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Design of a Greywater-Fed Hydroponics System

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Date: June 12, 2020

I HEREBY RECOMMEND THAT THE THESIS PREPARED
UNDER MY SUPERVISION BY

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ENTITLED

DESIGN OF A GREYWATER-FED HYDROPONICS SYSTEM

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Design of a Greywater-Fed Hydroponics System

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SENIOR THESIS

Submitted to
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and
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Abstract

To combat issues of local water insecurity, a hydroponics system was designed in partnership with LEAP 5 High School in Jane Furse, South Africa. Climate change, increasing human population, and continued environmental degradation all threaten access to clean drinking water. Approximately seventy percent of all freshwater is used for agriculture globally, thus threatening food security especially in developing countries where access to water is potentially volatile. The hydroponics garden system utilizes sustainable materials, a self-monitoring temperature controls system, and greywater input, to act as an educational tool for students and significantly reduce freshwater use compared to traditional, in-ground agriculture. An education plan accompanies the implementation of the system to provide an avenue for community engagement and encourage the adoption of alternative, water-saving farming methods. The hydroponics system was developed by observing the strengths of existing hydroponics applications in commercial and educational institutions. The successes of established systems guided rapid prototyping of grow beds, shading structure, and greywater filter. The fully built system reflected all major subsystems and was used to test the effectiveness of a hydroponics garden compared to a traditional soil garden, and the growth of lettuce plants confirmed the benefits of hydroponics. The hydroponics method of farming was found to produce triple the lettuce per the same volume of water when compared with soil faring. Additionally, 30% less energy was required to operate the hydroponics system and the cost of materials was decreased 50% compared to past student projects and existing systems commercially available systems. The greywater-fed hydroponics system proves that an inexpensive, durable design displays significant advantages over standard, soil farming. Educational assembly manuals and tailored education modules designed for the LEAP 5 High School will aid in the adoption of a potentially disruptive farming method to an agriculturally dependent region.

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Nomenclature

AC	Alternating current
CAD	Computer aided design
DC	Direct current
DO	Dissolved oxygen
DWC	Deep Water Culture
EC	Electrical conductivity
FEA	Finite Element Analysis
gph	Gallons per hour
gpm	Gallons per minute
LEAP	Langa Education Assistance Program
NTF	Nutrient Film Techniques
NPK	Nitrogen, phosphorus, and potassium
PPM	Parts per million
ROI	Return on investment
STEM	Science, Technology, Engineering, and Math

1. Introduction

The effects of climate change and environmental degradation are threatening the world's access to its most precious natural resource, freshwater. With a growing human population, it is essential to grow more food with less water.

Our project is made in partnership with Langa Education Assistance Program 5 (LEAP 5) high school, a STEM school that caters to economically disadvantaged students located in the Limpopo Province, South Africa. The implementation of a more water efficient farming method as an educational tool for students was the main project objective. In collaboration with students and faculty, a greywater-fed hydroponics garden was designed for the LEAP 5 campus.

Compared to traditional agriculture methods, our system puts more emphasis on sustainability and water conservation by using sustainable materials and recycling greywater produced by the LEAP 5 school kitchen. In doing so, the system becomes a benefit not just for the school, but for the entire Jane Furse community. The system was built to reduce the environmental impact of growing plants which are associated with traditional farming methods. To further increase the water efficiency in the system, a kitchen sink greywater filter will supply the hydroponics garden instead of using freshwater. A successful hydroponics system can provide both water and food security to agricultural communities in South Africa.

1.1 Water Scarcity

Globally, 70% of all freshwater is used for agriculture [1]. Estimates from the World Bank predict that, by 2050, "feeding a planet of 9 billion people will require an estimated 50 percent increase in agricultural production and 15 percent increase in water withdrawals" [1].

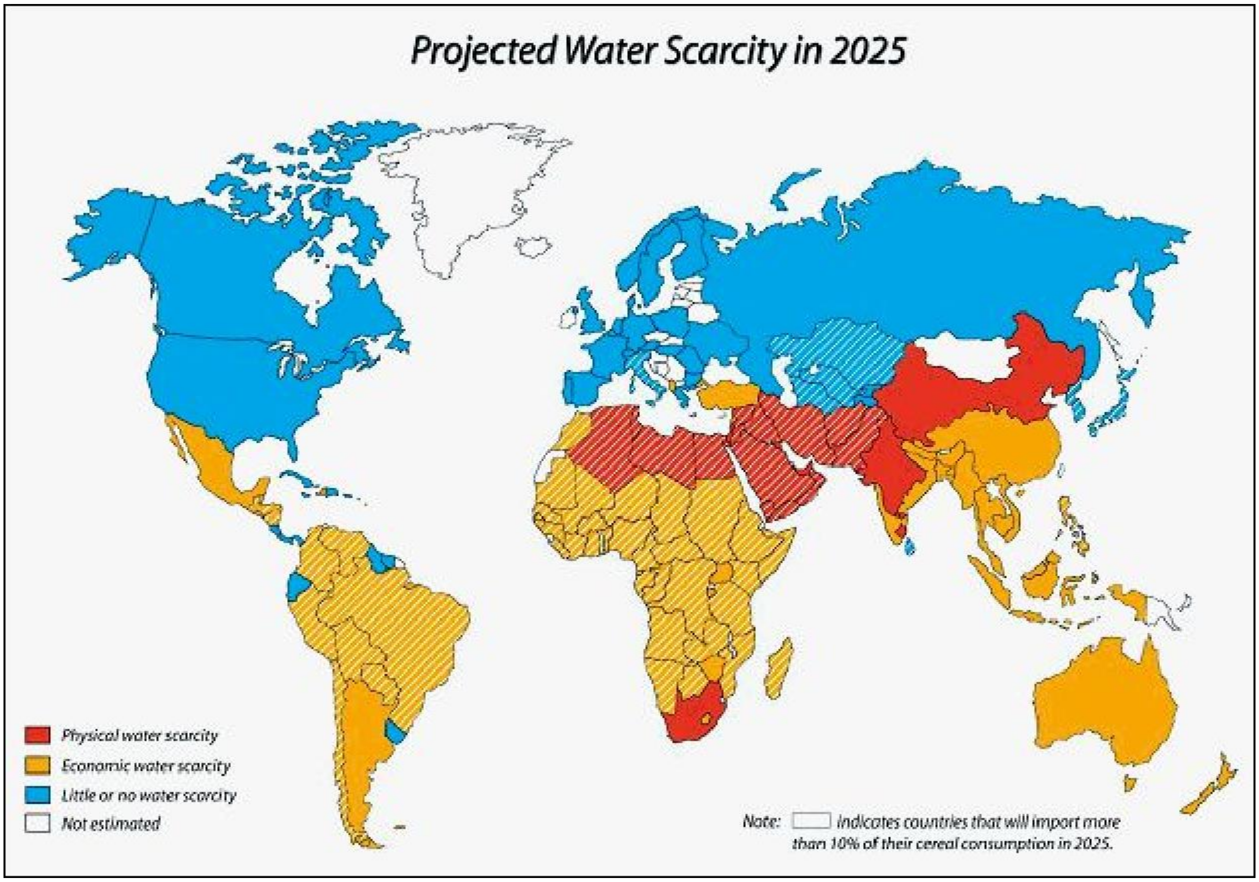

Figure 1: Map of the projected water scarcity globally by 2025 [3].

The overuse of freshwater in agriculture can create food and water insecurity, especially in developing countries. In sub-saharan Africa, 80.7% of all available fresh water is utilized for agriculture [1]. This is also the only world region unable to meet the minimum standards for sustainable safe drinking water, according to the United Nations' Millennium Development Goals [2].

South Africa is the wealthiest nation in sub-saharan Africa and has granted citizens the right to clean water access, yet over one million households suffer from water insecurity [4, 5]. The increasing frequency and severity of droughts, due to climate change, coupled with the diversion of freshwater to urban areas has significantly reduced the amount of available water to rural, agricultural communities [6, 7]. Water scarcity in the Limpopo Province, where our project is located, has forced communities to utilize natural sources of water that are often contaminated or polluted [7]. *Figure 2* shows the map of the country of South Africa.

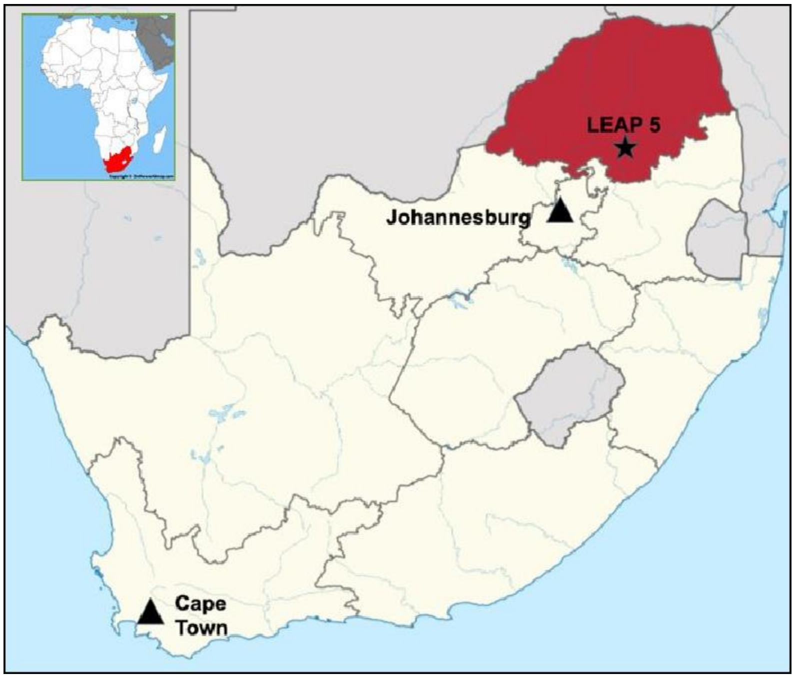

Figure 2: Map of South Africa with the Limpopo Province highlighted in red and LEAP 5 High School represented with a star [8].

Implementation of this more efficient farming method addresses water scarcity in South Africa, while still yielding adequate crops for consumption and profit. Hydroponics systems, or soilless farming, use more than 75% less water per kilogram of produce compared to traditional in-ground agriculture and increase the amount of produce grown per square meter described in Section 5.1 [7]. Fifty percent faster harvest times, freedom from pesticide use, the adaptability of the system to space constraints, and the opportunity to grow year round also make hydroponic systems a viable alternative for traditional in-ground farming.

1.2 LEAP 5 School of Science and Maths

An education plan was developed to accompany the implementation of the system that would provide an avenue for community engagement and encourage adoption of alternative, water saving farming methods in the wider community. With help from the Frugal Innovation Hub on campus, our team was partnered with LEAP 5 Science and Math Schools in South Africa. LEAP is a collection of math and science focused schools that caters to economically disadvantaged students across the country.

The fifth LEAP school reached out to the Frugal Innovation Hub in hopes of recruiting a team like us for their project. A couple of the project team members were interested in designing an aquaponics system and heard about this opportunity with the Frugal Innovation Hub in the Civil Engineering Senior Design Class in Spring 2019. The first contact our team made with LEAP 5 shortly followed. Raphael, the school's principal, and a handful of eager students came to us with an idea for an alternative solution to traditional farming. The students led the discussion with their eagerness to learn and grow peppers and carrots. Weekly progress meetings were organized for three months and featured constant messaging and communication. This was the motivating factor throughout our whole project, the high school students enthusiasm for us to come and teach them. Their three main priorities for a successful project were:

1. Agricultural & Water Conservation Education - this included hands on education and curriculum-based recommendations in the field of Engineering Design, Biology, and Business.
2. Fresh Produce Yield and Food Security - used for both the students and faculty at LEAP 5 and in the surrounding communities' food banks.
3. Replicable Across LEAP School System - LEAP 5 wished to be a catalyst for agricultural education across the South Africa school system

Our role in the project would be to create a physical learning module which both informs about water conservative farming methods, promotes food security, and shows that engineering can be applicable to these students' lives.

1.3 Project Background

Alongside the teachers and students from LEAP 5 High School, a greywater-fed hydroponics garden was designed and tested in Santa Clara with the intention of implementing the complete system in South Africa during Spring 2020. To address alternative agriculture, hydroponics is a method that supports plants' roots in nutrient rich water instead of traditional soil farming. To further address freshwater insecurity, the system would employ LEAP's kitchen sink wastewater (greywater) to supply the garden when water levels drop due to evaporation and evapotranspiration.

1.3.1 Educational Opportunities in Hydroponics

Implementing alternative farming systems requires community engagement and ownership to ensure the success and longevity of the technology. One of the central focuses of this project was STEM education and student involvement. Thus, 15 hours of lectures, activities, and experiments were designed to connect the fields of Biology, Biochemistry, Environmental Science, and Engineering to the on-site construction of the hydroponics system. The educational materials were developed to be implemented over a 5 day period (3 hours instruction/day) with 20 student ambassadors at LEAP 5.

The education piece had three main learning objectives: 1) to understand how climate change will impact both humans and plant survival, 2) to understand how the hydroponics system functions and be able to maintain it, 3) to empower students to make a positive impact in their own local communities. Lessons on plant biology and photosynthesis, biochemistry, ecosystem ecology, and climate science connected to different aspects of the hydroponics system. Plant biology, in particular, was a central focus of the education materials shown in *Figure 3*.

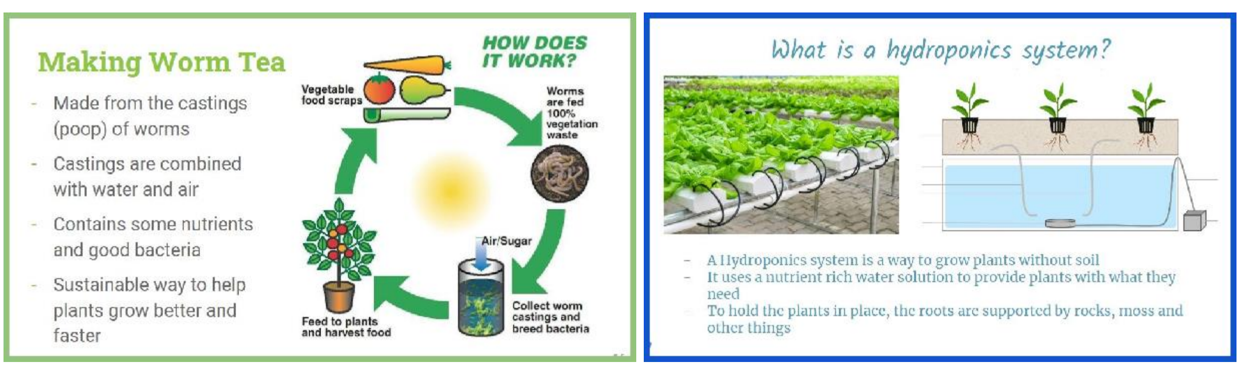

Figure 3: Sample lecture slides from the hydroponics curriculum.

Each lesson plan included two lab experiments or hands-on activities to practice newly learned skills and daily interaction with the hydroponics system to achieve the first two learning objectives. To address the third learning objective, the lesson plans included examples of student-led movements for climate change, such as speeches by Greta Thunberg, to inspire and empower students to address climate change in their school and larger local community. The educational materials allow for the learning and application of new science and engineering concepts, while providing an opportunity for students to improve local agricultural systems.

1.3.2 Approaches to Constructing a Hydroponics System

When starting a hydroponics farm, a specific type or multiple types of hydroponics systems must be selected. The most prominent types of systems are: Nutrient film techniques (NFT), Deep water culture (DWC), Drip irrigation systems, ebb & flow, and wicking. There are other techniques, but this document will not include a discussion of them because they were deemed unsuitable for our desired product. *Table 1* lists styles of hydroponic farming configurations and their major aspects.

Table 1: Summaries of unique characteristics relative to each considered type of grow bed. Blue highlighted rows were the systems chosen for the final design.

Type of Grow Bed	**Significant Characteristics**
Raft Bed (Deep Water Culture)	• Plants housed in holes on styrofoam rafts which float in a large reservoir of nutrient-rich water. • Requires sturdy construction of frame due to water weight.
Nutrient-Film Technique	• Plants housed in holes bored into long rails or large diameter pipes. • Single stream of nutrient-rich water feeds all plants in series.
Drip Line Irrigation	• Nutrient-rich water is delivered periodically to plants in a media through a pressurized flexible rubber drip line. • Each plant requires at least one thin rubber line resulting in large networks if the garden is large.
Ebb & Flow	• Plants rest in a media bed and water is delivered to flood the entire volume of the grow bed -- upon reaching a designated height, water is removed by a bell siphon. The process repeats. • If the system is large the fluctuation of each fill-drain cycle is a significant volume of water
Wicking Bed	• Nutrient rich water is delivered by a buried, perforated pipe. • A shallow reservoir is maintained below the topsoil and the water is then “wicked” towards the plants’ roots via capillary action.

