264 gallon tanks could replace the two 50 gallon (190 liter) barrels at the bottom. This change will increase the total storage capacity by 65%. With this upgrade, if demand is less than 12 gallons per day (84 gallons per week), CCAT will have enough water to last all summer. If CCAT uses more than 12 gallons per day, then there will be some days in the summer in which CCAT will not have enough water, defined in this document as unmet watering days (UWD). The installation of 500 gallon tank would not require any expansion for the current platform for the top tank.

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1 INTRODUCTION

CCAT is a student-run organization at Humboldt State University that focuses on the demonstration and the community education of appropriate technology (AT). Some examples of AT that CCAT showcases are: natural paint, a wall made of invasive beach grass, insulation consisting of blown-in cellulose, solar panels, cob benches, grey water marshes. CCAT projects are constantly evolving and changing; fostering the idea of the center as a “learning laboratory” rather than a “museum of appropriate technology.”

One of the projects that CCAT hopes to develop further is the rainwater catchment & solar water pump system located beside the tool shed. The system was first installed circa 2017. The 2019 CCAT Co-directors expressed their desire to improve the system and examine the water available for summer use. At the beginning of the project, the information available to users was not adequate. In addition, there were multiple locations with leaks. The objective of the Engineering 535: Development Technology class project was to give suggestions on how to optimize the current system to meet CCAT’s needs.

To re-design the system, the team followed the general engineering design process of defining the problem (1), doing background research (2), specifying the system requirements (3), then choosing a potential solution (4). Once a possible solution had been identified, it was developed (5), then tested and evaluated (6) against the previously established system requirements. The design team’s understanding of the problem was developed based on the project assignment, a meeting with the CCAT Co-directors, and with the input from the CCAT Project manager. The client’s main goal was to be able to use this system to water plants in the food forest on the south side of the tool shed all summer. This goal stems from the CCAT mission to “demonstrate that living lightly on the Earth is both practical and rewarding” (CCAT, n.d). Therefore, the re-design goals were established as follows: the system should provide enough water for the summer, enable CCAT’s future projects, and have little negative impact on the environment.

This report summarizes the team’s results and assessments based on the organization of the design process: first, the existing system is introduced with all necessary background research and a system assessment to better understand the system requirements. Next, the potential solutions are identified and assessed, which leads to a final recommended system. This document only covers the redesign of the physical system, the improved operations and maintenance (O&M) plans are in the supply side O&M report.

2 EXISTING SYSTEM

The rainwater catchment & solar water pump system is located near CCAT’s tool shed, on the southern side of CCAT’s grounds. The rainwater catchment system includes the tool shed roof, a collection of tanks located next to the toolshed, and one tank located on the hillside (Figure 1 & Figure 2). The solar water pumping system is located next to the bottom tanks (Tank 1, Tank 2, and Tank 3). From the bottom outlet valve, hoses can bring the water to almost anywhere on the CCAT grounds with the pressure provided by the height difference between the water in the top storage tank (Tank 4) and the point where the water is used. Further system investigations were done through site visits and measurements, meetings with CCAT members, and testing specific system components.

2.1 Physical Components

Figure 1. Aerial map of the Campus Center for Appropriate Technology (CCAT) Rainwater Catchment & Solar Water Pump system. The long pipes (yellow) are partially underground.

2.1.1 Water Flow Pathway

Rainwater is first collected on the tilted roof (catchment area) and then flows into the gutter (conveyance). The conveyance is covered by a loose mesh to prevent any large debris from entering into the and clogging the rest of the system. At the end of the conveyance, the water flows through a finer screen and enters the first flush system. The first flush system, located between the screen and Storage Tank 1, catches the first rush and the dirtiest part of the rainwater. Once the first flush system is filled, the rest of the rainwater can then enter the Storage Tank 1. This first flush system has a small hole in the bottom so that the water slowly empties out, and the first flush will be empty by the time of the next rainstorm. The three lower tanks are interconnected and maintain the same water level. The overflow pipe allows the excess water to escape if the bottom storage system is full. The water is pumped from the bottom tanks to Storage Tank 4 with the Aquatec pump powered by the solar panel (specifications found in Table 1) to be stored and used at a later time. The water is used by opening an outlet valve that draws from Storage Tank 4. There is an outlet valve located at the base of Storage Tank 4 as well as a valve located near the toolshed, by the bottom storage tanks and the solar panel.

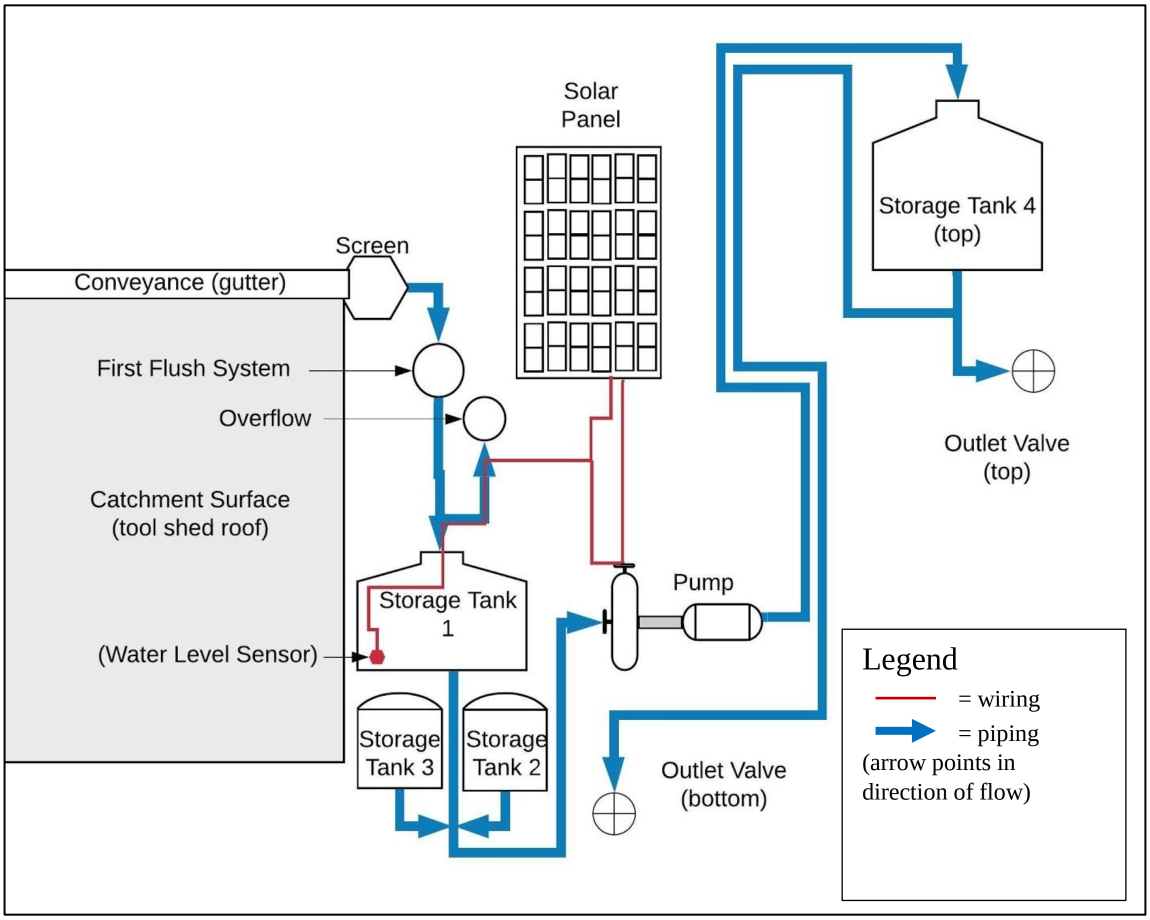

Figure 2: Diagram of rainwater catchment and solar pumping systems (not to scale)

2.1.2 Pump and Panel

The 135 watt (W), 18 volt (V) Direct-Current (DC) solar panel delivers power to the 192 W, 24 V DC pump, which is located directly below it (not spread out as in Figure 2). The effect of voltage mismatch between the solar panel and the pump on pump performance will be discussed in the next section. The pump is a five-chamber diaphragm pump that self-primes and is capable of being run dry (Aquatec, n.d). The pump inlet and exit are quick disconnect, non-threaded barb adapters. They are unsealed, and had noticeable leaks. The electrical circuit between the pump and the solar panel can be broken by the water level sensor when the water level is too low, essentially turning the pump off.

Table 1: Technical specifications of the pump and solar panel adapted from the manufacturer specification sheets. MPP stands for the maximum power point. GPM stands for gallons per minute.