Nutrient film techniques utilize a simple design consisting of a main reservoir and an angled grow tray which plants are fitted into. Water rich in minerals and nutrients enters from the uphill end of the grow tray as it is pumped from the reservoir. The water then flows down the tray, passing by each individual plant and soaking the root system before departing through the downhill tray side and returning to the reservoir [7]. Advantages to NFT are that it uses a continuous flow so no pump timing equipment is necessary. There are few moving parts to an NFT system and they can be customized and scaled with ease. The depth of water that flows through the grow tray is very shallow to compensate for the continual flow. The plants are able to wick water from the stream and draw as much as required. Different plants have different water needs so this presents a viable system if a diverse garden is desired. The NFT is not without disadvantages though. These systems are extremely sensitive to power outages and if a loss of flow due to no power or a clog in the input line occurs, the plants will wilt and die rapidly. Another negative for this system is the depletion of nutrients as the stream approaches the return to the reservoir. Plants all need nutrients and will draw from the finite supply as soon as they encounter the water. The plants growing at the downhill end of the grow tray do not encounter a stream of water as rich in nutrients and suffer slightly.

Deep water culture systems are extremely simple and are very relevant in the world of commercial farming. DWC is most effective for quick-growing, leafy greens which have significant water needs. The setup for a DWC is extremely simple and requires almost no moving parts and most importantly no water pump to circulate the water[9]. The DWC method only requires that the water be aerated so that enough oxygen is present for the roots to grow. Aeration is obtained by an air pump and airstone in most cases, both of which can be purchased at any aquarium or garden store with hydroponics products. The air pump draws air from the environment and transports it through flexible piping to an air stone which is a configuration of orifices that open up to the water tank containing the plants. *Figure 4* shows the DWC setup below.

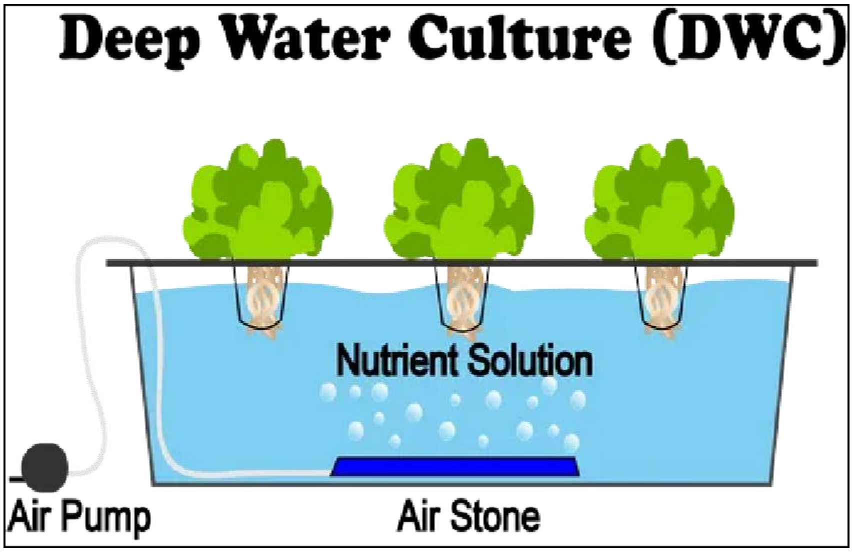

Figure 4: Schematic depicting basic DWC configuration [9].

An advantage of DWC growing operations is the maneuverability of the plants even once root systems have matured. The plants float on a styrofoam board (raft) which sits unattached to the water tank. Crops are attached to their own individual substrates which are inserted into holes bored in the rafts. Plants are easily moved by simply pulling the substrate with the root system attached. For the low maintenance, low investment market our group is targeting the DWC method is extremely desirable. These systems are expandable and are only limited by the size of the water tank which the rafts float in. The DWC systems are suitable for most plants except for long life plants that require a strong, supportive root base. Plants like squash, zucchini, and tomatoes are therefore not ideal for a DWC system. The largest and most profitable commercial hydroponics companies utilize the DWC systems however because of their low entrance costs and their enormous scalability [9].

The drip systems and the ebb & flow systems are very similar, and are most effective in smaller applications. They both require the plants to be fixed to individual pots filled with growing medium. The pots rest in a larger growing tray which water is able to circulate through. The difference is that drip systems direct the input of water directly to the individual plant pots by means of drip lines. The ebb & flow systems do not have the same type of individual watering, but rather fill the large grow tray with water periodically. Once the water level reaches a height threshold designated by an output valve, the entire system drains back into the reservoir.

The drip systems require a significantly greater amount of hardware because of the individual drip lines and the accessory piping necessary to transport each stream of water. The narrow drip lines are also prone to clogs if any solid material is encountered, or algae growth occurs. The conditions our hydroponics system will exist in is outdoors so solid contaminants and algal growth may present issues for this type of system. A schematic of these two systems is shown below in *Figure 5*.

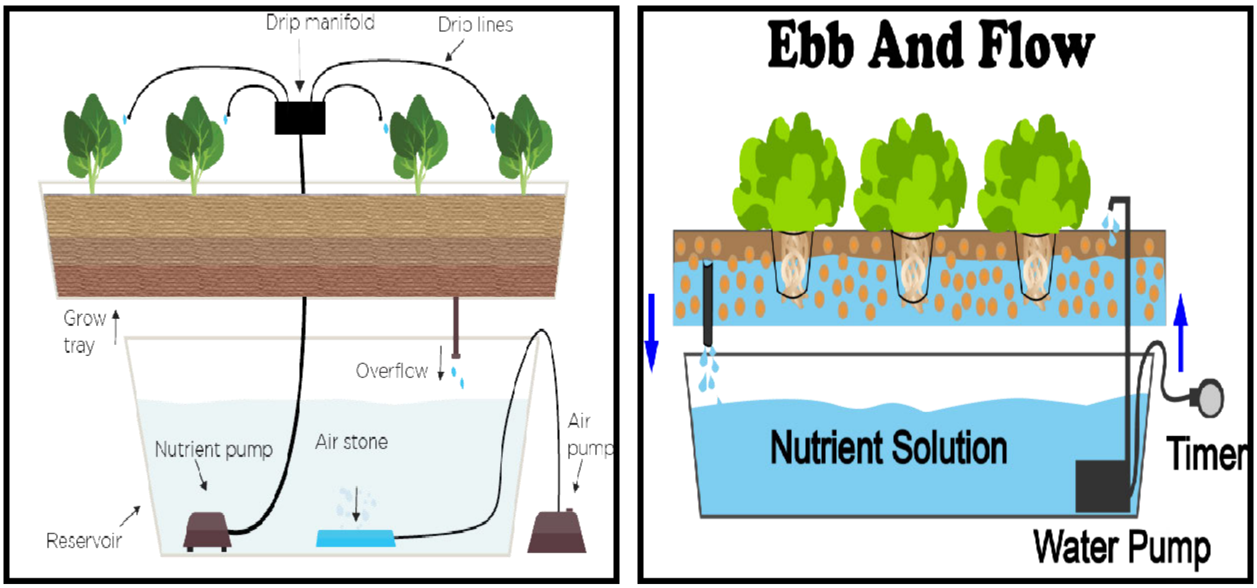

Figure 5: Side by side comparison of the similar drip and ebb & flow systems. The significant difference between the two is the presence of drip lines and drip manifold on the left image [10].

Wicking beds are made possible by a method of water delivery in which a shallow, water-permeable reservoir is sustained below several layers of soil, mulch, or other media. Water flows into the wicking bed through a perforated pipe that flows out from a drain placed at a height approximately 25% up the wall of the structure. It is critical, when constructing a wicking bed, to ensure that organic matter like soil or mulch does not infiltrate the water in the shallow reservoir. When organic material enters the anaerobic zone which exists in the reservoir, malicious bacteria and fungus growth is created and any plants in the wicking bed are negatively affected. The organic matter can be effectively separated from the reservoir by a landscaping cloth weighed down by a layer of sand.

1.3.3 Advantages of Greywater-fed Hydroponics Systems

Hydroponics are preferable to traditional farming methods due primarily to the drastic water savings and efficient use of space. Additional advantages include low upkeep and dramatically fewer pests due to the lack of soil and soil harboring insects and fungus. These advantages are made possible by the recirculating volume of water contained in the walls and pipes of the system. Once the specified volume of water is added to the system, only miniscule amounts are needed to comply with the needs of the plants. The source of these small quantities of water is delegated entirely to the greywater filtration system which requires maintenance no more than once a year. Certain hydroponics grow beds, especially the raft grow bed, are capable of supporting a plant density approximately five times greater than traditional agricultural methods. The increased density is made possible by the immediate availability of nutrients which are constantly contacting the plants' roots. In soil, nutrients are dispersed throughout the soil and plants must compete for a finite supply; in hydroponics, nutrients are abundant and their delivery to the plant is expedited. The rapid uptake of nutrients through the nutrient rich water also supports accelerated plant growth.

High entry cost and high-complexity are the two most significant detractors preventing widespread hydroponics presence in the agricultural industry. In order for hydroponics to succeed and become a truly disruptive technology the cost to produce such systems and the body of knowledge which supports a simple construction of these systems must be reinforced. The greywater-fed hydroponics system is significantly less expensive than systems on the market due to the frugal selection of materials and utilization of repurposed materials. Many of the frames and pipes which support the nutrient-rich water can be reused if they are not beyond repair, which has the potential to drive down the initial price of these farms and decrease the duration of time before these systems can return their investment.

2. Design Specifications

The design of the hydroponics system was constructed through a largely iterative process in which physical prototypes were constructed and tested in the Santa Clara University Forge

Garden and Civil Engineering Laboratory. Insights from the rapid build and tests provided critical information about the reliability and manufacturability for specific subsystems. Many design decisions were sampled from successful, local farms and verified through physical experimentation at Santa Clara University.

2.1 Customer Needs

The outdoor hydroponics product our group sought to construct featured multiple grow bed configurations and a self-correcting control system constructed with frugal materials for home and hobby applications with an educational focus. Hydroponics systems do not require any soil to grow and have the capability to scale to a large, commercial application, but our group only examined the smaller scale. Our group has provided educational tools through an output of monitored variables such as temperature, pH, and electrical conductivity, to a smartphone through the use of an arduino and the app service Blynk. The monitored variables give the garden owner opportunity to remotely examine the system and study how altering fertilizers and flow rates affect the water quality. The system features a deployable solar shade attached to a rigid frame that activates whenever a thermometer on the grow bed surface reaches a certain high threshold. The shading system allows outdoor gardeners an opportunity to grow a wide range of crops even during the hot summer months. Listed below is a table containing the potential customers we reached out to so that we may better understand the components they find desirable. Tabulating their needs allows our group to directly relate their recommendations to the design of our designed system.

Table 2: List of consulted clients and their most critical needs listed.

Contact	**Qualification**	**Primary Need Expressed**
Raphael Mugachi	Principle of South African high school, LEAP 5	Educational opportunity for students.
Alrie Middlebrook	Manager of Middlebrook Gardens in San Jose	System simplicity and durability with low maintenance.
Ken Armstrong	Founder of Ouroboros Farms in Half Moon Bay	Minimize pump work by using gravity assisted configuration and control temperature.
James Wang	Recent engineering graduate from Santa Clara University - constructed Loaves and Fishes aquaponics system	Shading system to prevent scorching of leafy greens on hot days.
Larry Vollman	Manager and gardener at Loaves and Fishes in San Jose	Emphasis on leak reduction and education.

2.2 Functional Analysis Decomposition

The hydroponics system our design team created features two significant types of input and two types of output. The inputs are separated into continuous and initial inputs. The initial inputs necessary to make the system capable of supporting plants are significant volumes of water and liquid nutrients. Once the system is established with these inputs it requires a consistent flow of electricity to operate the pump, a small volume of water provided by the greywater filtration system, and minimal nutrient solution additions. Additionally, heat in the form of temperature is a continuous input to the temperature sensor attached to the control system.

The outputs realized by the system are primarily the plants harvested at the end of their life cycle. The deployment or retraction of the solar shade is an intermittent output. The outputs related to the shade are based on the current temperature observed by a temperature probe on the surface of the grow beds. The magnitudes of the initial inputs and final outputs are proportional functions related to the size of the grow beds. Larger grow beds require a larger volume of water and liquid nutrients supplied initially. Much like the initial inputs, the single output of harvested crops varies proportionally to the size of the grow beds. A larger grow bed also requires a larger pump, but the scaling is not linear in relation to the area occupied by the grow bed like the water and nutrient volume. Pump sizing is primarily a function of head height observed and length of pipe which the water must travel before returning to the pump. The intermittent output realized by the shading system is consistent with the weather patterns of the region and the programmed deployment and retraction temperature.

2.3 Existing System Benchmarking

There are various hydroponics systems currently on the market ranging in size and cost. *Table 3* summarizes the variety of systems. Each of these commercial systems will be used to complete a benchmarking analysis.

Table 3: Summary of Current Hydroponic Systems on the Market

Name	**Manufacturer**	**Reservoir Size [gal]**	**Grow Bed Size [ft^2]**	**Price**
Aquasprouts Fountain [11]	AquaSprouts	6	0.8	$159.65
Miracle-Gro AeroGarden Harvest Elite [12]	AeroGarden	1/2	0.6	$169.95
Hydroponics EuroGrower 8 Site Complete [13]	HTG Supply	6	40	$616.65
Ebb & Flow Hydroponic Flood Table Kit [14]	ActiveAqua	70	16	$768.95
Hydroponic Drip System Flood Table Kit [15]	Botanicare	115	32	$1089.95
Aquabundance Home Aquaponics System [16]	The Aquaponic Source	200	45	$7,895.00

2.4 Rationale for System Specifications

Through the help of research and benchmarking commercial systems, our team set out a list of aspects that we wanted to include in our final design. *Table 4* ranks customer needs is ranked from 1-5 with 1 corresponding to a low priority and 5 corresponding to a high priority.

Table 4: Customer needs. Higher numbers equates to higher priority.

#	Subsystem	Need	Priority (1 - 5)
1	Software	Simplistic design for both students and teachers to interact with	5
2	Water	Ability to be reuse throughout system	5
3	All	Operational in rain and inclement weather	5
4	Structural Design	Ability to hold various loads (growth of plants)	5
5	Electronics/ Hardware/ Structural Design	Replacement of parts is seamless and easy to accomplish for students and teachers alike.	3
6	Structural Design	Safety	5
7	Electronics	Arduino operated and connected to sensors throughout system	5
8	Piping	Dependability/Minimal leakage	4
9	Structural Design	Weather resistance	5
10	Structural Design	Durability	5
11	All	Ability to be recreated at other LEAP Schools	2

12	Electronics	Longevity	4
13	Electronics	Ability to use electrical power from school and is low power	5
14	All	Simple educational training	3
15	All	Cost effective	3
16	All	Items needed purchased in South Africa	4
17	Structural Design	Sun shading system	5
18	Control System	Monitor and control surface temperature	4
19	Water Pump	Dependable, suitable for size of system, submersible	5

Variables including total mass, pump voltage, and motor ratings were additionally weighed in a metric to determine their relative importance. The most significant factors were size of the pump due to power usage and temperature range of the temperature probe so that environmental conditions could be controlled.

Table 5: Metrics table with units. Greater numbers indicate increased significance.

#	Need #	Metric	Priority (1 - 5)	Units
1	2,4,10,17	Total Mass	1	Slugs
2	6,9,10,1517	Min/Max Width and Height	2	feet
3	5,7,13,15, 16,18,19	Unit Cost	3	US Dollars/SA Rand
4	19	Pump Size	5	GPH
5	19	Pump Voltage	2	Volts
6	2,6,19	Environmentally safe	5	n/a
7	17	Motor Rated Torque (Shade system)	4	lb/in
8	17	Motor Rated Power (Shade system)	2	Watts
9	17	Motor Rated Voltage (Shade system)	2	Volts
13	2,18	Surface temperature sensor	5	Fahrenheit

After analyzing current products on the market, our team created a list of target specifications for our system that we strived to reach throughout the design and manufacturing process. *Table 6* goes into further detail of these benchmarking metrics.

Table 6: Benchmarking metrics for project's system (Target Specs).

#	Metric	Priority (1 - 5)	Units	Marginal Value	Ideal Value
1	Total Mass	3	Slugs	>5	<8
2	Min/Max Width and Height	4	feet	>5x5x5	<7x7x6.5
3	Unit Cost	3	US Dollars/SA Rand	<5000	~2000
4	Pump Size	5	GPM	>400	~550
5	Pump Voltage	3	Volts	>200	~230
6	Environmentally safe	5	n/a	Yes	Yes
7	Motor Rated Torque	4	lb/in	>2	~3
8	Motor Rated Power	4	Watts	>1/16	1/12
9	Motor Rated Voltage	4	Volts	>100	~130
13	Surface Temperature Sensor	5	Fahrenheit	>60	<80

2.5 System Configuration

Our team drafted, designed, and constructed a comprehensive hydroponic system that would fit within the parameters set out by our partner, LEAP 5 High School. Our system comprises multiple subsystems that are strategically interconnected in order to provide a working, viable system. In general, our project employs two different styles of grow beds, a raft bed and a wicking bed, to accomodate a larger range of vegetables in our system. Nutrients are delivered to the vegetables through a water recirculation system that prevents any unwanted water runoff that is found in traditional agricultural methods. To protect temperature sensitive plants, we designed a shading structure that would deploy a greenhouse shading material over the grow beds. Another aspect of the system layout is our greywater filter. Greywater refers to any wastewater that does not contain fecal matter. Since one of the primary goals of our project is to reduce the use of freshwater for agricultural needs, we developed our system around the reuse of greywater. A greywater filter is installed in the basin of a repurposed bathtub to filter fine mulch particles in order for the water to be safely introduced to the grow bed system. This system layout was promoted by the notion of designing a system to ultimately educate, reduce water waste, and produce vegetables.