Component	**Model Number**	**Power**	**Voltage**	**Current**	**Flow rate**
Solar Panel	DS-A18-135	135 W	18V DC (mpp)	7.5A (mpp)	n/a
Pump	2003-1E11-B736	192 W	24V DC	8.0 Amps	4.3 gpm

2.1.3 Pump Performance

Further testing was conducted to assess the impact of voltage mismatch between the solar panel and the pump on the pump performance. First, the pump capability was compared to the total dynamic head (TDH) of the CCAT system. The maximum pressure that the pump can pump against (max pump head) and the power required by the pump with a 24V power source was interpolated based on pump performance data (Appendix D). In order for the pump to work, the max pump head must be higher than TDH. At approximately 4.7 gallons per minutes (gpm), the max pump head was smaller than TDH, indicating that the maximum flow rate for the system under the appropriate voltage and power input is approximately between 4.6 and 4.7 gpm.

The 18V solar panel is mismatched with the 24V water pump. When tested, the solar panel was operating at 5.51A at 17.41V (96W) compared to the solar panel's nominal MPP of 7.5A at 18V (135W); a 29% decrease in power. At the time of the test, the operating flow rate of the pump was 3.5 gpm as opposed to the maximum flow rate of 4.6 gpm given the CCAT's system set up.

The pump efficiency as a ratio between hydraulic pressure and 24V power input was calculated to be in the range of 27% to 46%, dependent on the flow rate (Based on Appendix D-2). We observed the increases in the discharge pressure up to 60 pounds per square inch (i.e., the pressure the pump has to overcome) corresponded with the increases in the efficiency. Under the current pump and solar panel mismatch set-up, with the flow rate at 3.5 gpm and TDH at 29.76 feet, the hydraulic pressure (W) of the pump was 19.53W. The pump with the mismatched solar panel was performing at 20% efficiency based on the power provided by the panel at 96W[1].

The pump is not performing near its peak efficiency due to the solar panel and pump voltage mismatch. Since the solar panel is rated at a lower voltage than the pump, there is little danger to the system, the mismatch simply causes lower efficiency.

2.1.4 Operational Issues and Reconfiguration

During the series of physical site investigations, a number of operational issues were observed. First, the system had two significant leaks, one at the outlet valve attached to the tank drain for the top tank and one at the pump intake. Second, the pump was not functioning as expected with the direct sunlight on the solar panel—it was whining and the flow rate greatly reduced to trickles.

LEAK AT THE PUMP INTAKE

There were leaks on both the inlet and outlet of the pump due to loose hose clamps. The leaks were fixed by tightening up both hose clamps.

LEAK AT THE TOP TANK

The leak at the top tank was due to the incorrect pipe fitting at the tank drain. One of the mismatched pipes was broken during the investigation. A new, correctly fitting pipe will be purchased and installed by a different team that is also currently working on the system, the

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[1] We measured the panel performance and flow rate at two different time, but both around 2 in the afternoon on a sunny day. Thus, we assumed the same power was provided by the panel when the flow rate was measured.

solar washing station team in ENGR 305: Appropriate Technology. They will be using water from the top tank, connected to their in-progress solar washing station to be located at the northern end of the toolshed.

AIR INTRODUCED AT THE INTAKE PIPE

The pump operating issue required multiple iterations to diagnose and fix. The problem was first noticed when the team attempted to test the pump. When the power was provided to the pump with a variable power supply, the current draw fluctuated around 1 Amp (A); lower than the suggested current on the specification sheet. We found the pump was malfunctioning when the water level (in the bottom tanks) was at approximately one-third of full. At first, it was thought that there was a blockage in the pipes between the bottom tanks and the pump. So the lower pipes were disconnected and flushed. Some visible debris came out, but the problem persisted.

Upon further investigation, it was determined that air was introduced to the intake pipe between the lower storage tanks and the pump as a result of (a) the poor connection between the pump inlet and the elevated intake pipe (see Appendix C-3) and (b) the water level in the bottom storage tanks dropping lower than the elevated intake pipe. The pump was either not capable or very inefficient at drawing water past the air pocket. The pipe connecting the bottom tanks to the pump was adjusted so that the highest point in its arch was at the same height as the pump and the entire pipe remained as low as possible relative to the bottom storage tanks. This configuration should reduce the chance of air entering the system even with the poor connection.

2.2 Demand and Environmental Resources

The assessment of the system includes both the inputs (sun and rain) and the final output (i.e., water availability in the summer). Water availability depends on both water use, rainwater collected by the system, and the solar resource. Water demand depends on the people interacting with the system, but environmental resources are outside of human control, and can vary greatly.

2.2.1 Demand

Overall, the water availability in the summer depends on how much water is used. Water demand is outside the scope of this document, see the Demand Design Document (Cervantes et al., 2019). Water use last summer was estimated to be 80 gallons per day (560 gallons per week). The demand team estimated that, with their implementation advice, it could be reduced to approximately 3.4 gallons per day (24 gallons per week). It is possible for water demand to vary hugely between CCAT generations as different groups of students work on different projects and shape CCAT to reflect their own goals. For example, a team is currently investigating the possibility of a solar washing station using the water in this system, which would increase the water use.

2.2.2 Environmental Resources

Solar insolation and precipitation data for the site location were retrieved from PVWatts by National Renewable Energy Lab (NREL, n.d) and National Oceanic and Atmospheric Administration (NOAA, 2018) respectively. We collected the environmental resource data

(Appendix A) and conducted solar shading analysis using the Solar Pathfinder (Appendix A) to find the available insolation. For the current site, the solar resource is only available between 10 am and 5 pm (Appendix A) and precipitation is the lowest in the summer months of July and August (Figure 3). The current catchment system is able to catch 12,272 gallons annually based on average precipitation.

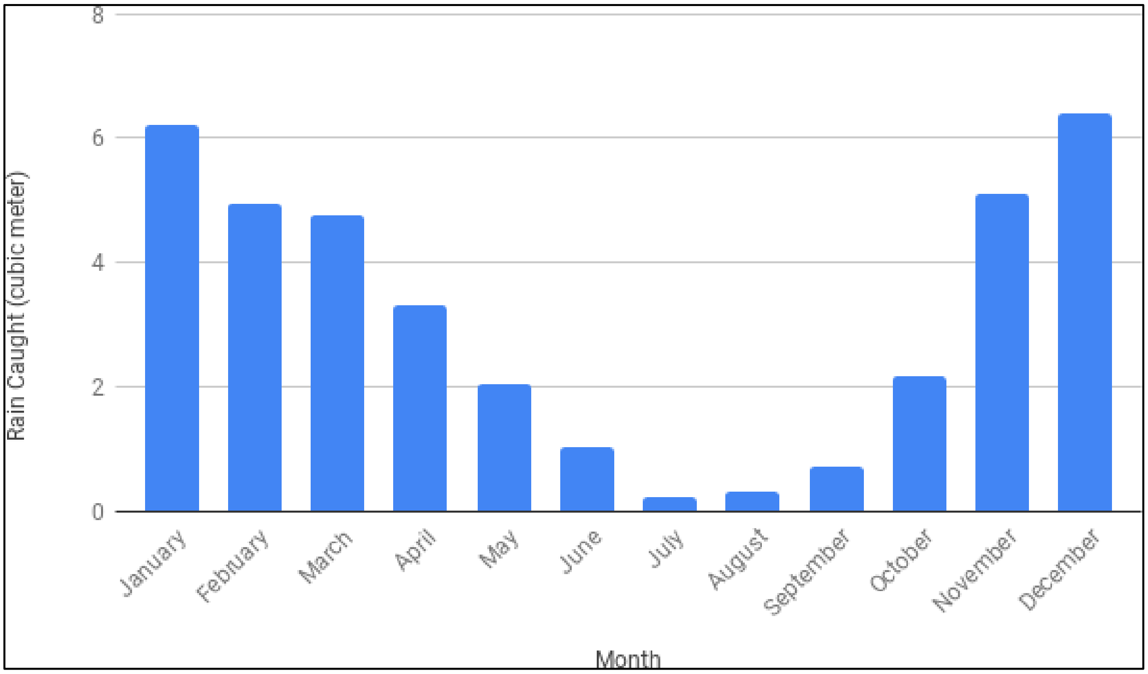

Figure 3: Rain caught, but not necessarily stored, in the rainwater catchment system each month based on the recorded monthly precipitation averaged over 30 years of data (NOAA, 2018) and assumed collection efficiency of 0.95 (Grafman, 2017)

2.3 System Operation Simulation and Performance Assessment

2.3.1 System Operation Simulation

The user demand, environmental resources, and system component specifications including the catchment area, storage tank capacities, pump capacity, and solar panel capacities were used to simulate the current system operation and evaluate its performance. The main performance metrics used to evaluate the system performance are (a) total annual usable water ("total usable water") and (b) unmet water demand (UWD). Total usable water is the total amount of water that is stored or passed through the system. It is calculated by summing the watering demand that is met and the amount of water stored in the system by the end of the year. The total annual unmet water demand is the difference between total annual water used from the system and the total water demand. See Appendix F for more detailed method description and the R script.

Based on the current system specifications and environmental resources, the system performance results were generated (Table 2). Note the total usable water is partially dependent on the water demand because the more water CCAT uses, the more total usable water due to an increased ability to recharge the limited storage. Consistent with the CCAT's problem statement, the simulation indicated that the stored water ran out in either May or July, depending on the amount of water demanded. If the demand was lower than 12 gallons per day (84 gallons per week), the system would be able provide water throughout the whole summer (Table 2). The UWD increased as the demand increased. During the summer, when rain events were infrequent, UWD was higher.

Table 2: System performance matrix based on the water used per watering event. 3.4 gallons per watering day is the result of implementing the demand reduction strategies. 7.1 gallons is the upper bound of the demand reduction plan. 80 gallons the estimated use last year.

Water required per watering day (gallons)	**Total annual usable water (gallons)**	**Unmet watering demand (UWD) (gallons)**	**UWD in days (days)**
3.4	1,420	0	0
7.1	2,281	0	0
12	3,404	17	1
20	4,336	945	47
35	5,615	3,066	88
50	6,263	5,731	115
80	6,448	12,522	157

2.3.2 Water Cost

At the demand of 80 gallons per day, the UWD is 12,522 gallons of per year which is equivalent to 1,674 cubic feet of water. The city of Arcata defines different water rates depending on the total usage volume as shown in Appendix E. Considering the current UWD and water rate, the total cost of water comes out to be $113 per year. However, because CCAT does not pay for the water (i.e., paid for by the University), this number is used as a reference rather than as a major design factor. If CCAT implements the demand reduction plan, the current system would be sufficient for their watering needs, so the bill attributed to the problems in this system would be zero.

2.3.3 System Component Sensitivity Analysis

Using the same calculations used in the system operation simulation, the capacity of each system component was adjusted independently to investigate the sensitivity of the system performance (i.e., total usable water). We found system performance to be most sensitive to the catchment area. Increased catchment area allows the system to catch more rain during the infrequent summer rains when the storage is nearly empty. Increasing system storage also increased the system performance noticeably, but with non-linear effects (Figure 4).

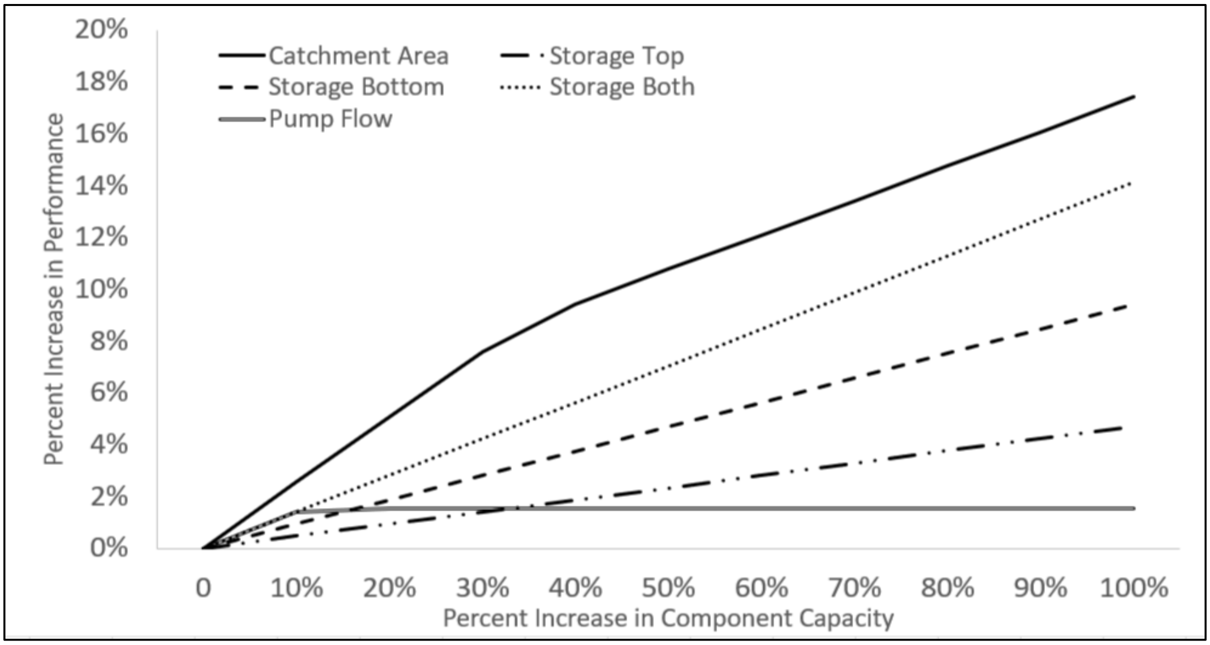

Figure 4: System performance sensitivity to each system component. This graph was created based on a possible water demand of 35 gallons

Finally, pump flow and solar panel performance were not limiting factors for system performance. A 20% increase in pump capacity (or flow) only led to a 1.8% increase in system performance. The system performance was calculated for a range of flow rate improvement (i.e., 0 - 100% increase from the current 3.5 gpm) for various storage tank sizes. The flow rate increase from pump (or panel) efficiency increase is negligible for the 500 gallon storage tank (Figure 5). Even with a 4,000 gallon tank, a 100% increase in flow rate only led to a 41% increase in the total annual usable water from the system. Furthermore, with the current pump, the maximum flow rate (i.e., 4.5 gpm given the CCAT system) limits the potential system performance gain to the left of the red line (Figure 5).

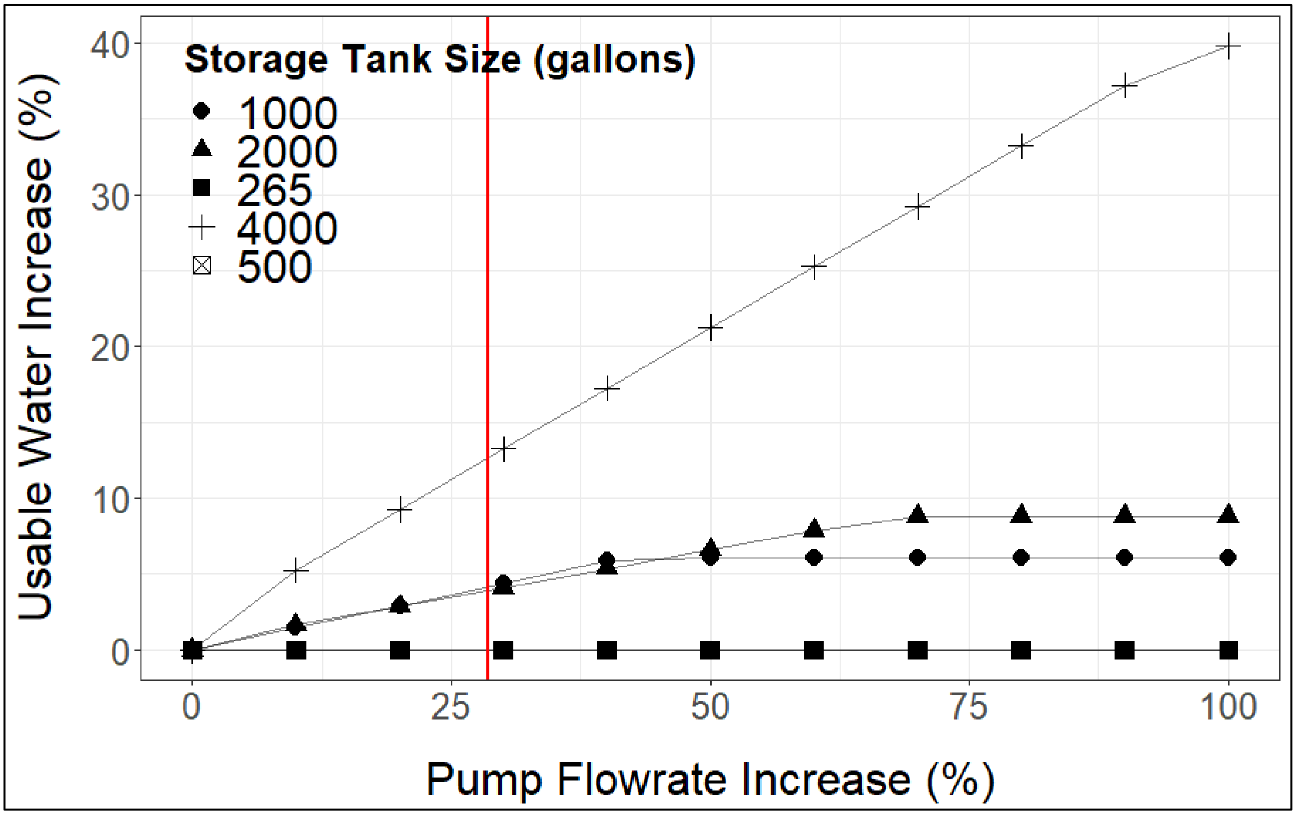

Figure 5: System performance sensitivity to pump flow rate. The current flow rate is 3.5 gpm and the red line indicates the maximum flow rate (i.e., 4.6 gpm) for the CCAT system.