The system cycle begins at the 55 gallon water reservoir in the center of the layout, a submersible pump draws water from the reservoir to the two raft beds on either side. The one pump supplies the water intake for both smaller cycles. Water slowly flows through the raft beds until it drains out the opposing end and into the wicking bed. When water reaches this secondary bed, a porous PVC pipe enables the water to distribute throughout the media. When the water level reaches a determined height, it then exits the first wicking bed and flows into the second. Again, the identical water flow process is completed in the second wicking bed compared to the first. Finally, the water is delivered back to the reservoir for the process to begin again. This same process is mirrored on both sides of the system.

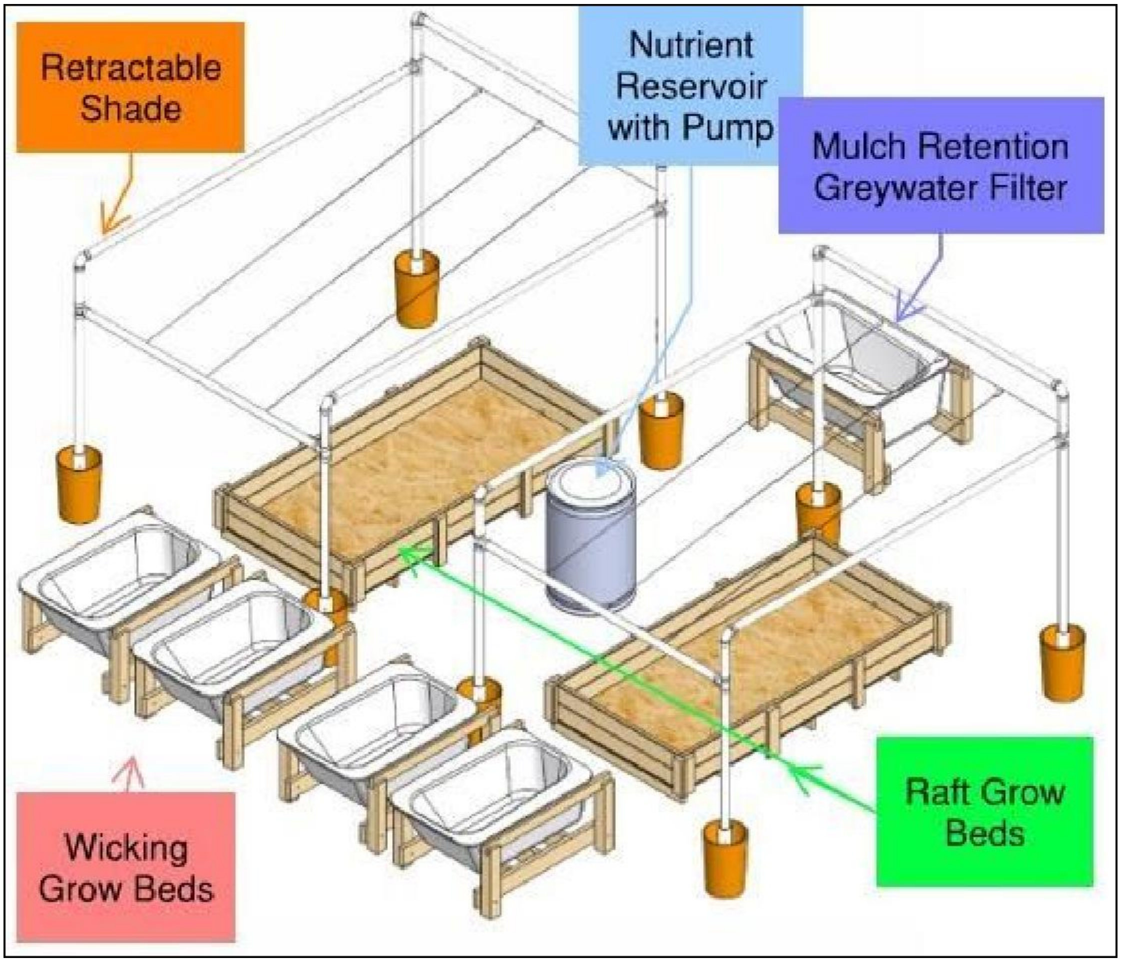

Figure 6: South Africa hydroponic system layout.

2.6 Project Management

The interdisciplinary nature of the project led to considerable overlap between departments as the holistic goal of delivering a hydroponic system was sought after.

2.6.1 Design Challenges and Goals

The project team came up with a preliminary list of challenges and constraints with our partners at LEAP 5 High School that were essential to the success of the project. Members from each department were assigned goals complementing their strengths as shown in *Table 7*.

Table 7: Design goals for each contributing engineering major

Major	Design Goals
Mechanical Engineering	• Configure grow beds, plumbing, and reservoir through an iterative process to optimize both grow area and potential plant diversity. • Weigh existing market options alongside immediate customer needs and select the optimal types of grow beds and water delivery • Minimize pump power consumption while still circulating the entire volume of water once every 3 hours. • Work with Civil Engineering to produce robust wooden frames for grow beds that can be easily reproduced. • Program and develop a self-monitoring and self-regulating temperature control system using a solar shade. • Produce a resilient manual shading system as a durable alternative to the automatic shading system. • Perform hand calculations and Finite Element Analysis to ensure the design of load-bearing subsystems has a factor of safety ≥ 1.7. • Select and employ leak-resistant plumbing solutions that will not deteriorate over time. • Develop graphical assembly manuals for each individual subsystem.
Civil Engineering	• Decrease freshwater needs of the hydroponics system by supplementing continuous water additions with filtered greywater. • Select an appropriate greywater filtration system through water quality testing. • Ensure filtered greywater is compliant with strict health and safety codes.
Engineering World Health	• Develop an informative and engaging lesson plan for use at LEAP 5 High School. • Ensure that the ownership for the designed project is received by the LEAP 5 High School.

2.6.2 Budget Consideration

The established budget contained three main sections accounting for all expected costs resulting from a half-scale hydroponics system at Santa Clara University and a full-scale system at the LEAP 5 high school in South Africa. The major individual contributions came from Santa Clara University, Xilinx, and the Frugal Innovation Hub grant. Crowdfunding was additionally utilized to further raise funds.

2.6.2.1 Expenses

Our group has seeked funding from the Undergraduate School of Engineering Program for the materials total. The materials detailed in our budget has covered the construction and operational functions of two hydroponics systems - one in Santa Clara, CA and one in Jane Furse, South Africa. Our Santa Clara prototype allows us to gain hands on experience with the plumbing, controls system, shading structure, and agriculture components. In doing so, our team has gained the knowledge required to optimize the system's growing conditions. Gaining this knowledge of the complete system has allowed us to replicate the design for LEAP 5 School.

Table 8: Cost of materials used to prototype the system in Forge Garden, Santa Clara.

CATEGORY	COST
Raft Bed	$363.19
Plumbing	$35.94
Wicking Bed	$65.36
Greywater Filter	$134.45
Shading Structure	$278.37
Controls System	$19.38
TOTAL:	**$896.69**

2.6.2.2 Income

In addition to seeking funding from Santa Clara University and from the Xilinx grant, we have set up a funding campaign on the crowdfunding website, GoFundMe. This campaign has been primarily aimed at obtaining donations from friends and relatives. However, this crowdfunding page has also been used to advertise our project to the public and to any organizations who may want to contribute to the cause.

Table 9: Fundraising sources/amounts

Fundraising		
Source	**Amount**	**Note**
School of Engineering Grant	$2,000	Grant for engineering students.
Crowdfunding (GoFundMe)	$2,710	Contributions from friends and relatives.
Xilinx Senior Design Grant	$3,500	Enables travel for projects with remote sites.
Frugal Innovation Hub Grant	$3,000	Supports travel expenses.
Engineering World Health Funding	$2,000	Funding for Engineering World Health students

2.6.3 Timeline

Our team succeeded in establishing and complying with an ambitious timeline in order to ensure the successful completion of our system in South Africa. The planned departure date was March 20, 2020 and our group accelerated our construction and validation efforts in order to produce a product which would satisfy the needs of the LEAP 5 High School.

The Gantt chart, shown in *Table 10*, was created so that project action items were completed in a timeline conducive to rapid development. A more detailed table provides specific dates to track planned completion of items against their actual completion. Our team successfully managed to complete the majority of key milestones on the aggressive schedule which promoted project completion before the planned deployment at the High School in South Africa.

Table 10: Timeline of key tasks

Action	*Fall 2019*	*Winter 2020*	*Spring 2020*
Research			
Prototyping			
Finalizing Design			
Manufacturing			
Verification & Testing			

The initial research and conceptual designs were the most time consuming and under-scheduled tasks our team encountered. Our team decided to invest our time in research, prototyping, and conceptual design because of the firm March 20th deadline. Initial testing and designs were proved effective before major construction occurred. Once the designs were validated through a prototype, rapid full scale construction was completed with few setbacks.

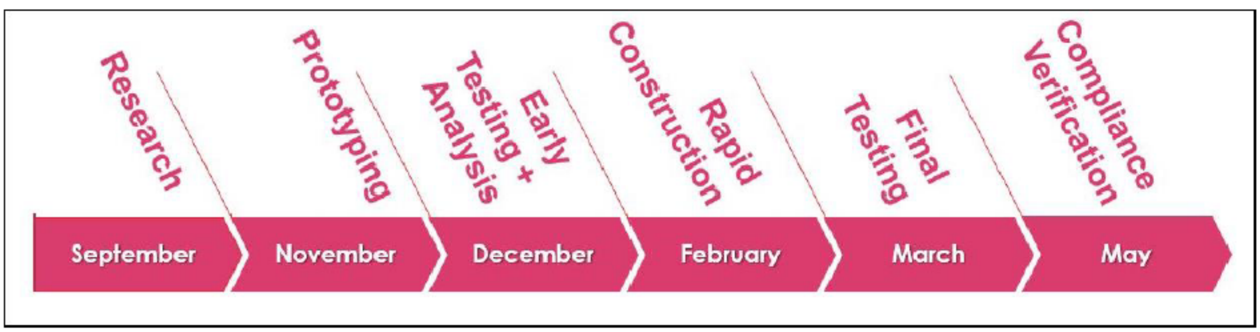

Figure 7: Overview of project schedule timeline.

2.6.4 Risks and Mitigations

It is essential to determine any potential risks that can come about during designing, manufacturing, and deploying a successful product especially when it comes to an agricultural system. Below is a list of potential risks that were considered throughout the senior design project.

2.6.4.1 Risks

Several physical hazards were identified before the construction of our system. The hazards were largely due to the labor involved in producing hardware constructed of wood, metal, and plastic. Chemical agents due a pH adjuster and chemical sealants were also cited as potential means for minor injury or irritation. The operations relevant to the project were deemed to be low risk for injury because of proper hazard investigation and training.

Table 11: Detail of hazards which may incur during manufacture of project.

Item	Physical Hazard or Agent
1	Operation of power tools and equipment to cut, fasten, and drill both wood, ABS pipe, and PVC pipe. There is a potential to maim oneself with improper power tool operation.
2	Team members trimming plants and plant-root substrates using snips or knives could be injured.
3	Use of fertilizers and pH adjusters (phosphoric acid and potassium hydroxide) since skin contact can cause minor dermal irritation
4	Skin irritation due to sunlight exposure and physical labor in Santa Clara University Forge garden

2.6.4.2 Mitigations

For every hazard identified, at least one mitigative action incurred. All preventative actions were confirmed with University officials to ensure that both the safety of the team members involved in construction in addition to any individuals who may come in contact with the system would not be injured.

Table 12: Detail of preventative actions taken by team to remedy potential hazards.

Item	Risk Mitigation Action
1	All team members underwent powertool training and certification at Maker Lab.
2	Extreme caution will be executed with sharp objects.
3	Appropriate street clothing (long pants, closed toed shoes), safety glasses will be used in working environments when operating any power and hand tools.
4	All team members reviewed safety precautions and know to thoroughly rinse if irritation occurs.
5	Nitrile gloves will be used when handling fertilizers and pH adjusters.
6	Follow all instructions from Forge Garden Organic managers and maintain compliant with their rules and regulations when on premises.

2.6.5 Team Management

In order for this project to be successful in this brief time period of six months, each team member was assigned to manage a specific subsystem. While there was a lead for every subsystem, our team emphasized collaboration with each other and would always seek others advice, ideas, and help when it came to complete these sections of the project.

Alex Estrada was tasked with being the lead of the shading structure. After the team's concept selection, Alex focused on work with Civil Engineering Lab Manager, Brent Woodcock. Over the six month course, they collaborated on the construction of the shading frame, stepper motors operation, building manuals, and the structural integrity of the entire subsystem to promote safety and effectiveness.

Kathryn (Katya) Fairchok was in charge of pump flow design and calculations. She calculated flow rate and head loss in the system based on material roughness and geometry, and she identified the pumps to be used in the system. Additionally, Katya was in charge of the Blynk app development. She worked on the circuitry for the temperature sensor, the code for the wifi chip transmitting data to the app, and the app interface. Katya also was in charge of all fundraising efforts, material, and donation management. Finally, Katya performed the CAD development and graphic design for the system components.

Andrew Feldmeth developed project timelines and led research and construction of hydroponics grow beds and plumbing orientation. Critical industry contacts were established through connections made by Andrew Feldmeth. The commercial connections provided useful insight and feedback on our approaches to creating an effective hydroponics system. Additional effort was dedicated purely to ensuring that the hydroponics system was easily replicable, durable, and encouraged learning outcomes for the high school students. A template of assembly manuals for each subsystem were designed so that system owners could trace the construction of the system from raw materials to finished product in ten steps or less through clear graphics.

Andrew Jezak was tasked with delivering sufficiently filtered greywater that was suitable for use in a hydroponics garden. The conceptual design and preliminary prototypes were tested for water quality by him. Along with assisting in the design and build of the grow beds, plumbing, and shading structure, Andrew also had a role in tracking expenditures, performing the cost- benefit analysis, and ordering materials for use in South Africa.

Biology students in the Engineering World Health program support and collaborate with engineers on their senior design projects. EWH students specifically help the team to create projects that are frugal, impactful, enduring, and culturally appropriate. For this project, the EWH students focused on the creation of 15 hours of education materials. This curriculum included lectures, experiments, activities, and daily interaction with the hydroponics system. The most important aspects of the education materials were the connection to the hydroponics system and the empowerment of students to make an impact in their local communities. During the planned travel to LEAP 5, the EWH students were to implement and oversee all of the education of LEAP 5 students utilizing the materials mentioned above.

3. Subsystems

The hydroponics system our group has built consists of five principal subsystems: grow beds, shading structure, data logging, plumbing orientations, greywater filtration system. The details of each subsystem will be discussed in the following sections. Each of the defined challenges of the project were paired with a specific subsystem to overcome these obstacles. Every challenge had to be deliberately addressed in a subsystem in order for our project to be successful.

3.1 Grow Beds

The grow beds are a focal point of the hydroponics system and the success of the subsystem is the measurement of success for the entire system. Grow beds were required to be durable and capable of rapid construction. The final designs were largely inspired by and adapted from observations recorded during visits to successful large-scale hydroponics and aquaponics farms.

3.1.1 Raft Bed

The raft bed is the grow bed which provides up to 96 plants per 4' x 8' module. The entire frame is built using just 2x4's 2x6's and a ½" thick OSB board. It is simple in that it requires a very basic frame construction with commonly available lumber and no awkward brackets or fixtures. Many of the large commercial farms used the same beds, but rather than being in 8' long sections they were 80' long. Water is delivered to the raft bed from the nutrient reservoir by a submersible pump on a timer. The subsystem contains the largest volume of water in the system and acts as a buffer as the nutrient-rich water cycles through. The water in the bed is approximately 9 inches deep and on it floats four 2' x 4' "rafts" which are ¾" thick styrofoam insulation boards which contain 24 holes with a small net-pot per hole to house the plant. The raft bed is a great system for our project because it is extremely low maintenance and very durable. These were two defining qualifications in our grow bed selection and the raft bed proved exceptional. The large body of water is very good in summer months too because it acts as a thermal reservoir due to water's high capacity for heat which helps keep plants cool.

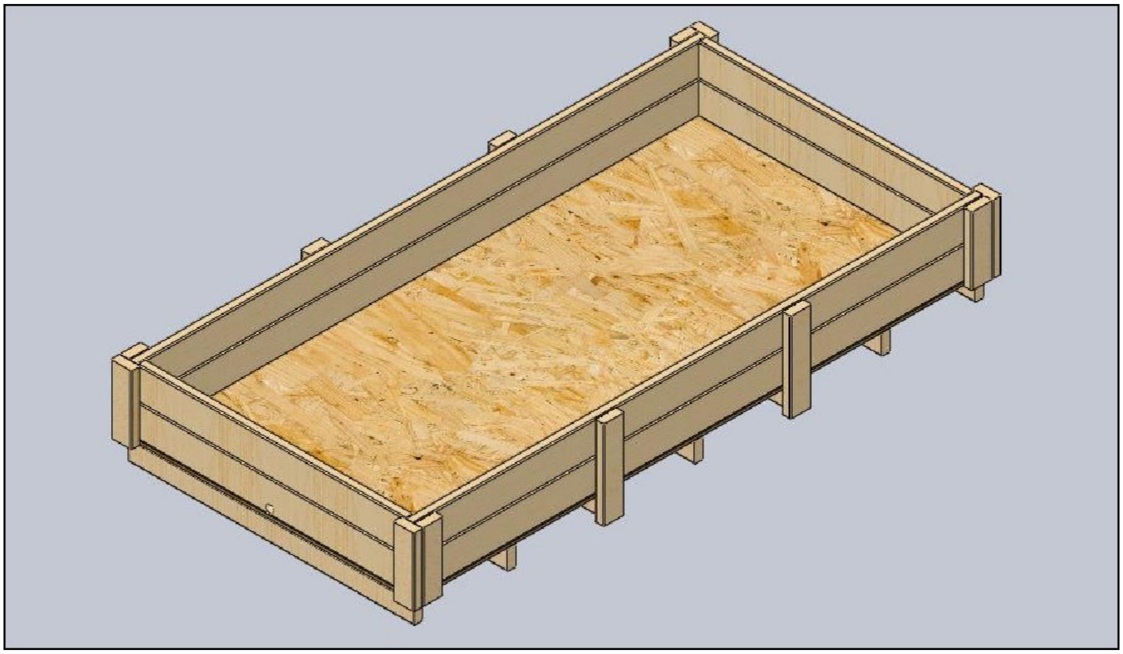

Figure 8: Model of raft bed frame.

The almost 200 gallons of water housed in the raft bed weigh over 1500 lbs. and required careful analysis to ensure that the frame could support the load. A hand-calculation strength analysis was performed and indicated that with a beam spacing of 16 in. there would be a factor of safety of 1.9 -- acceptable for our durability standards. These beams would be supported by eight cinder blocks, four on each long side. The ground under the cinder blocks was levelled and tamped to ensure that the raft bed was even and that water would not pool up. In order to validate our hand-calculations, we devised a Finite Element Analysis, with a mesh refinement placed on the bottom face of the beams spanning the width of the bed. These beams saw the greatest moment, yet still remained comfortably under the yield point. The max stress was seen on the edges which represent the worst-case scenario if the beam was only in contact with a tiny sliver of area on the cinder block. The high stress at these worst-case edges proved to be above yield so we could expect to see slight compression failure, but on the observed system there was a larger contact surface area from beam to cinder block and no compression failure or surface splintering was observed. The analysis on the raft bed further reinforces the fact that this is a hardy grow bed and even in worst case scenarios, it can yield crops with little to no impact on its productivity.

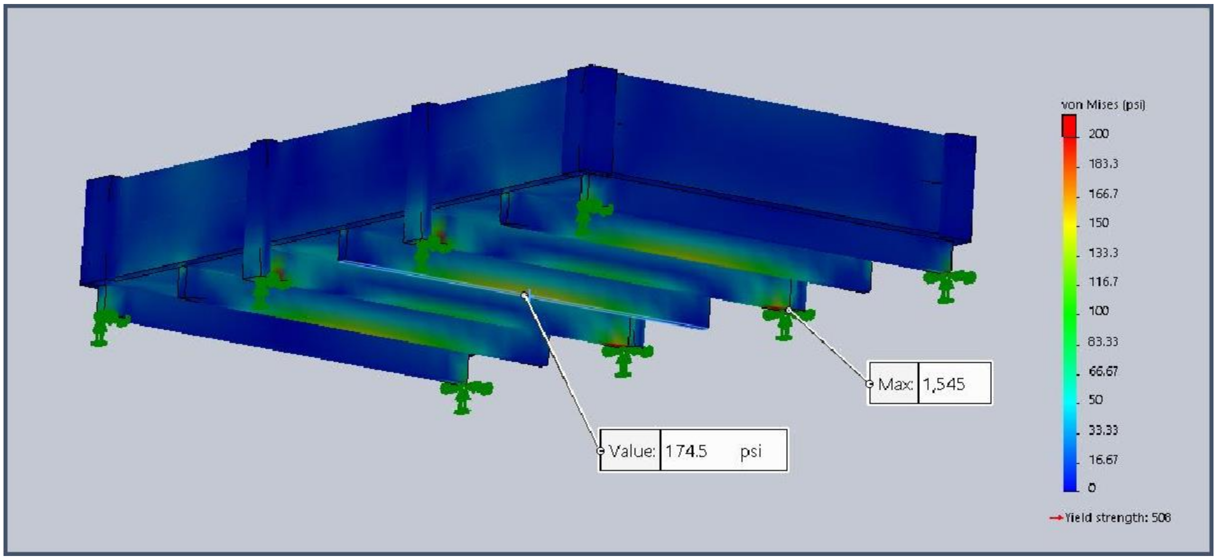

Figure 9: Finite Element Strength Analysis of raft bed frame with simulated water loading

The raft bed is the first grow bed to receive nutrients from the nutrient reservoir, before the water flows into the wicking bed. As seen in the image on the far left, the rafts present the opportunity to have plants at different stages in their life-cycle growing simultaneously. This adaptability is key to our objective of providing a system that can grow multiple types of plants simultaneously. In the photo, you can see colorful romaine lettuce (the largest), Butterhead lettuce (medium) and arugula (the youngest and smallest). Plants are harvested by removing the raft and trimming them at the stalk. The old roots are composted and net-pots which anchor the root of the plant are then reused to house a new seedling. The seeds are sprouted in coco coir -- a loamy media made from coconut fibers -- placed in propagation trays. The plants spend about two weeks from seed to seedling before they are transplanted to their final destination in the raft. Our first harvest of lettuce took approximately 50 days from seed to harvest which is almost two times faster compared to lettuce that grows in the soil. The raft bed is a very ideal system to fill the needs identified by our client the LEAP 5 high school. The ability to simultaneously grow a variety of leafy greens at different life cycles gives the students at LEAP 5 and the gardeners at the Forge Garden the tools to explore hydroponic growth in a wide variety. The raft bed is a perfect high-production, high-density grow bed when paired against the more versatile wicking bed which the water enters next.

3.1.2 Wicking Bed

The wicking bed is a crucial piece in our system because it allows the gardeners to grow longer lived fruiting and flowering vegetables like broccoli, tomatoes, peppers, and even potatoes. This is the largest strength of the wicking bed and why it compliments the shortcoming of the raft bed. Because there is no deep, anchoring substrate in the raft bed, lighty leafy greens are prefered. The deep soil and clay ball aggregate allows long-term plants to receive the support they need to produce a successful yield. On the surface the wicking bed may appear just like a normal raised garden bed but it uses a unique water delivery method. Instead of watering from the top of the soil -- allowing a significant portion of that water to go unused due to surface evaporation -- water is delivered through a perforated pipe along the entire length of the planter base and it "wicks" up to the roots. The wicking is a result of the capillary action which delivers water from the water-saturated lower layers up through the soil to the deepest roots of the plants. Giving water straight to the roots from the bottom helps the plants grow bigger and faster. When designing the system our team considered ebb & flow systems and drip line irrigation but found that wicking beds again were superior due to their simplicity and less maintenance. An advantage of wicking beds is that a small volume of soil is used, alongside expanded clay balls, so that compost can be utilized which further boosts the productivity of the plant.

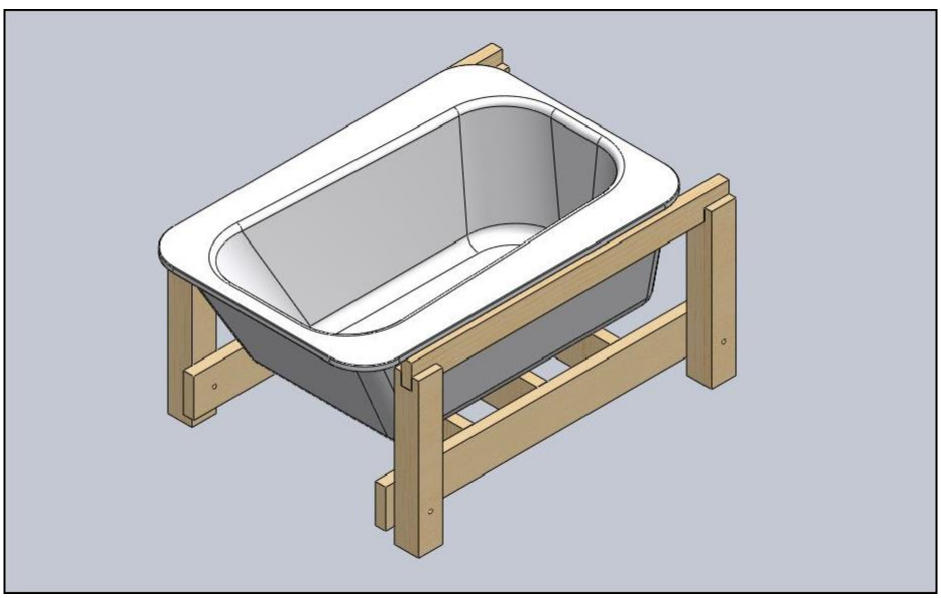

Figure 10: Model depicting the bathtub used to house the soil and the frame.

The wicking bed relies on a multi-layer system to deliver water from a shallow reservoir at the bottom of the bed to the plants' root systems. The layers are needed to protect against destructive anaerobics zones created by perpetually wet regions not exposed to oxygen. These anaerobic regions will cause root rot and release a foul smell which could ruin a harvest. As seen in the side-view image there are four distinct layers: a loose gravel reservoir which is constantly submerged in the flowing water; a weed mat to prevent plant roots from entering the shallow gravel laid out which is permeable to water, but shields the reservoir roots; a thin layer of sand then adds a redundant separation layer keeping the organic soil matter out of the gravel reservoir, but allowing water to easily permeate; and finally a 10-12" thick section of expanded clay balls and soil. The clay balls are great because they are very light and keep the soil in the bed from becoming hard packed, which would discourage the capillary action. In the Forge Garden, this grow bed was housed using a thick plastic recycled bed donated by the Forge, but in South Africa our team will utilize a series of bathtubs which. The LEAP 5 school has great access to discarded or otherwise unused materials and were informed that they were in possession of 5 large bathtubs with nearly identical dimensions to the plastic bed located at the forge.

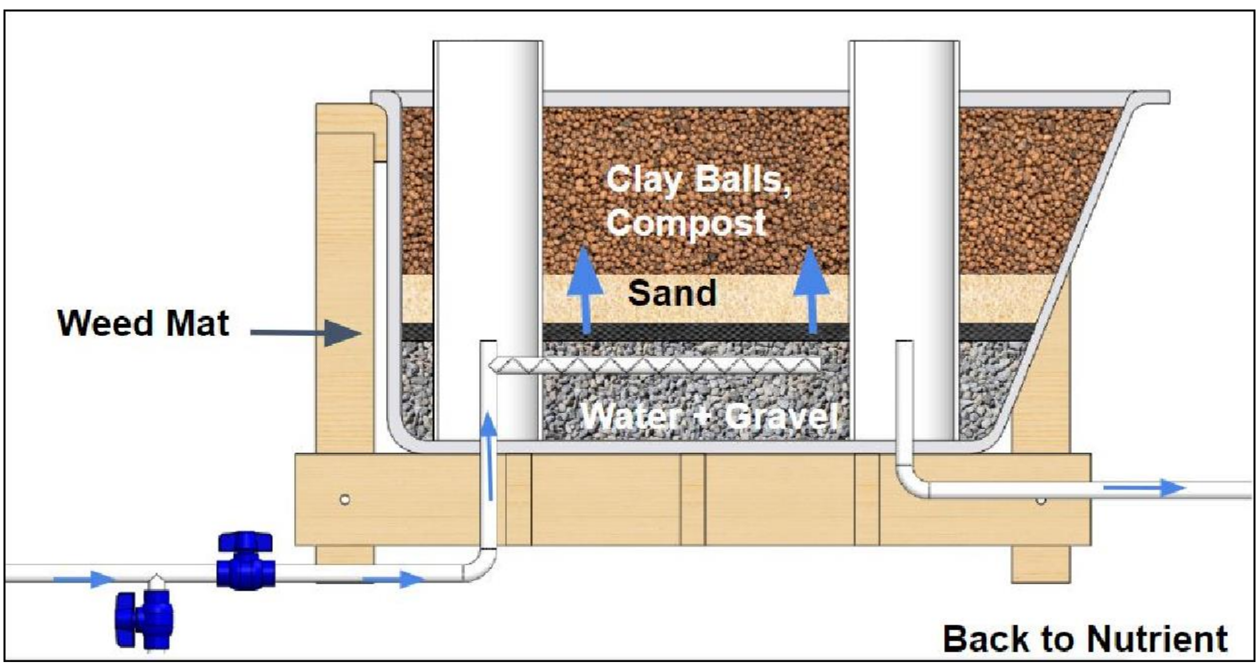

Figure 11: Cross section of wicking bed plumbing and layers.

3.2 Shading Structure

While benchmarking and researching for our project, we noticed an outstanding issue with a previous system. After touring the aquaponic system at Loaves and Fishes (in San Jose), our team quickly recognized the lack of growth coming from the leafy green raft beds. Investigating further, the volunteer farmers explained that the lack of growth was due to an excessive amount of sun exposure and high temperature. Leafy greens can easily bolt due to an inadequate climate. Therefore, our team set out to solve this issue in these hydroponic agricultural systems. To ensure that the system we ultimately produce would be able to promote the growth of leafy greens in raft beds, we decided to implement a shading structure above the raft beds to keep the leafy greens in the ideal temperature range. Understanding that leafy greens require both direct sunlight and reasonable climate to grow, our shading structure will be retractable to provide direct sun exposure for parts of the day while protecting the vegetables during daily peak temperatures.

3.2.1 Design Considerations

When it came to determining the type of shading structure, it was essential to determine the best effective design that would work seamlessly among the other subsystems and promote the growth of the leafy greens. Our group has produced a list of aspects and requirements for the concepts that we developed: manufactuability, durability, materials, accessibility to grow beds, aesthetic, effectiveness, and assembly. Once the designs were complete, according to these aspects and requirements, they were analyzed and rated on a scaling system of 1-5 (with 1 being the least desirable and 5 being most desirable). Once the scoring was completed, the points were summed and compared among other design scores to determine which option best fits our system requirements.

Each of the following shading systems designs utilizes a sun shading cloth that, depending on the grade, only allows a certain amount of sun to permeate the material. The selection on the type of material will be discussed in further detail later in this chapter.

3.2.1.1 Design 1: Hand Fan Design

This first initial design was inspired by a hand fan (*See Appendix A1)*. Throughout the day, the 'fan', which is constructed of PVC and connected to a motor at the base of the grow bed system, would expand and retract depending on the temperature reading from the control system. There are 4 PVC pipes for each grow bed module with each bed having their own individual shading material coverage. Looking at a single grow bed, 2 of the 4 PVC pipes would remain vertical while the other 2 PVC pipes will be directly connected to the motor at the base in order to deploy. The main takeaways from this first design is that there is an accessibility issue. The grow beds require consistent maintenance, harvesting, and planting to the grow beds because of the short radius of the shad structure and that this system requires twice the amount of material due to its nature of 2 'fans'.

3.2.1.2 Design 2: Reinforced Hand Fan Design

This second design was a byproduct of the first design concept (See Appendix A2). We recognized the issue that came about with twice the amount of material needed to operate Design 1. In consequence, we reduced the shading fabric and motor quantity to a single unit. This layout can be described as acting like a convertible car cover. This design utilizes 10 PVC pipes (5 on each side of the grow bed) all connected to each other by the shading material and rope. When deployed, the structure will expand by a rotating motor connected to the PVC pipes. There will be a total of 3 pipes on either side of the grow beds that will remain above ground level (one vertical and two at 45 degree angles). In summary, this will be the most aesthetic design and would guarantee shading over the grow beds but not on the sides. This design option is very complex and may be difficult to build over the grow beds.

3.2.1.3 Design 3: Square Frame Design

This final design option is unlike the other two previous concepts (See Appendix A3). This particular shading structure design does not wrap around the entire grow bed but instead is propped up above the system. This concept consists of piping which is stabilized by footings. This system will act like a horizontal garage door compared to the classic vertical doors that we see on houses. The main takeaways are that this design would be accessible on all sides of the growbed, would be easy to manufacture, and would be simultaneously effective.

After analyzing each design, *Table 12* was constructed to determine which concept best fit our set out aspect and requirements.