3 PROPOSED SYSTEM CHANGES

A number of potential solutions were examined both quantitatively and qualitatively. Potential solutions were first identified via a brainstorming session and the sensitivity analysis. Overall, it was found that the ideal solution is a function of the water demand. If demand is low, then the system does not need to be changed, otherwise, we recommend installing additional storage.

3.1 Potential Solutions

To develop potential solutions, a brainstorming session was held to try to think “outside the box” for potential solutions. Most of the ideas that rose out of this brainstorming session were not viable because they were too expensive in terms of either money, time, or space. Next, possible solutions that involved only small changes to the current system were developed. Based on the sensitivity analysis (Figure 4) increasing the catchment area is the most effective way to increase water availability in the summer months based on a demand of 35 gallons per day. Increasing the roof area of the toolshed was not feasible based on feedback from the CCAT project manager. A second option was connecting the system to the yurt roof, but that roof is not appropriate for rainwater catchment. The final option was installing new catchment area, but CCAT indicated that there was no space. The second best component to change, based on the sensitivity analysis, was the storage volume. Based on feedback from CCAT, this was the best option and is investigated further below. The system was not limited by solar energy availability or pumping capacity, so changing these components was not considered because improvements in these areas would not significantly change the system performance.

3.2 Assessment of Storage Solutions

3.2.1 Theoretical assessment

A number of changes in the storage volume were investigated. Based on the simulation, it was clear that increasing storage at both the top and bottom tanks was the most effective (Appendix F). The existing infrastructure consists of a flattened 69” x 69” platform on the hillside. This platform could be enlarged if needed but would require coordination with Facilities Management (FM). Next to the toolshed, there was not much extra room, but if the existing pickle barrels were moved a larger tank could be put in that location. The current configuration of the pickle barrels prevents them from being fully utilized: the barrels empty through the bottom, which means that they are raised above ground level to allow for piping beneath them. Since they are raised, the top of the barrels is above the overflow pipe, meaning that the pickle barrels cannot fill to their full capacity. This was taken into account when potential storage solutions were evaluated. The team first evaluated a number of potential storage configurations at both the top and bottom, ranging from adding 500 gallons to 3,000 gallons (Appendix F).

The simulation (Section 2.3.1 and Appendix F) was used to assess the effects of the current system and the three potential system changes.

- Current system: two pickle barrels (50 gallons each), one IBC tank (264 gallons) at the bottom and one IBC tank (264 gallons) at the top
- 500 Gallons: two IBC tanks at the bottom and a new 500 gallon tank at the top
- 1000 Gallons: two IBC tanks at the bottom and a new 1,000 gallon tank at the top
- 3000 Gallons: two IBC tanks at the bottom and a new 3,000 gallon tank at the top

Overall, at low watering demand (below 12 gallons per day), the current system is sufficient, as shown in the horizontal line indicating zero days of unmet water demand in Figure 6. The red line at 7 gallons per day (approximately 50 gallons per week) is the projected high daily demand according to the Demand design document (Cervantes et al., 2019), indicating that the current system could be sufficient. When the daily watering demand exceeds 12 gallons but below 15 gallons per day, a 500 gallon tank would allow CCAT to use this system for water all summer. If demand is over 25 gallons per day (203 gallons per week), not even a 3,000 gallon tank would provide water all summer (Figure 6). The demand last year was estimated to be 80 gallons per day (560 gallons per week).

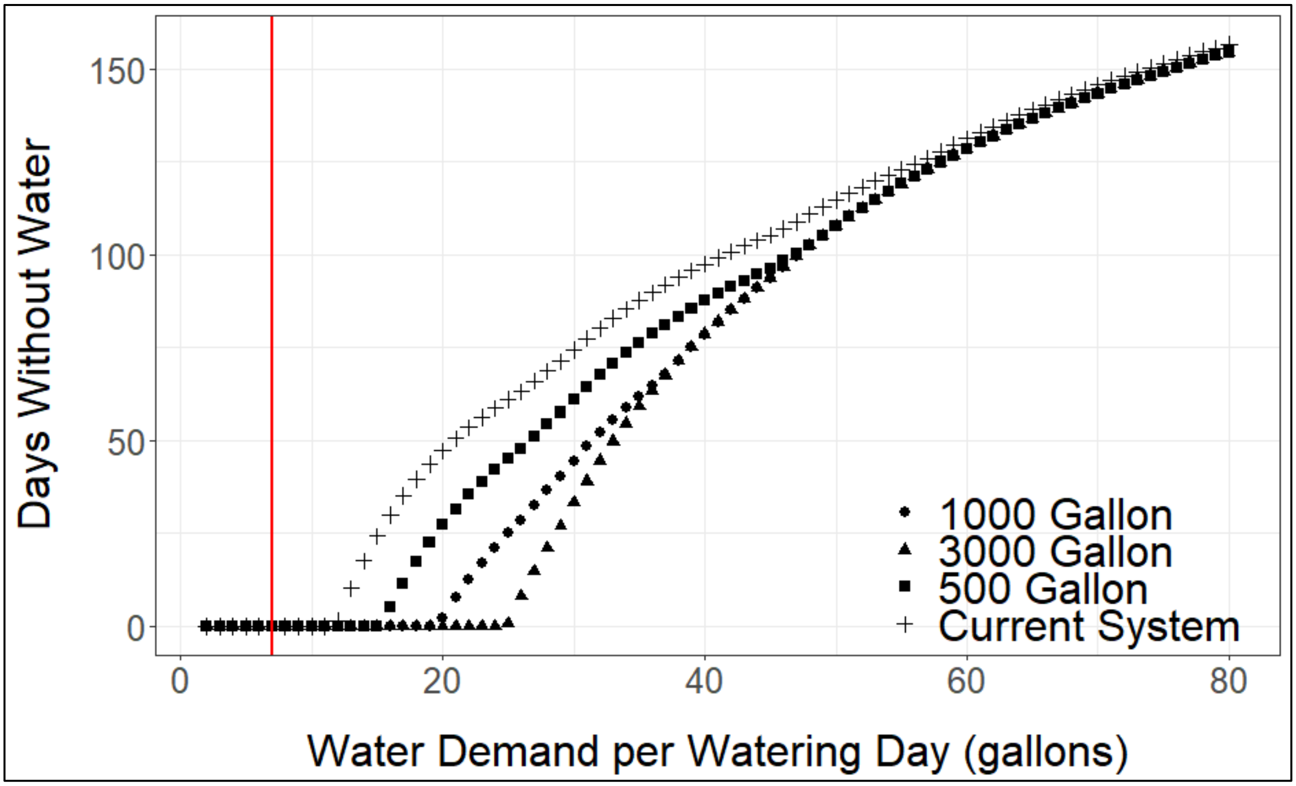

Figure 6: Days without water based on the watering demand (gallons per day) for different system designs.

3.2.2 Cost Assessments

Three potential tank sizes were considered (Appendix G). The 500 gallon tank will cost approximately $350, the 1000 gallon tank $560, and the 3000 gallon tank $1100 (Humboldt Water Tank, 2019). The 500 gallon tank is the recommended storage tank. A 1,000 gallon tank would have a larger footprint, so the edges of the tank would be close to the edge of the existing foundation structure and might require an upgrade to the existing platform. For the largest storage tank, the 3,000 gallon tank, the hillside foundation would need to be expanded and more planning would be needed.