Table 13: Concept Selection Matrix for Shading System

Consideration Areas	Design 1	Design 2	Design 3
Manufacturability	3	2	3
Durability	3	3	4
Materials	3	2	3
Accessibility to Grow Beds	2	1	5
Aesthetic	3	5	1
Effectiveness	2	2	4
Assembly	2	1	2
Total Score	18	16	22

After comparing all three designs shown in *Table 12*, it was determined that Design 3 would best suit our needs. While Design 1 and 2 were very close in scoring, Design 3 is the obvious winner due to the grow bed accessibility, durability, and effectiveness.

3.2.2 Finalized Detailed Design

Our team ultimately decided to construct and design two operating systems for our final design. Both manual and automatic operation will be the driving forces for the deployment of the shading material. We created the manual system because we wanted to ensure that our South Africa system could be easily maintained, reducing the amount of electronic components that were ultimately needed for the automatic system. On the other hand, the automatic system would be constructed and prototyped here at Santa Clara University. This motorized system alleviates the duty of monitoring the hydroponics system throughout the day. While the automatic system would be ideal, it was not feasible for manufacturing in South Africa. In both cases, the overall design and construction of the structure are identical.

Both structures consist of ABS weather resistant pipes which are stabilized through concrete footings. This frame-like design allows access to the grow bed from all sides of the system. Metal cable is used as a "railing" guide to prevent the shading material from drooping down and interfering with the grow beds below. The shading system subsystem can be seen in *Figure 12*.

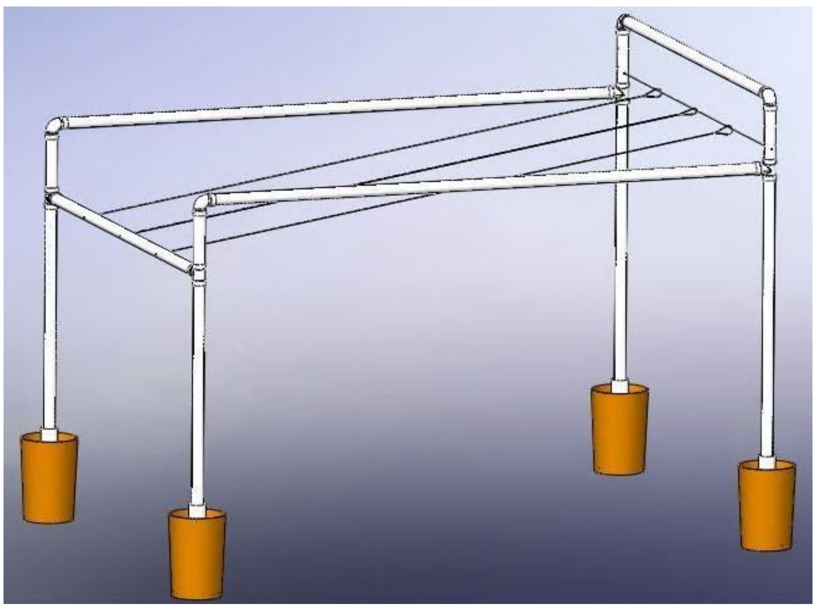

Figure 12: Shading Structure Subsystem.

The overall goal of this design of the shading structure is to protect the leafy green vegetables below from extreme high temperatures while still promoting accessibility to garden beds. Through research, our team found that an adequate temperature range for leafy greens were in the range of 60°F-80°F [17, 18, 19]. With this understanding that leafy greens require both direct sunlight and reasonable climate to grow, our shading structure is to be retractable to provide direct sun exposure for parts of the day while protecting the vegetables during daily peak temperatures. A fully deployed and retracted system can be seen in *Figure 13*.

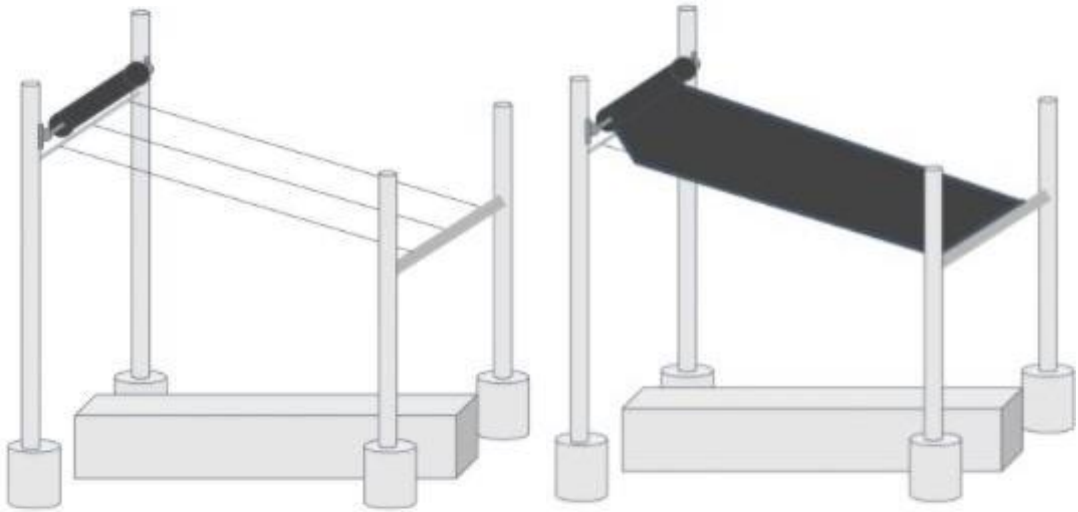

Figure 13: Shading Structure retracted and deployed.

3.2.3 Manual Consideration

The design of the manually operated system employs a shading material that is meant for human interaction. The shading material is woven through tensioned rope tied along the length of either side of the structure for easy manual deployment and retraction depending on the heat intensity throughout the day. During peak hours of the day when solar radiation and temperatures peak, the shading material would be deployed over the grow beds by pulling the material through the rope with minimal effort. *Figure 14* depicts how the rope is strategically inserted into the shading material's grommets.

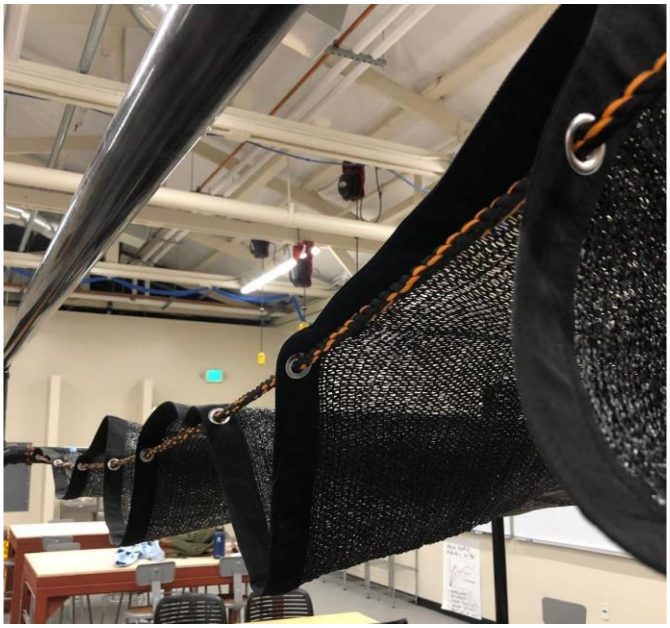

Figure 14: Rope interwoven between shading material grommets.

3.2.4 Automatic Consideration

The automatic shading structure removes the human dependence factor and is instead being driven by inline stepper motors. This motorized system alleviates the duty of monitoring the hydroponics system throughout the day. Motors are attached to the vertical ABS structure and are connected to each other through a horizontal pipe where the shading material wraps around. Both motors work in unison with each other to deploy the shade over the grow beds. Stepper motors were chosen for our application due to the fact that their angle of rotation can be precisely controlled and that they can possess holding torque without the need of the motor to be powered.

Through the use of an Arduino, a connected waterproof temperature sensor on the surface of the raft beds constantly monitors the temperature. When the sensor reads a temperature out of suitable range for the vegetables to grow, the Arduino would then send a signal to the stepper motors to rotate to deploy the shading material.

3.2.5 Analysis of the Shading Structure

The object of the analysis is to focus on the structural integrity of the shading system. This system exists to provide adequate shade to the grow beds in order to prevent scorching the vegetables due to solar radiation as well as extremely high temperatures. This scorching is due to the high surface temperatures of the raft beds that would be significant enough to damage the leafy greens. Our team set out to conduct two main analyses on the shading structure: stress and thermal studies.

A stress analysis was conducted on the automatic shading operating system. More specifically, a stress analysis on the ABS pipe where the stepper motors attach onto was conducted. This test was performed to determine the durability and maximum stress of the critical region that the part may endure. The shading material is relatively lightweight with a total of 18 lbf being applied to the two motor pipe connections. Our group has assessed the possible failure modes -- bearing of the ABS and shear of the bolts -- and neither appear problematic visually. In addition to failure under the expected load of the system, a maximum allowable vertical load before bearing failure was calculated. Our analysis specifically looks at how the motor load will affect the strength of the framing structure, given a minimum pipe diameter, and resolve the question of the feasibility of whether or not ABS can be used for this subsystem as opposed to metal tubing.

A thermal analysis was conducted on the surface of the raft grow beds. It was brought to our attention through previous senior design teams, master gardeners, as well as hydroponic companies, that surface temperature of the grow beds are vital to the growth of the vegetables planted in the system. Through research, our team discovered that leafy greens require a temperature range of 60°F-80°F to prevent their growth from bolting [17, 18, 19]. Shading materials are produced with varied shading porosity percentages in order to be used in a wide range of applications. With this in mind, our senior design group set out to determine the adequate shading material porosity to select in order to keep these vegetables within their acceptable temperature range. A thermal simulation was conducted to see what type of shading material would be required for our system to combat the direct sunlight throughout the day. The solar shade material will ultimately be selected due to the corresponding temperatures on the surface of the grow beds.

3.2.5.1 Stress Analysis

The critical region of the design which requires analysis is depicted below in *Figure 15.* In *Figure 15*, equally distributed weight of the motor, tubing, and solar shade material is applied on both ABS pipes evenly (See Appendix B1). The forces that are felt on the motors are then translated to the ABS piping structure that the motor is mounted on. This entire weight must be supported by the four bolts located on the two bearing brackets on opposite sides of the horizontal shade tubing. The length and weight of the tubing assembly are 7 feet and 18 lbs, respectively. While these product specifications were provided to us by each manufacturer, our team strives to test various loads on the shading structure that would be due to forces outside of the system (examples include: students leaning on the structure, forces applied to structure when shading material is retracted, ect.)

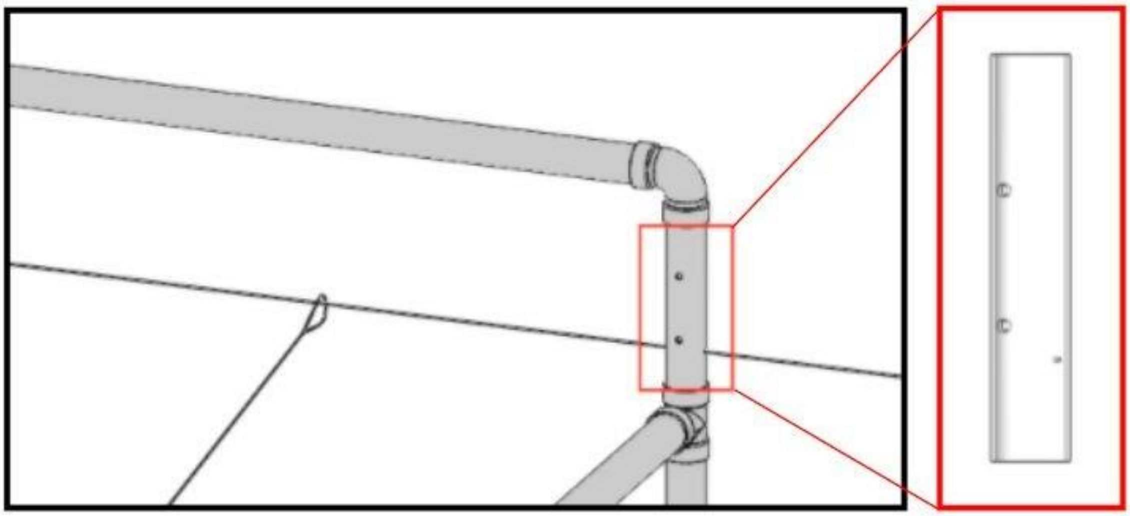

Figure 15: Stress analysis was conducted on this selected ABS pipe. This pipe section can be found on either side of the shading structure for a total of two sections.

The specific shear forces realized by the two bolts on the bracket are illustrated in the hand drawing Free Body Diagram shown in Appendix B2. The forces experienced by the bolts in Appendix B2 are assumed to have two degrees of freedom about the x and y-axes. These bolts will support both the shading material as well as the motor and will connect these two items to the main structure of the shading system. The horizontal tubing inflicts its weight in the negative-y direction and initiates a corresponding positive-y force in the supporting bolts. The only forces witnessed in the x-direction are due to the secondary shear from the weight of the horizontal tubing assembly.

The stress analysis sought to determine the Von Mises stress due to a distributed load of 18 lbs. This load was selected because it is the combined weight of the undeployed solar shade material, the cylindrical ABS pipe the shade is coiled around, and the cylindrical motor assembly. The location of the load for the model is established inside the face of the two holes on the top section of the ABS fitting where the 3/8 inch bolts fasten. Since the applied load on the bolts are theoretically distributed evenly, each pair of bolts would support half the total load of 18 lbs (9 lbs as a pair and 4.5 lbs individually). The load on the bolts accounts for the total distributed load generated due to the weight of the tubing assembly. The ABS has a thickness of ¼ inches, which makes it the most narrow section of the system. The small thickness and relatively low tensile strength justify the analysis compared to other system components.

Our team expects the ABS section will not suffer any failure due to the low weight of the tubing that is causing the external force. ABS would most likely fail due to bearing stress rather than shear because of the thin wall thickness of the pipe and the comparatively low tensile strength. Neither case is very likely due to the low weight however. The weight is only 18 lbs in total, therefore it is highly unlikely that any failure is observed. Hand calculations were completed in order to determine our hypothesis (See Appendix B4 and B5 for details). The most inexpensive and readily available ABS pipe will suffice.

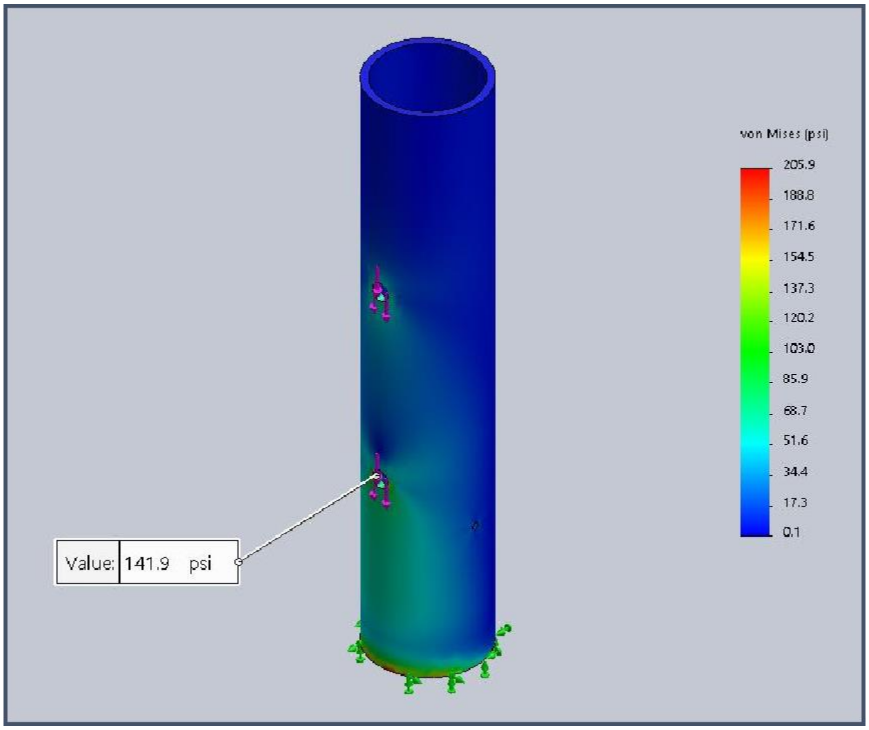

Figure 16: FEA of top ABS section where bearing bracket fastens. Both holes were loaded with identical force. Maximum shear stress is approximately 142 psi. The value generated by the FEA is distant from tensile strength and therefore very secure and durable.

The FEA results shown in *Figure 16* and hand calculations both establish ABS as a workable material by a wide margin. The two methods of analysis generate different maximum shear stresses (142 psi for the FEA and 173.7 psi for the hand calculations), but are on the same order of magnitude and convey similar maximum loading outcomes. Neither result approaches the tensile strength of ABS and even in the bearing stress case the factor of safety is greater than 21. The bearing failure mode is the most likely region in which the system will fail because the ABS experiences a stress of 272.4 psi. Even in this failure mode, there is no realistic opportunity for the ABS to fail because the material contains a tensile strength of 5903 psi. A second calculation was performed to determine the maximum vertical load which the selected ABS could withstand before failure is probable. The maximum force was determined to be approximately 195 lbs. This specific section of ABS pipe can withstand a maximum vertical load of 195 lbs, so caution must be taken so that persons do not grab hold of and exert their maximum body weight on the pipe.

The two most significant learning outcomes for the FEA from this exercise are that apparent failure modes may not actually be critical and it is necessary to investigate and analyze external situations separate from the weight of system components. Superficially, the system appeared very stable, the shear forces experienced by ABS and bolts were much smaller than the tensile strengths. The most significant problem faced when performing the FEA analysis was managing the connections on the assembly model of the shading structure. Ideally, our group would have merged the parts to create one solid piece, but our assembly included several different materials with varying properties, so merging and analyzing the system as a whole would not produce a satisfactory result. The solution to connection issues was to analyze just the critical section and create a simulated load where the bolts attach to the ABS. The conditions for this simulation cause the case to not entirely represent the actual load and differ from our hand calculations.

3.2.5.2 Thermal Analysis

The radiation onto the shading material itself can be observed in hand sketches in Appendix B3. As shown in the sketch, the solar shade material needs to prevent unwanted direct sunlight when the surface of the grow beds become too hot to host vegetable growth. It is imperative that we determine the ideal percentage of porosity that the shading material is required to possess. Shading material will be placed as a barrier between the sun and the polystyrene grow beds, where we can test to discover what shade material achieves a temperature most near the ideal range of surface temperatures (60°F-80°F) for these grow beds. Initial radiation and material properties are listed below.

The thermal analysis was conducted when the angle of the sun produces the maximum irradiation values. The latitude and longitude of Jane Furse, South Africa were selected to provide an accurate assessment for the angle of radiation impacting the solar shade and grow beds. The latitude and longitude were determined to be 24.7617° South and 29.8728° East. Various percent porosity of solar shades were utilized to decrease the intensity of the solar radiation and produce a variety of temperature results.

Our group expects the surface temperature to decrease on the grow beds as the solar shade percent porosity increases. With more coverage combatting the direct radiation during the day, we believe that there will be a decrease in temperature. Initial thermal hand calculations were conducted to determine the team's hypothesis (See Appendix B3 and B6). For this thermal analysis the main mode of failure is temperature level departing the permissible range because there is a possibility that the solar shade material will not have a great enough effect on the surface of the grow beds.

Three common commercial shading materials were simulated to see how they would affect the raft bed surface temperature. Appendix B7 shows an example of how these thermal tests were conducted and how temperature data on the styrofoam raft beds were read. *Table 13* shows the surface temperature results of the four trials conducted.

Table 14: Percent solar shade porosity tested compared to the grow bed surface temperature.

Percent Solar Shade Porosity	Surface Temperature [Fahrenheit]
0%	95
15%	87
50%	74.2
90%	68.7

Reviewing the thermal analysis, our team's hypothesis was correct. It was proven that by increasing the shading percent coverage, the styrofoam grow bed's surface temperature decreased as a result. It should be noted that the temperature of the entire bed will not be as constant as is shown in the CAD simulations (see Appendix B7) due to solar positioning changes throughout the day as well as the vegetables providing some shade to the bed. It can be concluded that a shading material of 50% porosity and higher can be used for our raft grow bed. Since styrofoam is the most widely used grow bed media for hydroponics, we do not believe that we need to test other materials but rather focus on how to provide the ideal growing environments for vegetables that will use this material. To visualize the temperature and shading percentage relationship *Figure 17* was created as an aggregate of all temperatures and their specific shading conditions. From the figure it is apparent that after tht 50% shading value is reached, the slope of the temperatures is less steep.

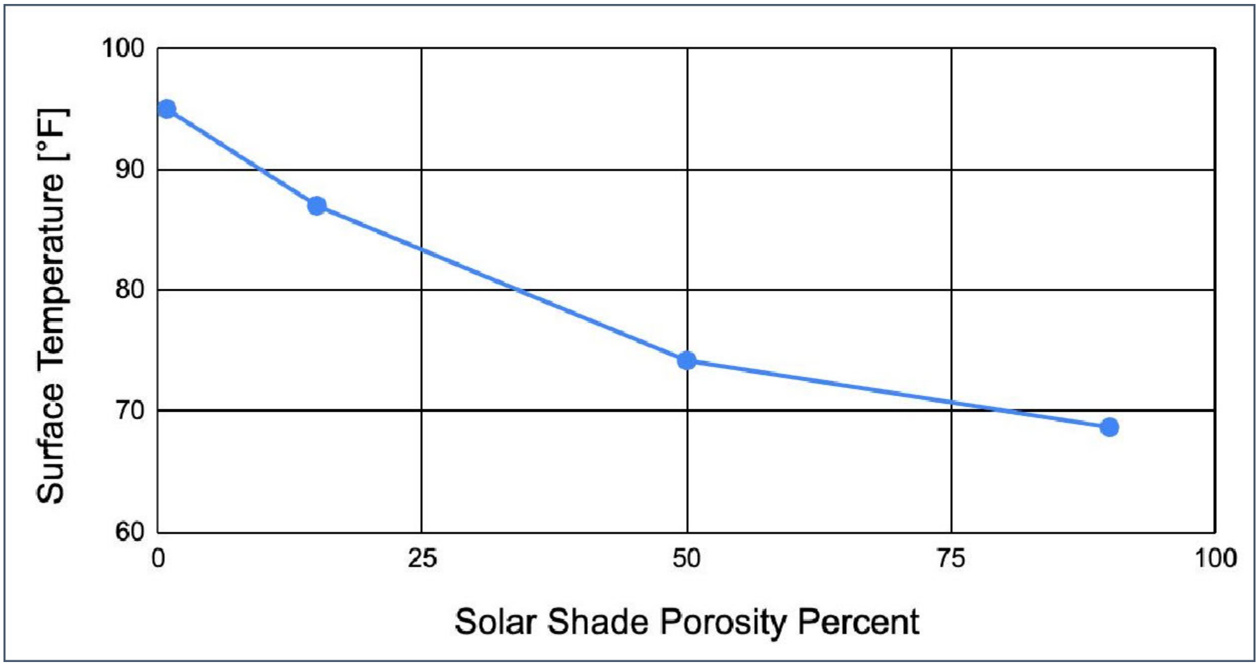

Figure 17: Non-linear relationship between shading percentage and temperature.

The thermal analysis has imperfections because the complexity of a heat transfer process cannot be adequately packaged into an environmental thermal model. The model corroborated that increasing the radiation control of the solar shade decreases the temperature observed on the grow bed. The exact values obtained from the model are not guaranteed as exact and should be confirmed in physical tests. Unknown factors including other sources of radiation (reflections or heating elements), increases in convective coefficient due to wind, precipitation and relative humidity are not constant and a model cannot entirely account for all factors. The physical testing will provide us the information to ultimately determine the correct percentage of radiation control for the solar shade.

The thermal analysis provided information that directly aligned with our hypothesis - greater shading percentage in the material correlates to a lower temperature in the grow beds. The resulting temperatures on the surface of the grow beds were not conclusive however. The thermal model cannot properly account for the convective losses, sources of irradiation aside from the sun, and did not consider the latent heat associated with the relative humidity of the climate. The factors outside of the scope of the thermal model limited the effectiveness of the model and encouraged our group to perform extensive physical testing with a prototype to determine the actual temperatures at the surface of the grow beds. The testing can be performed with a thermocouple and shading materials with different shading percentages.

3.3 Plumbing

The intention of the plumbing orientation was to minimize the sizing requirements for the pump so that a smaller, less expensive pump could function successfully. The plumbing was entirely constructed using PVC pipe and requires a very low head height so that a relatively small pump can effectively circulate a large volume of water. Leaks were largely prevented through the use of special interface fittings such as bulkheads and uniseals.

3.3.1 Pump Selection

The Forge Garden system only circulates about half of the volume of water as the system designed for South Africa, so two pumps needed to be selected. In order for us to minimize energy usage, we needed to calculate the best pump to use for each system. It is neither good for our energy usage nor for our hardware to use a pump which is unnecessarily large or small for the kind of flow rate needed to sustain the system.

Head loss was calculated taking into account the relative roughness of each material in use as well as the equivalent straight piping lengths for the fixtures in the system which alter the direction of flow (see example calculation spreadsheet in Appendix C1).

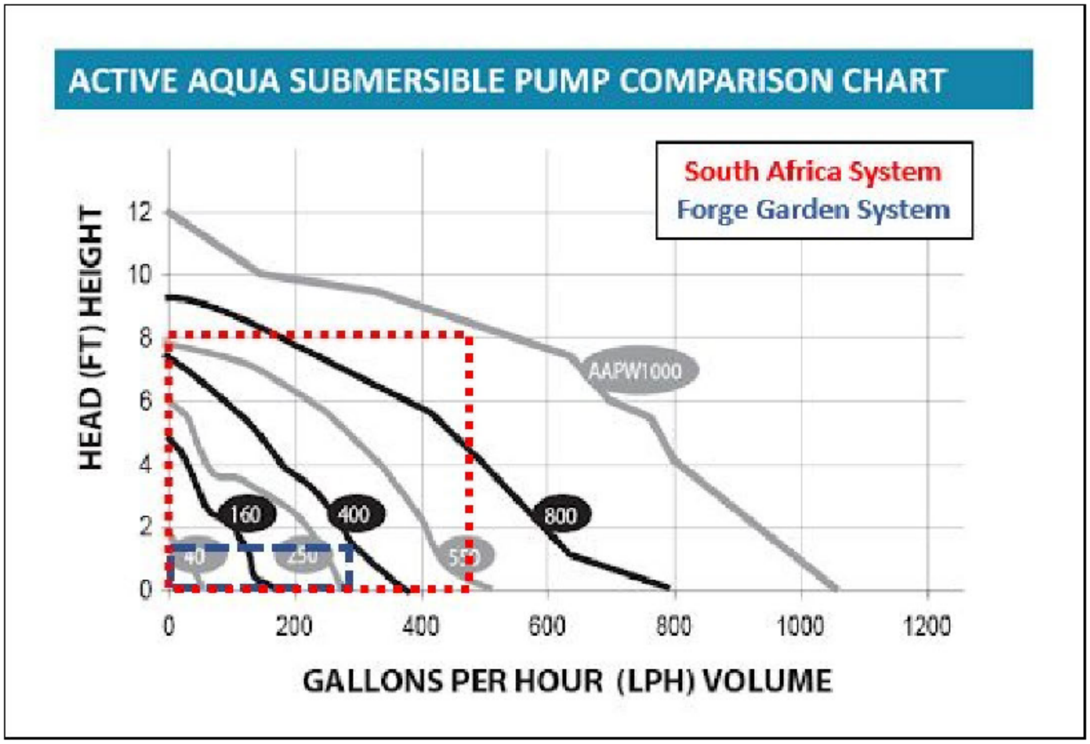

Figure 18: Pump curves for each of the Active Aqua submersible pumps ideal for hydroponics, with both systems flow requirements. [20]

Taking into account the volume of water in each system, the flow rate necessary to deliver nutrients to the plants and prevent mosquito breeding, and the head loss due to system components, we found the best pump sizes to be a 400 gph pump for the Forge system in Santa Clara and a 1000 gph pump for the much larger system in South Africa.

Table 15: Volume and volumetric flow rate requirements and corresponding head loss for each system.

	South Africa System	Forge System
Water Volume (gal)	485	278
Flow Rate (gpm)	8	5
Total Head Loss (ft)	8	2

We also needed to prevent leakage as much as possible, both to make sure that the plants are getting the nutrients they need and also to prevent unnecessary water waste. Additionally, we wanted to minimize loss of pressure, lack of adjustability, and difficult maintenance. We experimented with several different kinds of seals including liquid silicon, trimmed gaskets, and epoxy, before settling on using Bulkheads for flat, rigid surfaces and uniseals for all other surfaces. Both are relatively easy to install and maintain, and both can easily withstand the pressures present in our system. Uniseals are also very affordable, so in the event that any of the seals wear out, they can be easily removed and replaced at minimal cost.

We considered using two pumps in the system, because this would allow more freedom with flow rate adjustment and plumbing requirements, so we considered how this would affect the overall costs of the system, shown below in *Figure 19*.

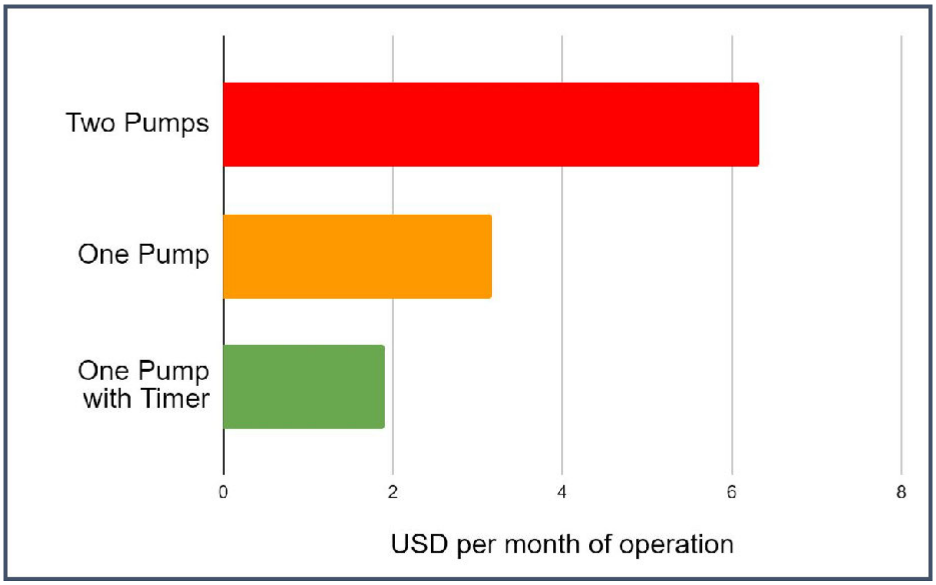

Figure 19: Pump cost comparison for different pump system setups.

Using a single pump for the system essentially cuts monthly operation costs in half for system circulation. Additionally, it makes maintaining the system easier since there is only one pump to maintain. By adjusting our design so the majority of the system operates using gravity, this was easily attainable. Additionally, by adding a timer, we also reduced the costs and the energy needed for the system. The timer cycles the system enough to keep the water moving at the necessary rate without wasting energy and potentially flooding the system. Should the timer or the pump need to be shut off for any reason, ball valves are placed in the system such that the grow beds can be isolated from the reservoir.

3.4 Greywater Filter

One of the main goals of the project was to conserve water when compared to traditional soil farming. We identified an opportunity to use LEAP's existing greywater catchment system as our water supply for the hydroponics garden. In general, greywater refers to any wastewater that does not contain fecal matter. In LEAP's case, they captured water from a dishwashing sink that is routed underground to irrigate a lawn on campus.

The scope of the greywater filter is to supplement the water lost due to evaporation and/or leakage. Our team estimated this quantity of water to be about half of the total volume per month (1000 L). Based on LEAP 5's observed water production conducted by the project team's contacts, the surge for washing dishes in the kitchen was around 200 L/day. Assuming that this surge would come essentially in one load as the students washed their dishes after lunch, the capacity of the surge tank was set to handle 300 L. Since each round of dishwashing will not be needed to top off the hydroponics garden, a tee-branch is fitted to redirect greywater to water the existing lawn if the hydroponics system does not need to be topped off.

3.4.1 Greywater Filter Design Alternatives Analysis

The project team considered a number of different low cost and low maintenance filters. The following alternatives were evaluated for use in this project and compared to each other for suitability in this project.

3.4.1.1 Alternative 1: EcoSense Worm Filter

The EcoSense Worm Filter is designed for greywater filtration by removing organic particles and grease, prior to final dispersal. It is a purchased product that would then be filled with local materials. The main structure is a HDPE potable water tank sourced conventionally from marine suppliers. There is a system of three screens that separates a worm filled mulch basin and an outlet reservoir.