3.2.3 Feedback Process

Client feedback was a vital part of the design process. A progress meeting was held to present ideas to the clients and receive feedback once potential solutions had been identified. At this meeting, feedback was requested about the potential system changes, the best metric to communicate results, potential changes in water demand, and about the feasibility of operation and maintenance plans (not discussed in this report). CCAT staff expressed a preference for installing additional storage on the hillside rather than next to the storage shed. Regarding performance metrics, they agreed that the proposed “days of watering” would be an understandable metric, but someone suggested using the “last day of water” as another way to communicate the performance of the system too.

Another meeting happened between a member of the Supply Team, Anh Bui, with CCAT Co-director Jacob Gellatly, and Facility Management (FM) Director of Planning, Design & Construction, Michael Fisher. This group assessed the top tank and suggested that instead of adding a second 264 gallon tank, it would be easier to switch out the current tank with a larger tank, possibly a 500 gallon tank. For large tanks, FM said that the base might have to be widened, which would necessitate construction efforts involving adding gravel and wood framing. Mike Fisher was willing to work with ENGR 535 class to improve the platform if the team came up with the platform measurements. It is vital that any construction efforts are planned in collaboration with Randy Davis, CCAT Facilities Managements liaison, so that the work does not cross the boundary of the Labor Union.

3.2 Recommended System

The system recommendation depends on CCAT's demand. If CCAT is able to decrease their daily water demand to approximately 3.4 gallons per day (24 gallons per week) as described in the Demand design document (Cervantes et al., 2019), then the current system does not need to be upgraded. As shown in Table 2, the suggested demand is between 3.4 to approximately 12 gallons for CCAT to have enough water for the whole summer.

However, there is not much margin for error if CCAT only pursues demand reduction. If CCAT expects to use more than 12 gallons per day (84 gallons per week), adding storage to the system is the best solution. The best option is to add a larger top tank and move the current top tank (Tank 4) to the bottom to replace the red pickle barrels (Tanks 2 and 3).

The 500 gallon tank would not require the involvement of FM, while the larger tanks would. A 500 gallon tank would fit on the current 69" by 69" platform on the hillside, and allow CCAT to have demand up to 15 gallons per day throughout summer. The current top 264 gallon tank can replace the two pickle barrels that are currently part of the bottom storage system. This option is the best because of the available space, feedback from the CCAT members, cost of the tank, cost of changing the hillside foundation, and potential future demand.

The base area of the 500 gallon cylindrical tank is 12.56 square feet with a diameter of 48 inches (4 ft)(Humboldt Water Tank, 2019). The height of the tank would be 73 inches (6.08 ft)(Appendix G). The tank is available in Eureka, CA and can be easily shipped to CCAT in Arcata. The net cost of the tank is estimated to be around $350, excluding the shipping costs, labor costs and other contingencies. The tank is made of polyethylene and weighs 90 lbs. It has one inlet, one outlet and one manway (lid). The outlet drain is a 2-inch polypropylene (PP) female National Pipe Thread (NPT) bulkhead fitting and the manway is a 16-inch threaded vented manway. New piping would also be needed for this reconfiguration. Estimates of component costs in dollars and person hours are in Table 3.

Table 3: Costs of adding 500 gallon tank

Tasks/Items	Cost ($)	Persons required (at least)	Time cost per person (hours)
Buy the 500-gallon IBC tank	350	1	2
Move top IBC to lower storage area	0	4	1
New plumbing between the two bottom IBCs: 1 ½’’ x ¾’’ adapter, 1 ½’’ PVC pipe, IBC tank drain adapter	30	3	1.5
Move replacement tank to the top storage area	0	4	2
Reconfigure replacement tank plumbing (¾’’ PVC pipe x 10’, ¾’’ PVC tee x2, tank drain adapter	25	2	1

4 CONCLUSION

The rainwater catchment and solar pumping system at CCAT is limited primarily in its storage capacity. Based on Humboldt County’s weather data this system can catch approximately 1,900 gallons during a day of rainfall. Currently, the storage capacity totals 628 gallons (2,271 L), with one 264 gallon tank (1,000 L) located on a hillside 26 feet above the pump, and three tanks next to the pump, on the southern side of CCAT’s toolshed (one 264 gallon tank and two 50 gallon pickle barrels). Based on the pump curve, system curve, and solar shading analysis, the pump can deliver between 11 and 35 gallons per day to the top tank.

It is clear that the total water available from the catchment is not being fully utilized, because the system cannot store rainwater when the tanks are already full. Only 31% of available water from the catchment is being used by CCAT annually. Based on our assessment and client feedback, we recommend CCAT first implement demand reduction measures as suggested in Demand Design Document (Cervantes et al., 2019). If CCAT is not able to implement these measures, we suggest storage addition by replacing the 264 gallon (1,000 L) tank on the top with a new 500 gallon (1,892 L) tank, and using the 264 gallon tank to replace the 50 gallon barrels at the bottom. The recommended position of the new tank is the same place as the current top tank. If CCAT decides to install a larger tank than the recommended one, it is possible that a new platform will be needed. A new base would cause significant planning and installation costs. In addition, Facility Management would have to be involved.

If CCAT chooses to replace the top tank with the 500 gallon (1,892 L) tank, it would cost CCAT $350 for the tank and approximately $55 additional cost for new piping. The head of the system would increase 35.5 inches or approximately 3 feet. The pump would still operate and deliver approximately the same amount of water as the existing system.

In conclusion, CCAT should revise the rainwater catchment and solar pump system based on their expected water demand. If they are able to conserve water to the point where they are only using less than 12 gallons per day (84 gallons per week), then they do not need to upgrade this system. If they are expecting to use more than 12 gallons per day at any point in the future, then additional storage should be added to the system. Based on the analysis completed during this project, we are proposing switching the top tank with a larger tank, then using the top tank to replace the pickle barrels that are currently located next to the tool shed. With a new top tank of 500 gallons for storage and demand at less than 12 gallons per day, CCAT would have water for gardening available all summer.

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APPENDIX

Appendix A: Environmental Resources

A-1 Rainwater catchment volume

The available rainwater was calculated based on the 30 year averages published by NOAA (2019). This volume was compared to 2018 precipitation to try to look for the error. The average precipitation values were used to assess both the current and the proposed system.

Table A-1: Rainwater catchment volume using 30 year average and 2018 precipitation

	Precipitation 30 year average (R1) (inches)	**Collection surface (A) (m2)**	**Efficiency of metal collection surface (e)**	**Needed conversion factor (k)**	**Volume using 30 year average (V1) (m3)**	**V1 conversion to gallons**	**Precipitation 2018 (R2) (inches)**	**Volume using 2018 precipitation (V2) (m3)**	**V2 conversion to gallons**
January	8.23	37.21	0.95	0.03	6.22	1644.01	9.19	8.25	2179.99
February	6.55	37.21	0.95	0.03	4.95	1308.42	2.97	2.67	704.52
March	6.28	37.21	0.95	0.03	4.75	1254.48	8.35	7.50	1980.73
April	4.36	37.21	0.95	0.03	3.30	870.95	5.34	4.80	1266.72
May	2.69	37.21	0.95	0.03	2.03	537.35	0.97	0.87	230.10
June	1.34	37.21	0.95	0.03	1.01	267.68	0.48	0.43	113.86
July	0.29	37.21	0.95	0.03	0.22	57.93	0.02	0.02	4.74
August	0.42	37.21	0.95	0.03	0.32	83.90	0.02	0.02	4.74
September	0.95	37.21	0.95	0.03	0.72	189.77	0.32	0.29	75.91
October	2.87	37.21	0.95	0.03	2.17	573.31	0.89	0.80	211.12
November	6.73	37.21	0.95	0.03	5.09	1344.37	5.68	5.10	1347.37
December	8.44	37.21	0.95	0.03	6.38	1685.96	5.40	4.85	1280.95

A-2 Solar shading analysis

Solar shading at the current panel location was calculated using Solar Pathfinder. The panel is located on the south side of the toolshed, right next to the bottom tanks. The panel is shaded by nearby trees for most of the day, but the hours vary by season, see Figure A-2. In general, there is no direct sunlight on the panel before 10 A.M. or after 5 P.M.

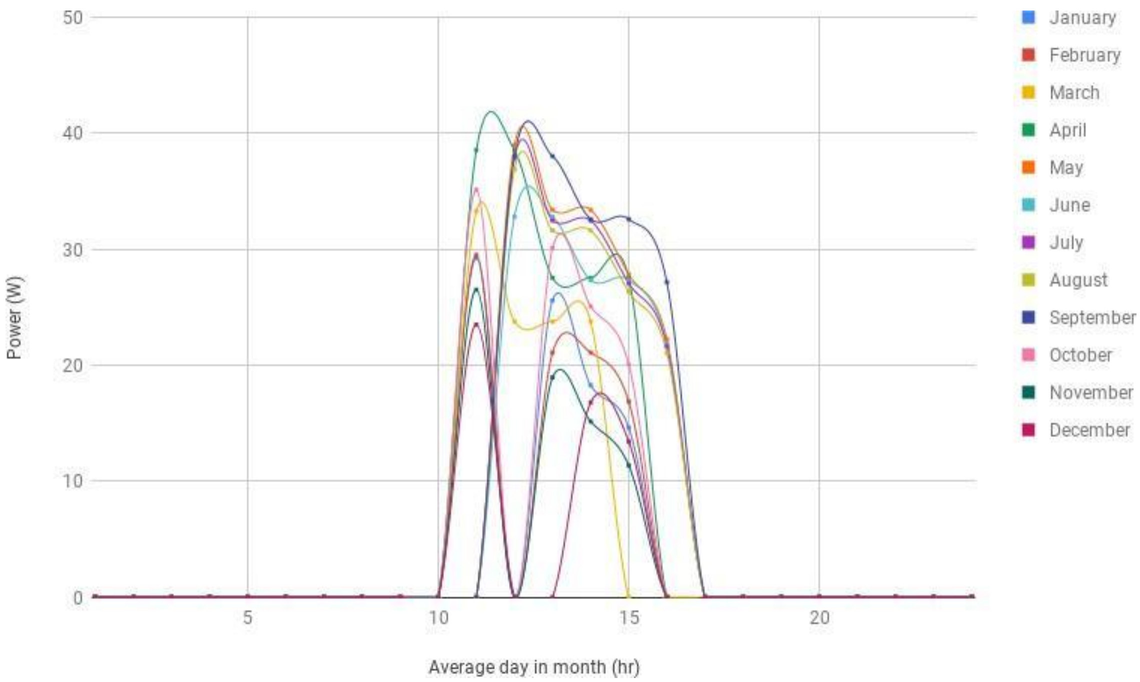

Figure A-2: Power delivered by solar panel based on solar shading analysis

Based on the shading of the panel, general insolation in Arcata, and the solar panel rated capacity, the power delivered by the panel was calculated (Table A-2). On days when it is not rainy, the pump can deliver about 20-40 Wh per hour between 11 A.M. and 4 P.M.

Table A-2: Average daily power delivered by solar panel for each month at CCAT solar water pump location

	January	February	March	April	May	June	July	August	September	October	November	December
1	0	0	0	0	0	0	0	0	0	0	0	0
2	0	0	0	0	0	0	0	0	0	0	0	0
3	0	0	0	0	0	0	0	0	0	0	0	0
4	0	0	0	0	0	0	0	0	0	0	0	0
5	0	0	0	0	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	0	0	0	0	0
7	0	0	0	0	0	0	0	0	0	0	0	0
8	0	0	0	0	0	0	0	0	0	0	0	0
9	0	0	0	0	0	0	0	0	0	0	0	0
10	0	0	0	0	0	0	0	0	0	0	0	0
11	29.25	29.52	33.27	38.54	0.00	0.00	0.00	0.00	0.00	35.11	26.51	23.50
12	0	0	23.77	38.54	38.95	32.80	37.88	36.88	38.02	0	0	0
13	25.59	21.08	23.77	27.53	33.38	32.80	32.47	31.61	38.02	30.10	18.94	0.00
14	18.28	21.08	23.77	27.53	33.38	27.33	32.47	31.61	32.59	25.08	15.15	16.79
15	14.62	16.87	0.00	27.53	27.82	27.33	27.05	26.34	32.59	20.07	11.36	13.43
16	0	0	0	0	22.26	21.86	21.64	21.07	27.16	0	0	0
17	0	0	0	0	0	0	0	0	0	0	0	0
18	0	0	0	0	0	0	0	0	0	0	0	0
19	0	0	0	0	0	0	0	0	0	0	0	0
20	0	0	0	0	0	0	0	0	0	0	0	0
21	0	0	0	0	0	0	0	0	0	0	0	0
22	0	0	0	0	0	0	0	0	0	0	0	0
23	0	0	0	0	0	0	0	0	0	0	0	0
24	0	0	0	0	0	0	0	0	0	0	0	0
Monthly average (W)	87.74	88.55	104.57	159.68	155.79	142.11	151.50	147.50	168.37	110.36	71.96	53.73

Appendix B: System measurement

The catchment area, conveyance, and associated tanks measurement of the current system were taken. Using Grafman's formula (2017), the catchment area was calculated to be 37.21 m^2. The storage volume was converted into gallons within the document.

Table B-1. Catchment area (roof) measurement

Description	Measurement	Unit
Roof length	7.41	meter
Roof width	5.2	meter
Tilt	15	degree

Table B-2. Conveyance (gutter) measurement

Description	Measurement	Unit
Gutter Height	4.5	cm
Gutter Width (Top)	5.5	cm
Gutter Width (Bottom)	3.5	cm
Gutter Length	7.41	m
Gutter Tilt (parallel to length)	1	degree

Table B-3. Storage (tank) measurement

Description	Measurement	Units
Volume	1	m3
Elevation difference relative to pump tank	19	in
Volume for each of the two extra storage barrels	190	L
Elevation difference between tanks	26.529	ft
To lowest distribution point	14.25	ft
Between distribution point and tank	19.2	m
Elevation between top tank and highest distribution point	4.54	ft

Appendix C: Physical System Adjustments

A number of changes have been made to the system to improve general system operations. During the process of investigating the physical system, a number of issues came to light. First, there was an air bubble in the pump intake hose, probably due to the leaky connection between the pump and pipe. This affected the pump performance. The pump was lowered about 1 foot so that the water in the tanks would be exerting pressure through the intake pipe for lower water levels as well. In addition, the team changed the system so that the intake pipe was lower than the pump at all points. Finally, the connection between the intake pipe and the pump was tightened with a better fitting hose clamp. These changes will prevent air from getting caught in an arch in the pipe.

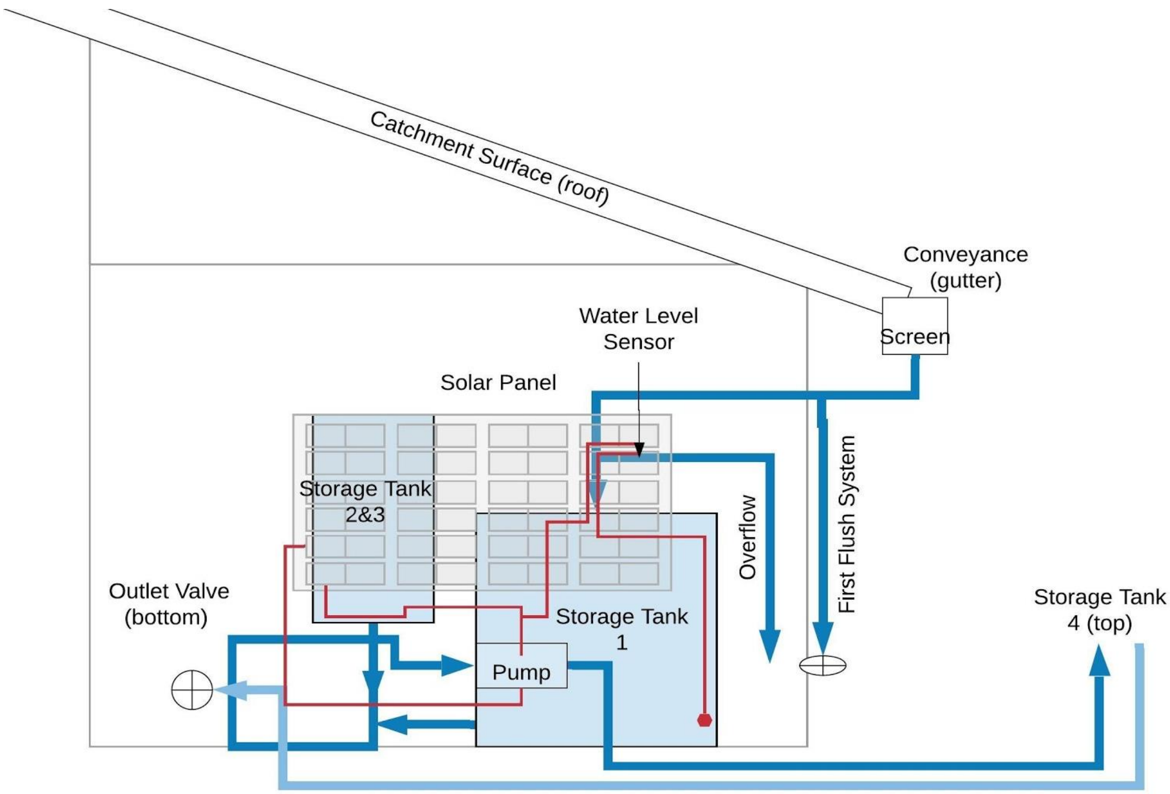

Figure C-1: Elevation of the system after operational adjustments. This diagram is close to scale