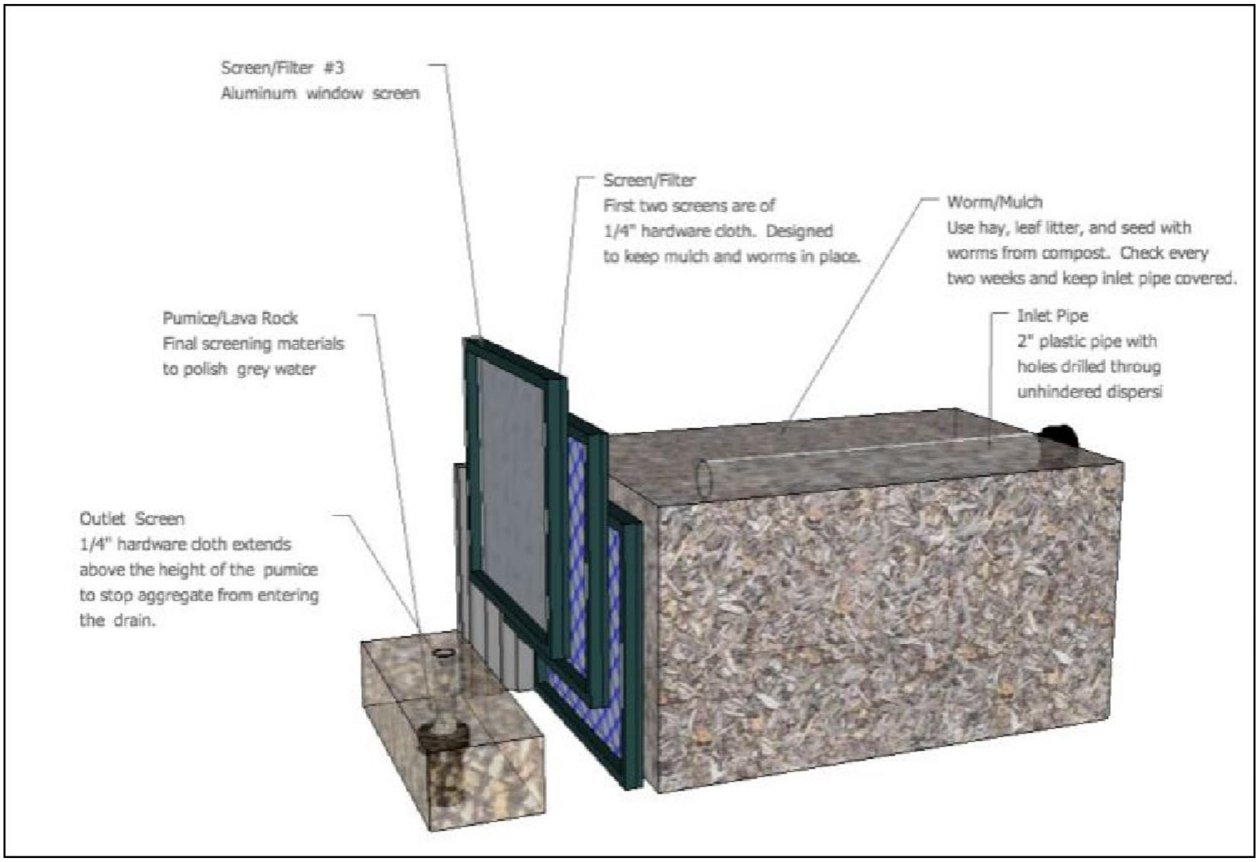

Figure 20: The EcoSense Worm Biofilter comprises a worm/mulch basin where influent is captured, a system of three screens for separation and filtration, and an outlet reservoir. The three screens are made out of ¼" hardware cloth [21].

Advantages of this system would be its storage underground and effectively proven filtration of the greywater. A handful of disadvantages also come with using this system including pumping effluent to the surface, not using local materials, and frequent maintenance on the three screens.

3.4.1.2 Alternative 2: Bioretention Filter

The second alternative evaluated is a common method for reducing the amount of pollutants in stormwater. A bioretention filter is composed of layers of permeable media such as sand, gravel, soil, or peat. Stormwater (or in this case greywater) would be filtered through a layer of native plants, mulch (to capture oils and grease), soil, and sand. The percolated water would feed into an outlet pipe at the bottom of the filter. *Figure 21* details the entire process.

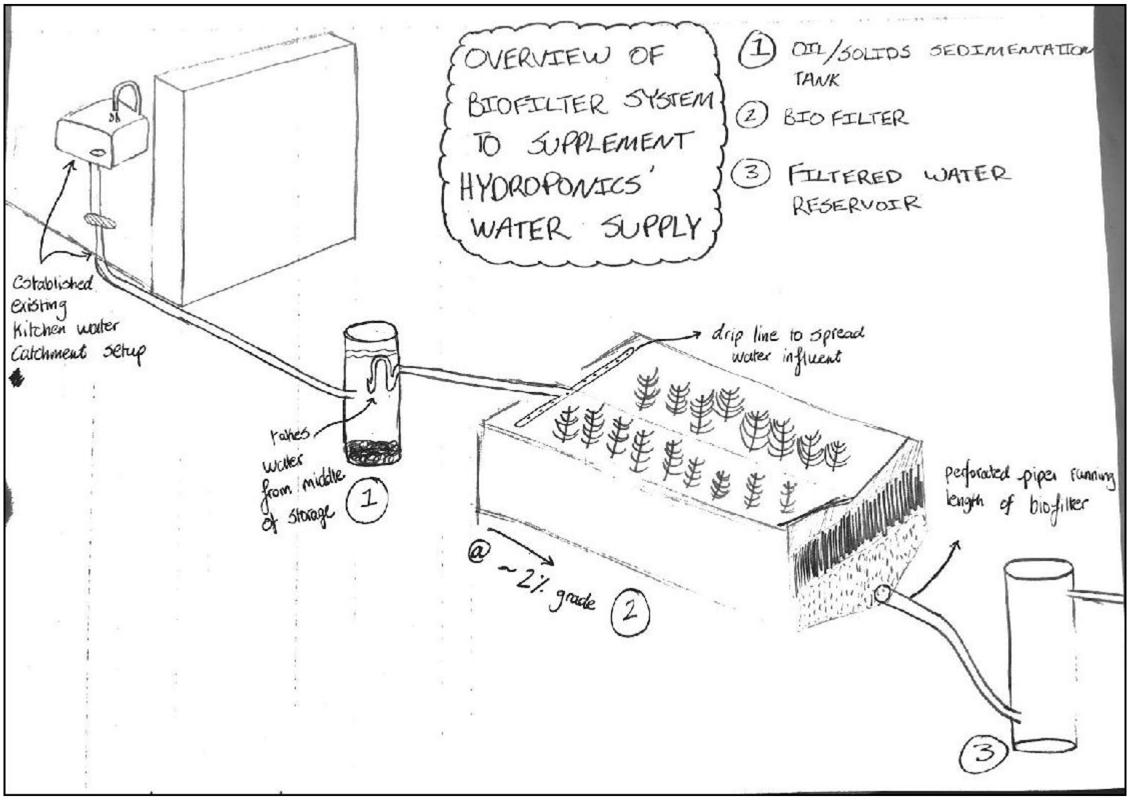

Figure 21: Displays the sink to the filtered path of the proposed bioretention filter for LEAP 5. The surge tank (number 1) would also act as the sedimentation tank separating solids from grease and taking fresher water out of the middle of storage. A bioretentio

Advantages of this system are its use of local materials - the piping would be reused as well as large reservoir tanks. Disadvantages include a buried perforated pipe in the bioretention filter that could be difficult to access. Further detail for the Bioretention filter design can be found in Appendix F.

3.4.1.3 Alternative 3: Mulched Surge Tank with Constructed Wetland

Constructed wetlands are a proven filtration method for greywater and use locally produced and reused materials effectively. An old bathtub would act as the container for the wetland with pipes and reservoirs also being repurposed. A mulched surge tank would provide for the initial filtration of grease and oils coming directly from the kitchen sink. A rhizome network (root system) of native aquatic plants is used in this filter to remove harmful bacteria and nutrients from entering the hydroponics system. *Figure 22* details the process further.

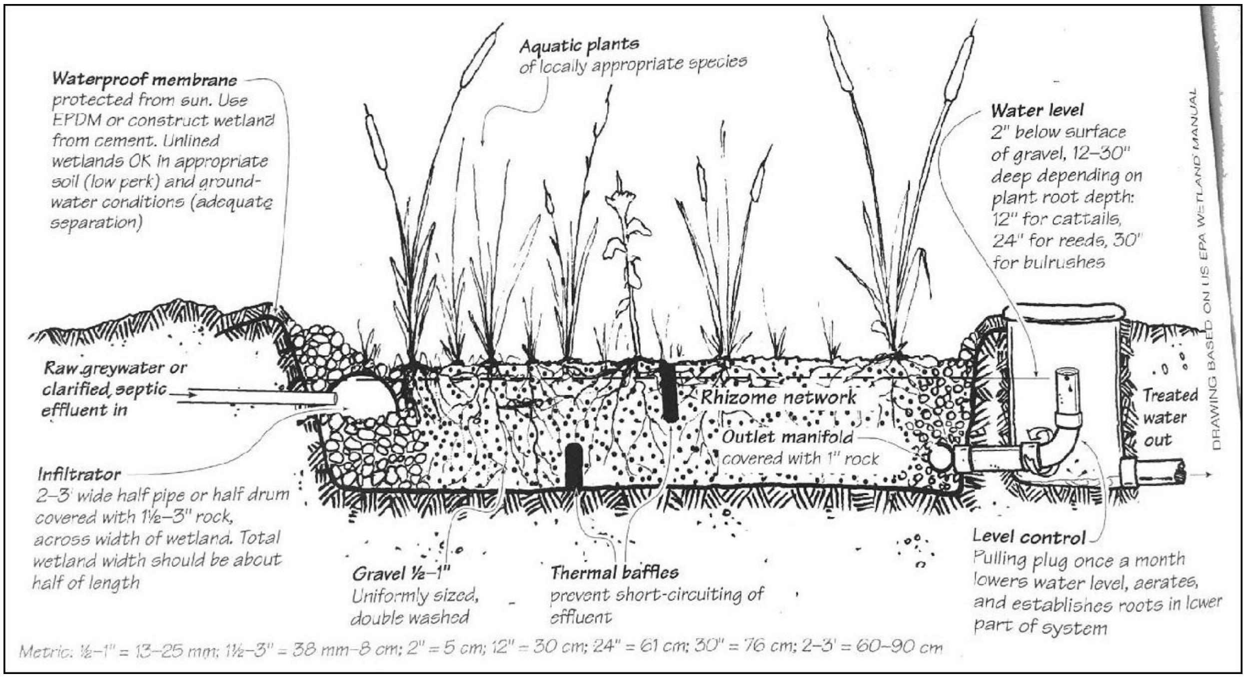

Figure 22: Displays the functions of a constructed wetland. Influent to the system is distributed into a bed of gravel that then flows into the root system of the aquatic plants. An outlet pipe is situated 2" below the surface of a mulch bed in a catchment reservoir for future use. The mulched surface is key as it will limit smell and access to the greywater beneath [22].

The biggest advantages of this system are the use of recycled materials and the overall simplicity of the system. Maintenance is low except for lowering the water level once a month. Disadvantages include the unknown energy costs associated with transporting the filtered water from reservoir to nutrient tank in the hydroponics system. Further visual details of the Constructed Wetland Greywater Filter can be found in Appendix F.

3.4.1.4 Selection of Best Alternative

Based on the constraints and criteria outlined for the project, a weighted matrix was produced to judge each alternative against the other. A weight was given to the constraints and criteria (1-10, with 10 being the best) based on their importance to the project's goals and objectives. After this was determined, each alternative was ranked in performance for each constraint and criteria. The final score was calculated by multiplying the weight and performance for each alternative.

Table 16: Performance of alternative greywater filters based on established criteria.

		Rating (1-5)			***Score = Weight x Rating***		
Criteria	***Weights (1-10)***	*EcoSense Worm Filter*	*Bioretention Filter*	*Mulched Constructed Wetland*	*EcoSense Worm Filter*	*Bioretention Filter*	*Mulched Constructed Wetland*
Simplified	*7*	*3*	*4*	*5*	*21*	*28*	*35*
Low Maintenance	*8*	*2*	*4*	*4*	*16*	*32*	*32*
Safety of Greywater Storage	*9*	*4*	*3*	*4*	*36*	*27*	*36*
Uses Recycled Materials	*6*	*1*	*4*	*4*	*6*	*24*	*24*
Minimal Adaptation to Existing System	*4*	*2*	*3*	*3*	*8*	*12*	*12*
Minimize Energy Consumption	*3*	*3*	*5*	*4*	*9*	*15*	*12*
Durability/ Resilience to Surrounding Environment	*5*	*4*	*4*	*5*	*20*	*20*	*25*
Easy Access for Maintenance	*2*	*3*	*2*	*4*	*6*	*4*	*8*
			TOTAL SCORE:		***122***	***162***	***184***

According to the matrix, a Mulched Constructed Wetland scored the highest. This design was further manipulated in order for it to be a part of our Preliminary Design in the following section.

3.4.2 Greywater Filter Final Design

Initially, a constructed wetland and bioretention filter were tested to determine their effectiveness. The vertical bioretention's slow infiltration rate was not ideal; and, the constructed wetland would remove nitrates and nitrites from the water which could be a source of nutrients for the growing vegetables. By suspending the greywater in just mulch for at least an hour, the undesired soaps and oils present would be soaked up allowing cleaner water to pass through. The filter uses a repurposed bathtub and impermeable baffles to promote water circulation and maximum surface contact with coarse mulch. A mesh sediment strainer at the end of the filter catches fine mulch particles that exit with the effluent. The final design is shown in *Figure 23*.

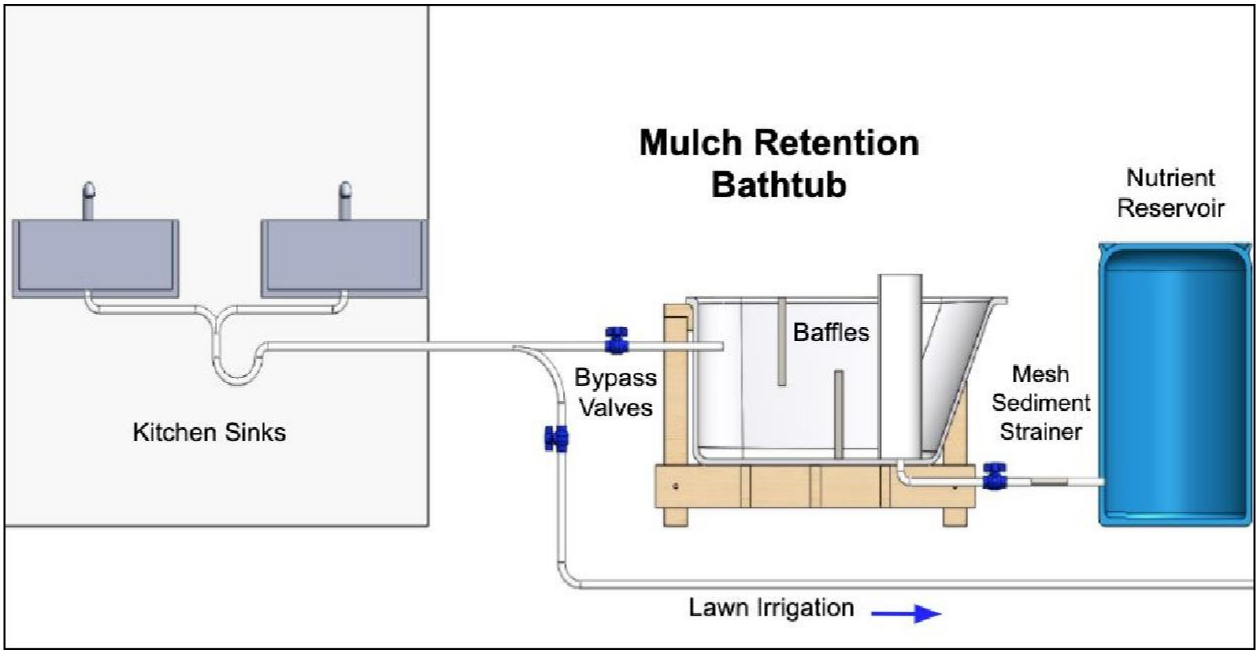

Figure 23: Greywater filter orientation at LEAP 5.

3.5 Controls and Data Logging

The self-monitoring controls system served as a feature of the educational curriculum, to aid in real-time data collection. The main control/data logging system involved a temperature sensor probe on the surface of the grow beds connected to the Blynk app, a digital dashboard where iOS and Android phones can control an Arduino with a graphic interface. To determine what the temperature threshold is for scorching of the plants and to also inform the students what the temperature of the raft beds is at any given time, our team decided to use a digital, waterproof temperature sensor which is attached to the surface of the raft beds at all times. This sensor is connected to a Node MCU wifi chip which broadcasts the temperature reading over wifi. This chip uses Arduino code, so we wrote a program to read the sensor data and send it over wifi to the Blynk app IoT platform. This code, shown in Appendix D1, takes readings in both Fahrenheit and Celcius every second. Using the Blynk app development tools, We created a user interface which displays the numerical values for the reading as well as a live histogram for up to a month of data.

However, to be able to analyze the data, the students need to be able to manipulate the graphs and add labels to critical values. We set it up so the students can export the raw data in the form of a csv file to a template excel spreadsheet which automatically adjusts the axes to appropriate ranges and adds callouts for the maximum and minimum temperatures experienced by the plants (see Appendix D2). The students will create these graphs on a weekly basis, and they will then be able to see trends in the data which might affect the crop health.

This interface was tested effectively using a temperature probe, and pH and electrical conductivity (EC) probes will be added to fully survey the system. By including a data collection system, the students would be able to develop their own experiments using the system and analyze data to confirm hypotheses.

4. Results

The early completion of a fully functioning hydroponics system provided our team with one harvest of approximately 40 heads of lettuce. The results were mixed due to limited accessibility to the Forge Garden, yet the romaine and butterhead lettuce fared excellently in the spring conditions.

Figure 24: 50-day growth of butterhead (left) and tri-color romaine lettuce (right).