Figure C-2: The team covering the panel with t-shirts to prevent the pump from operating during adjustments

(a) (b)

Figure C-3: (a)Before system adjustment and (b) After system adjustment. Photos were taken from the eastern side of the system. The major adjustments comprised of changing pipe configuration and lowering the position of the pump were highlighted in yellow rectangles

(a)

(b)

Figure C-4: (a) Before system adjustment and (b) After system adjustment. Photos were taken from the southern side of the system. The pump as seen in (b) is closer to the ground after adjustment

Appendix D: Pump performance

Pump Capacity

The monthly pumping capacity of the system was calculated based off the power delivered to the pump. The amount of water pumped each day is calculated as the daily peak sun hours times the pumping capacity (Table D-1). Peak-sun-hours is converted from the average power delivered per day by the panel. Monthly gallons pumped is based on the average daily volume pumped and the number of days in the month. Monthly pumping capacity is one of the key inputs in the system simulation. Overall, pumping capacity is the lowest in the winter months, because there is less sun during these months since it rains so much.

Table D-1: Monthly average gallons per day pumped to the top tank

Month	**Wh/m2/day**	**Average day peak sun hour (kWh/m2/day)**	**Daily pump capacity at 3.5 gpm (gal)**	**Days in month**	**Monthly pumping capacity at 3.5 gpm (gallons)**
1	87.74	0.09	18.43	31	571.18
2	88.55	0.09	18.60	28	520.69
3	104.57	0.1	21.96	31	680.74
4	159.68	0.16	33.53	30	1006.01
5	155.79	0.16	32.72	31	1014.19
6	142.11	0.14	29.84	30	895.31
7	151.5	0.15	31.82	31	986.29
8	147.5	0.15	30.98	31	960.25
9	168.37	0.17	35.36	30	1060.73
10	110.36	0.11	23.18	31	718.43
11	71.96	0.07	15.11	30	453.36
12	53.73	0.05	11.28	31	349.75

The pump and the panel were mismatched. It was, therefore, important to look at how the low voltage provided by the panel affects the pump. The manufacturer provided some data regarding pump performance and efficiency based on its rated voltage (Table D-2).

Table D-2. Pump performance manufacture data with calculated hydraulic pressure, power input and efficiency

Pump performance data							
Discharge		**Pump head**		**Voltage (V)**	**Hydraulic Pressure (W)**	**Power Input (W)**	**Efficiency (%)**
PSI	**Feet H2O**	**Flow (gpm)**	**Current (AMPS)**				
70	161.7	3.1	8.5	24	94	204	46.26%
60	138.6	3.25	7.6	24	85	182	46.49%
50	115.5	3.5	7	24	76	168	45.30%
40	92.4	3.75	6.1	24	65	146	44.56%
30	69.3	4.15	5.1	24	54	122	44.24%
20	46.2	4.45	4.3	24	39	103	37.51%
10	23.1	4.8	3.2	24	21	77	27.18%
Open	0	5.15	3	24	0	72	0

Maximum Pump Head was calculated based on the manufacturer's specs and the Total Dynamic Head was calculated based on the current system installed at CCAT. At all flow rates lower than 4.7 gpm, the head provided by the pump is greater than the system head, so the pump is sufficient for the system at these flow rates (Table D-3). The power required to provide that head was also calculated, but it is still not certain how the panel and pump interact.

Table D-3. Pump performance based on flow rate, interpolated maximum head that pump can push, and interpolated power required for pump to work

Flow rate (gpm)	**Total Dynamic Head (ft)**	**Max Pump Head (ft H20)**	**Power required (W) (24V nominal voltage)**	**Max Pump Head > TDH**
3	28.96	158.4	89.73	TRUE
3.5	29.76	120.23	90.42	TRUE
4	30.67	82.06	91.2	TRUE
4.5	31.68	43.89	92.07	TRUE
4.6	31.89	36.26	92.25	TRUE
4.7	32.11	28.63	92.44	FALSE
4.8	32.33	20.99	92.63	FALSE
4.9	32.56	13.36	92.83	FALSE
5	32.79	5.73	93.02	FALSE

Appendix E: City of Arcata water rate

The cost of water for CCAT was calculated based on the City of Arcata water rate. These numbers were used for comparison purposes during the economic analysis of the proposed system (Table E-1).

Table E-1: Cost of water provided by the City of Arcata according to usage volume

Water Usage	Cost ($)
Base Rate Inside City (5/8" & 3/4" meters)	13.43
Consumption 0-3 hundred cubic ft/per H.C. Inside	3.42
Consumption 3-4 hundred cubic ft/per H.C. Inside	3.69
Consumption 5 hundred cubic + ft/per H.C. Inside	7.23

Appendix F: System simulation equations and R Script

Total annual usable water, Q_{annual}, is calculated by summing the watering demand that is met and the amount of water stored in the system by the end of the year. The formula used for calculating Q_{annual} is

$Q_{annual} = D_{annual} - D_{unmet,annual} + S_{state,top,month=12} + S_{state,bottom,month=12}$

Where D_{annual} is the total annual watering demand; $D_{unmet,annual}$ is the total annual watering demand that is not met; $S_{state,top,m=12}$ and $S_{state,bottom,m=12}$ are the water storage state by the end of December. D_{annual} is calculated by

$$D_{annual} = \sum_{month=1}^{12} D_{month}$$

Where D_{month} is the watering demand of the given month and is calculated by

$$D_{month} = d_{watering,month} \times D_{watering\ event}$$

Where $d_{watering,month}$ is the days with the watering need of the given month and $D_{watering\ event}$ is the watering demand per each watering day. $D_{watering\ event}$ is variable across a range of possible quantity, while $d_{watering,month}$ is calculated by multiplying the days in the given month with the possibility of rain for the given month. The assumption that CCAT waters the garden every day when it is not raining in the non-rainy season (i.e., April to October) and every other day when it's not raining in the rainy season (i.e., November to March) is incorporated by dividing the watering days of the given month by 2. The equation is

$$d_{watering,month} = \begin{cases} d_{month} \times p(rain) \div 2, & during\ rainy\ season \\ d_{month} \times p(rain), & otherwise \end{cases}$$

Unmet annual water demand, $D_{unmet,annually}$, is calculated by

$$D_{unmet,annually} = \sum_{month=1}^{12} S_{state,top,month-1} + P_{actual,month} - D_{month}$$

Where $P_{actual,month}$ is the actual amount of water pumped in gallons for the given month and $S_{state,upper,month-1}$ is the top storage state from the previous month or 0 if the month is January.

$P_{actual,month}$ is calculated by

$$P_{actual,month} = \begin{cases} S_{potential,top,month} + D_{month} & P_{max,month} \geq S_{potential,top,month} + D_{month} \\ P_{max,month} & P_{max} \leq S_{potential,top,month} + D_{month} \end{cases}$$

Where $P_{max,month}$ is the maximum amount of rain water the pump is able to pump in the given month with the given precipitation and is calculated by

$$P_{max,month} = \begin{cases} S_{state,bottom,month-1} + R, & P_{capacity,month} \geq S_{state,bottom,month-1} + R \\ P_{capacity,month} & P_{capacity,month} \leq S_{state,bottom,month-1} + R \end{cases}$$

Where $P_{capacity,month}$ is the maximum amount of the water the pump is able to pump in the given month and R is the amount of the rain caught with the current catchment area. $P_{capacity,month}$ is calculated by

$$P_{capacity,month} = q \times \frac{60min}{hour} \times PSH_{month}$$

Where q is the maximum flowrate of the pump for the CCAT system; PSH_{month} is the total peak solar hours of the given month.

```
R-script for the system evaluation

# System Component Variables ---------------------------------------
-------

# Unit Conversion #
lit.to.gal <- 0.264172 # liter to gallon
cubft.to.gal <- 7.48052 # cubic feet to gallon

# Pump #
q <- 3.5
# flow rate in gpm, current system is 3.5 gpm with the panel. Pump cap
able of pumping up to 4.6 gpm with the system if 24V power provided.

# Storage tanks #
storage.cap.up <- 1000*lit.to.gal
# 1 IBC
storage.cap.bottom <- (1000*lit.to.gal)+ 190*2*lit.to.gal
# 1 IBC plus two additional 190 liter barrels

# Environmental #
precip <- c(8.23,6.55,6.28,4.36,2.69,1.34,0.29,0.42,0.95,2.87,6.73,8.4
4)
# monthly average of precipitation in inches, using 1982 - 2010 averag
e right now
precip.foot <- precip/12
# precip in foot
rain.poss <- c(0.42,0.44,0.38,0.28,0.17,0.075,0.02,0.025,0.075,0.20,0.
38,0.445)
# daily rain possiblity from Jan to Dec

# Building #
catchment.area <- 37.213
# catchment are in meter square
catchment.area.sqft <- catchment.area*10.7639
# catchment in sqft

# Panel #
panel.output <- data.frame(month = c(1:12),
                           days.in.month = c(31,28,31,30,31,30,31,31,3
0,31,30,31),
                           max.power.wh = c(365.579,421.676,475.312,
                                            550.635,556.391,546.59,
                                            541.087,526.797,543.126,
                                            501.627,378.748,335.784),
                           power.factor.shading = c(0.24,0.21,0.22,
```

```
                                                        0.29,0.35,0.26,
                                                        0.28,0.35,0.31,
                                                        0.22,0.19,0.16)
)
panel.output$shaded.power.wh <- panel.output$max.power.wh * panel.outp
ut$power.factor.shading
# actual power output with shading
moving.panel.lever <- 1
# a factor, 1.2 meaning 20% more solar resources than now, 1.0 current
condition

# Demand #
water.use.each.time <- 35
# how much water in gallon is used per watering day


# Function - DON'T CHANGE THIS ----------------------------------------
-----

system.monthly <- data.frame( month = c(1:12),
                              days.in.month = c(31,28,31,30,31,30,31,3
1,30,31,30,31),
                              peak.solar.hour = panel.output$shaded.po
wer.wh * panel.output$days.in.month * moving.panel.lever/1000,
                              precip = precip,
                              total.caught = precip.foot*catchment.are
a.sqft*cubft.to.gal,
                              rain.poss = rain.poss
)

solar.pump <- function (peak.solar.hour,total.caught,rain.poss,month,d
ays.in.month,...){

  days.watering <- days.in.month - rain.poss*days.in.month
  demand <- days.watering * water.use.each.time

  if(month %in% c(1,2,3,11,12)){
    demand <- demand /2
    # winter months, only water every other non-raining day
  }



  storage.potential.up <- storage.cap.up - storage.state.up
  storage.potential.bottom <- storage.cap.bottom - storage.state.botto
m
```

```
  # calculate the available storage potential left in the beginning of
the month

  pump.cap <- q*60*peak.solar.hour
  # pumping capacity (gallon/month) with given pump and peak solar hou
rs

  if (pump.cap >= storage.state.bottom + total.caught){
    pump.max <- storage.state.bottom + total.caught
    # maximum amount of water that could be pumped is the total bottom
storage plus caught rain
  } else (pump.max <- pump.cap)
  # maximum amount of water that could be pumped is the pumping capaci
ty if it does not exceed total bottom storage plus caught rain

  if(pump.max >= storage.potential.up+demand){
    # if pump can pump more than top storage potential plus demand
    pumped <- storage.potential.up + demand
    # the actual amount pumped is the top storage potentail
  } else if (pump.max < storage.potential.up + demand){
    pumped <- pump.max
  }
  # else the actual amount pumped is the maximum amount of water the c
ould be pumped

  storage.state.bottom <<- storage.state.bottom + total.caught - pumpe
d
  # the storage level at the bottom tanks

  if(storage.state.bottom > storage.cap.bottom) {
    storage.state.bottom <<- storage.cap.bottom
  }
  # if the storage level at the bottom is beyond the storage capacity,
the level is set to the capacity [overflow]
  storage.state.up <<- storage.state.up + pumped- demand
  # the storage level at the top tank is the previous level plus actua
l amount water pumped minus water use demand
  if(storage.state.up > storage.cap.up){
    storage.state.up <<- storage.cap.up
  }
  # if the storage level at the top is beyond the storage capacity, th
e level is set to the capacity [float valve]
  # this should never happen because the pumped.max limit the amount o
f water to be less or equal to the top tank storage potential

  unpumped.water <- pump.max - pumped
```

```
  # how much water could have been pump, but did no get pumped due to
the top tank storage limitation

  if(storage.state.up <0) {
    unmet.demand.up <- storage.state.up
    storage.state.up <<-0
  } else {unmet.demand.up <-0}

  return(list(round(storage.state.bottom),
              round(storage.state.up),
              round(unpumped.water),
              round(unmet.demand.up),
              round(demand),
              round(pumped,digits = 0),
              round(pump.max),
              round(pump.cap),
              round(total.caught))
  )
}

# get result ---------------------------------------------------------
-----

storage.state.up <- 0
storage.state.bottom <- 0
# reset tank storage

result<-
  mapply(solar.pump,
         month = system.monthly$month,
         peak.solar.hour = system.monthly$peak.solar.hour,
         total.caught = system.monthly$total.caught,
         rain.poss = system.monthly$rain.poss,
         days.in.month = system.monthly$days.in.month)


design.name <- data.frame(month = c(1:12),
                          storage.state.lower = unlist(result[1,]),
                          unpumped.water = unlist(result[3,]),
                          storage.state.upper = unlist(result[2,]),
                          unmet.demand.upper = unlist(result[4,]),
                          demand = unlist(result[5,]),
                          pumped = unlist(result[6,]),
                          pump.max = unlist(result[7,]),
                          pump.cap = unlist(result[8,]),
                          rain.caught = unlist(result[9,])
```

```
)

# Total water used
sum(design.name$demand) + sum(design.name$unmet.demand.upper)

# Total unmet demand
sum(design.name$unmet.demand.upper)

# Total usable water
sum(design.name$demand) +
  sum(design.name$unmet.demand.upper) +
  design.name$storage.state.lower[which(design.name$month==12)] +
  design.name$storage.state.upper[which(design.name$month==12)]
```

Appendix G: Assessment of Storage Solutions

A number of potential storage sizes and configurations were assessed with the system simulation. Table G-1 summarizes the results of the simulation. Figure G-2 shows the approximate scale of a 500 gallon tank located on the hillside platform where the top tank is currently located.

Table G-1: First re-design assessment with replacement tank volume at 500, 1000 and 3000 gallons

Design, Replacing Tank	**Material Cost ($)**	**Water Required per Watering Day (Gallons)**	**Annual Water Stored and Used (Gallons)**	**Annual Unmet Watering Demand (Gallons)**	**Unmet Watering Demand (Days)**	**Redesign Improvement (Days)**	**$/Extra Day of Watering Per Year**
Original	NA	20	4703	945	47	NA	NA
500 Gallon Tank Top	349.99	20	5174	709	35	12	29.66
500 Gallon Tank Bottom	349.99	20	5108	809	40	7	51.47
1000 Gallon Tank Top	559.99	20	6069	208	10	37	15.20
1000 Gallon Tank Bottom	559.99	20	6608	309	15	32	17.61
3000 Gallon Tank Top	1099.99	20	7631	0	0	47	23.28
3000 Gallon Tank Bottom	1099.99	20	9527	0	0	47	23.28
Original	NA	35	6068	3066	88	NA	NA
500 Gallon Tank Top	349.99	35	6446	2830	81	7	51.91
500 Gallon Tank Bottom	349.99	35	6474	2930	84	4	90.07
1000 Gallon Tank Top	559.99	35	6946	2330	67	21	26.63
1000 Gallon Tank Bottom	559.99	35	7974	2430	69	18	30.82
3000 Gallon Tank Top	1099.99	35	7631	1643	47	41	27.06
3000 Gallon Tank Bottom	1099.99	35	12347	430	12	75	14.61
Original	NA	50	6931	5565	111	NA	NA
500 Gallon Tank Top	349.99	50	7166	5329	107	5	74.15
500 Gallon Tank Bottom	349.99	50	7337	5430	109	3	129.63
1000 Gallon Tank Top	559.99	50	7632	4863	97	14	39.89
1000 Gallon Tank Bottom	559.99	50	8836	4930	99	13	44.09
3000 Gallon Tank Top	1099.99	50	7631	4863	97	14	78.35
3000 Gallon Tank Bottom	1099.99	50	12932	2929	59	53	20.86

Figure G-2: 500 gallon tank's height close to scale