The success of the lettuce verified that a raft grow bed is capable of supporting a plant density of four plants per square foot with no significant nutrient deficiencies. The beds featured an approximately 80% survival rate with no pesticides and only a single large liquid nutrient addition at the beginning of the life cycle. The liquid nutrients used were entirely organic and sourced from plant extracts. The macronutrients had a balanced NPK and no micronutrients were added. An additional arugula raft was planted but all crops bolted likely due to a specific lack of nutrients. The two types of lettuce fared very well and grew rapidly despite the low macronutrient levels and the lack of micronutrients.

Significant plant growth was observed in the wicking bed. Eight tomato plants were planted in the wicking bed and after 60 days all plants have survived and expanded rapidly. Metal cages were added to the wicking bed so that the rapidly growing tomato plants would have additional structure to support their stems and stalks when the plant begins to produce tomatoes.

Figure 25: Significant tomato growth in the wicking bed (foreground) and leafy greens in raft bed (background).

4.1 Filtered Greywater Quality

One of the main goals of this project was to conserve freshwater. Instead of utilizing the already limited freshwater source in the Limpopo region of South Africa, our team was determined to solely utilize kitchen greywater to fill our grow beds. A final design of the Mulch-Retention Filter for the greywater was constructed and tested for water quality using a kitchen sink greywater in Santa Clara shown in *Figure 26*. The test determined how effective the filter was to lower the nitrate, nitrite, total hardness, total alkalinity and pH levels of the greywater to prove if it was safe to use in the hydroponics system.

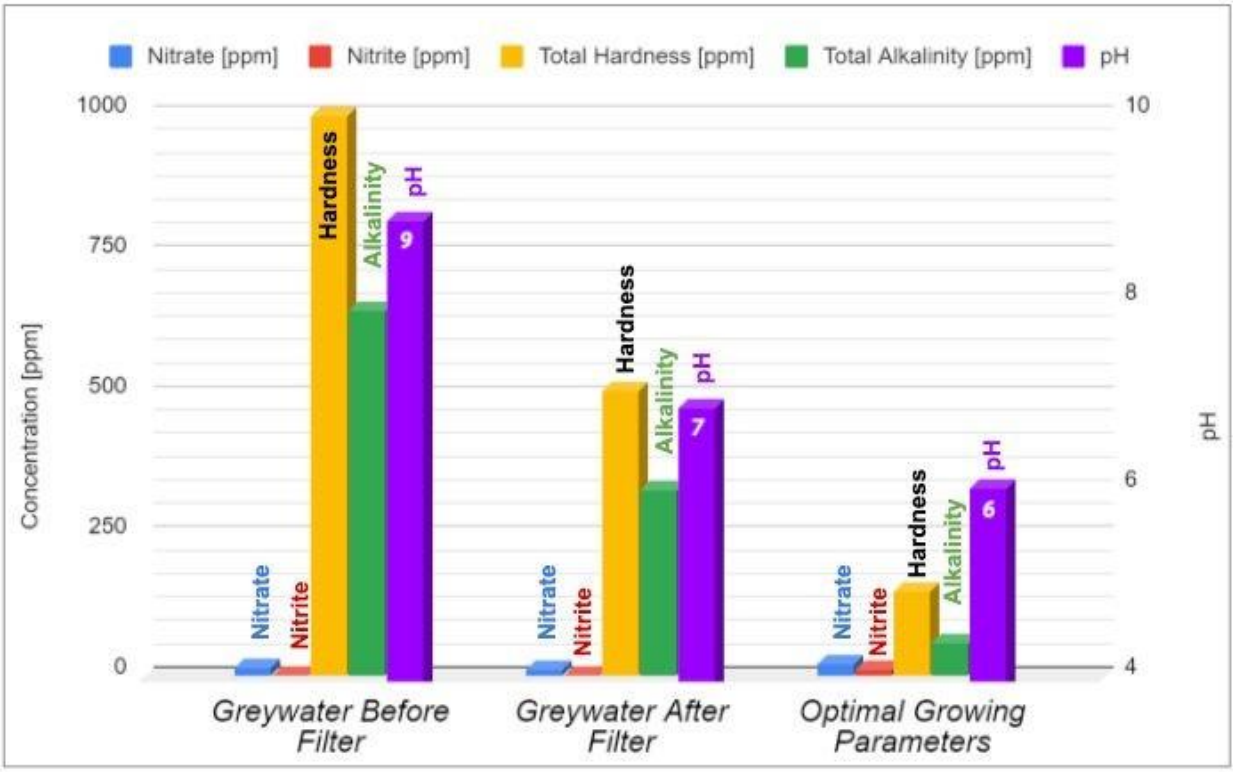

Figure 26: Measured water quality difference between kitchen sink greywater and after it has passed through the Mulch Retention Filter compared to optimal vegetable growing parameters. Parameters tested include nitrates, nitrites, total hardness, total alkalinity, and pH.

Figure 26 shows that the mulch greywater filter decreased total hardness by 50%, total alkalinity by 20%, and pH by 2. The project team anticipates that the pumped groundwater in Jane Furse will differ from that in Santa Clara, especially with respect to total hardness and alkalinity. Nitrates will be added to the system from an outside nutrient solution introduced to the system. Through this filter testing, our team was able to determine that we would be able to successfully deploy a hydroponic system that is directly fed by greywater instead of utilizing vital freshwater that can be rather used for human consumption. This outcome proved to be a positive environmental impact that would ultimately alleviate the already strained freshwater supply in the region.

5. Sustainability Analysis

The conservation of clean drinking water was a major focus in the design of the hydroponics garden. Low water usage was made possible through efficient grow beds and a greywater filter to incorporate existing greywater of unknown quality. Energy usage was additionally decreased due optimal pump sizing and the timer which regulates the uptime of the water pump.

5.1 Water Savings

Using our data from the prototypes first lettuce harvest, a water savings analysis was conducted to determine the system's usage compared to a raised bed soil garden. The baseline soil garden assumed the same grow area as the hydroponics garden with a 4 inch depth of irrigation every 4 days. The hydroponics garden is assumed to have replaced ½ the total volume of water each month. With these assumptions in mind, an annual projection of expected produce yields and the gallons of water used per pound were calculated. Results are shown in *Table 17*.

Table 17: Water savings and annual yield comparison between the hydroponics design and a soil garden baseline with the same grow area.

Type of System	***Annual Yield [$]***	***Water Usage per Lb. [gallon/lb.]***
Hydroponics Garden	$1,068.62	3.90
Baseline Soil Garden	$431.05	8.25

The hydroponics garden tested in Santa Clara's Forge Garden used less than half of the water and produced over two times the yield when compared to a baseline soil garden. Results were gathered from the prototypes first romaine lettuce harvest and compared to a Cornell University study's soil production [23].

5.2 Energy Savings

The design and development of a greywater hydroponics system mitigates many negative impacts of conventional agriculture, including the inefficient use of water, large land requirements, dependence on concentrated and toxic pesticides, and soil degradation through erosion.

5.2.1 Assumptions Related to the Use of Our Project and the Scope of Influence.

Several factors were assumed in the construction of the hydroponics system. Most factors were centered around the durability and sustainability of the project. Focus was placed on energy and water savings as well as utilization of commonly available resources. Assumptions are as follows:

- Significantly reduced water usage compared to traditional farming
- Electricity costs that are outweighed by the freshwater water savings and increased crop yield.
- The materials utilized to construct the system are reused as much as possible and are otherwise sustainable in their production.
- Our system will be more environmentally friendly since it is designed to fit the school's needs rather than retrofitting an existing commercial system for the necessary production size.

5.2.2 Materials Environmental Analysis

Using readily available materials at the school in South Africa as well as a mixture of both plastic and wood, the energy use for our system is significantly lower than that of a commercial system made entirely of plastic and metal shown in *Figure 27*. Additionally, the flow design of our system requires only one pump to operate whereas the commercial system needed eight, one for each of the grow beds. Compared to completely packaged, commercial systems our hydroponics product is much less expensive per square foot of grow space and does not rely on entirely new materials. The materials used in constructing our design can be repurposed from past projects and sourced locally. Commercial products on the market do not have this advantage and also must require shipping which amounts to transportation costs and significant emissions. Purchasing a commercial system does provide nearly as much ownership of the system either and if a piece breaks it likely must be replaced using spare parts sold by the company, which will amount to further transportation costs and emissions.

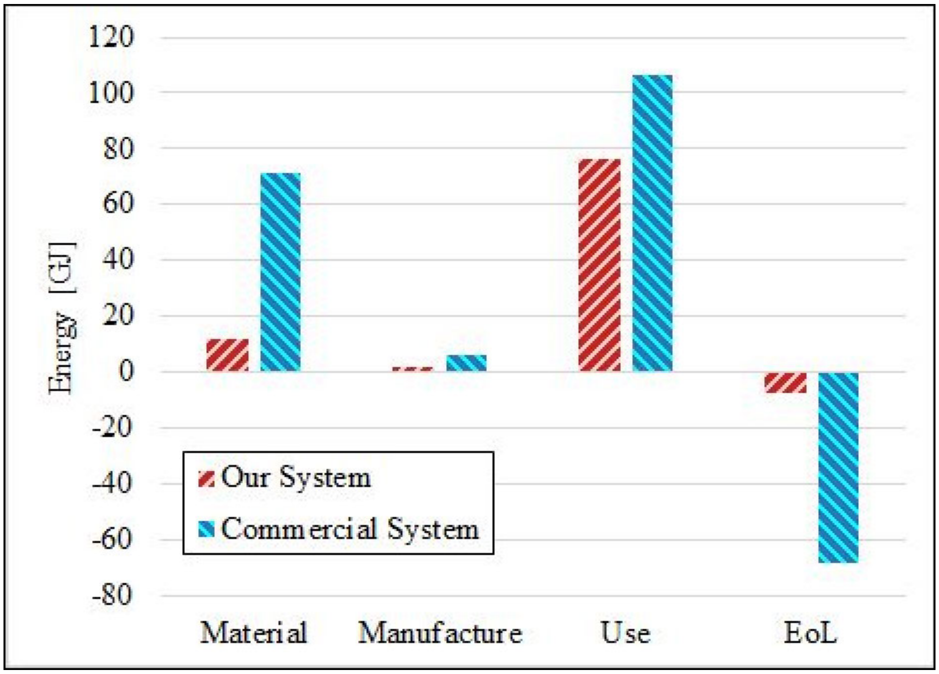

Figure 27: Graphical representation of the energy use of the South African system compared to the energy use of a Commercial Setup, retrofitted to produce the same grow space as the project system over the course of a 1- year use time. Energy use in categories of energy from materials used, manufacturing processes, the use life of the product, and the End of Life (EoL) potential are compared in the figure above. Graph made using the CES EduPack Eco Audit program [24]

By discovering new ways that greywater can be used, our team was able successfully provide an agricultural system that does not require freshwater intake. Instead, this freshwater can be used by both students and faculty for drinking in a region that is greatly affected by climate change and limited access to clean water. Ultimately, our system conserves the use of freshwater by only needing greywater to grow our crops. The economic analysis conducted helped us come to the conclusion that our system utilizes close to 4 times less water per pound of produce with a shorter payback period compared to traditional soil based farming. The reduction of fresh water usage due to the greywater system is also accompanied by a reduction in the energy used to manufacture the system in the first place. By reducing the amount of plastic used in the system and by combining the raft bed and media bed reservoirs, we created a more energy-efficient system than what is currently commercially available.

6. Business Plan

The adaptive hydroponics garden product was created to primarily service local farmers with a limited budget and minimal access to drinking water. The primary stakeholders related to the product benefit from the creative, durable, and adaptable design. The hydroponics product is non-profit and attempts to diminish the barriers so that small, non-technical farmers may utilize the benefits of hydroponics farming.

6.1 Business Plan Executive Summary

Regions with limited access to freshwater and agricultural households with limited access to many acres of land are the targeted market for hydroponics. The potential for high density growth regardless of soil quality is extremely appealing to regions where bountiful harvests may be impossible due to geographic or weather factors. The low price point and highly customizable nature of the systems give the hydroponics farmer the freedom to build and expand what works and move away from what does not. The most significant limiting factor to the hydroponics market is the initial price point. Driving the price down through the use of local and recycled or repurposed goods assists the designed hydroponics system in overcoming the hurdles that have stifled the growth of the industry. The simple design as displayed in the assembly manuals additionally reduces the perceived complexity and improves the durability of the product, granting a reliable sense of ownership to the buyer.

6.2 Perceived Markets

The prime market for the hydroponics product are agricultural households who depend on a stable production of crops to feed their family or sell to generate income. The greater markets are very broad and applicable to the suburban gardener interested in an alternative method, an urban gardener who wants to make good use of their limited growing space in a sustainable manner, or the industrial farm interested in scaling up production without the need for additional harmful chemicals added to the topsoil. The large-scale industrial application is especially beneficial to facilities which have an excess of greywater. The filtration system in series with the hydroponics grow beds provides unmatched energy and water savings. Profits associated with the density and rapid production advantages of hydroponics over traditional methods are scalable, so expansive farms have the potential to generate significantly more revenue. In the financial studies conducted using our product, the density of hydroponics is four times greater than that of traditional soil farming. The expanded yield compounds with the 60% faster growth rates seen in our hydroponics garden compared to soil farming.

The most significant advantages our product displays is due to the collaboration with local farmers who will be the primary stakeholders in the product. The needs expressed by the primarily low-income agricultural community were centered around durability of the system, a wide range of crops supported, and high yield. These needs were referenced constantly and developed through dialogue between the stakeholders and the designers of the farming system. The critical local input and high level of adaptability makes the product very attractive compared to existing products on the market. Nearly all existing products are very discrete in the materials and the method of construction required to produce the hydroponic system which leaves little room for local specification. The existing markets feature primarily self-contained systems which have significantly higher expenses per yield. The product designed by our team is extremely affordable if the overall yield is compared to the initial costs and the local farmer will regain their investment after just a year and a half of steady production.

6.3 Business Objectives

The goal of our product is to provide information about hydroponics so that farmers in targeted areas may choose to employ hydroponics and improve their agricultural situation while decreasing their fresh water needs. The objective of the product is to disperse catered information about the benefits of hydroponics through the success of the physical system. The hydroponics system is an effective tool for the small or large scale agriculture to insulate themselves from the mounting water scarcity and insecurity in primarily impoverished regions threatened by the effects of climate change. The primary objective is supported through the significantly lower price point, without compromising quality or production. A lower cost of entry helps dissolve the barriers preventing widespread access to hydroponics systems especially in impoverished regions. Water is transported from a nondescript 50 gallon barrel, which could be substituted if an existing hard-walled, plastic water container is already available, to two unique grow beds. Each grow bed is capable of growing plants up to four times as densely as traditional farming because of the availability of nutrients in the steady-stream of water. A shading system, either automated or manual, provides climate control for the grow beds and a greywater filter constructed from commonly available materials conditions kitchen wastewater so that it can be inputted into the grow beds water supply. Our product details specifically how to construct the modular grow beds, shading system, and greywater filter.

The sustainability of the product is augmented by the non-physical nature of the system. The designed hydroponics system is not reliant on specific materials, rather it is scaffolding with which to create a customized hydroponics system specific to the environment of the customer. The primary product is information which will lead to successful plant yields, greater than yields that could be accomplished using traditional soil farming. The provided assembly manuals are reflective of our successful experimentation with hydroponics, but the geometries, materials, and sizes of all subsystems are open-ended so that the customer has some creative license given their specific environment.

6.4 Manufacturing

The hydroponics garden system is reliant on local manufacturability. When designing the project, significant emphasis was placed on rapid manufacturability because the construction window of the flagship system at the LEAP 5 High School in South Africa was only five days. Manufacturability of the system is a potential bottleneck we identified about our eventual construction in South Africa. The bottleneck was investigated and remedied through the construction of a half-scale prototype at Santa Clara University's Forge Garden. Each subsystem was constructed from start to finish and then verified with a successful crop harvest. Building each component of the system provided a clear picture of the manufacturing duration each component required.

One focus of the designed system is the utilization of recycled or repurposed materials We targeted repurposed materials to build the infrastructure of our system because these materials are often significantly less expensive, they do not require transportation because they are already available, and they promote a sense of ownership for the customer. The LEAP 5 High School explained they could provide us with old bathtubs, excess irrigation piping, mulch, gravel, and soil. We planned to source timber, hardware, and power tools from a local supply store less than a kilometer from the school's campus. Manufacturing occurs on the side of the customer so as sales expand, greater expenses are not required to support growth. To reach greater markets, more system options could be prototyped and documented so that regions with environments different from arid, warm South Africa could be specified.

6.4.1 Assembly Manuals

To promote straightforward construction of our team's subsystems we have created step-by-step assembly manuals. Each subsystem is taken from raw materials to finished product in 10 steps or less through clear visual guides. The images and steps are extremely clear requiring no words and can be easily interpreted regardless of educational background. Every subsystem had the requirement that it must be constructed rapidly in the rural High School in South Africa. Through the use of simple geometries and only locally sourced materials we emphasized the need for manufacturability in our design. We believe these manuals are critical to the LEAP 5 community and any others who choose to make their own successful systems. On the left is the original storyboard of our raft bed manual. On the right you can see the finished product.

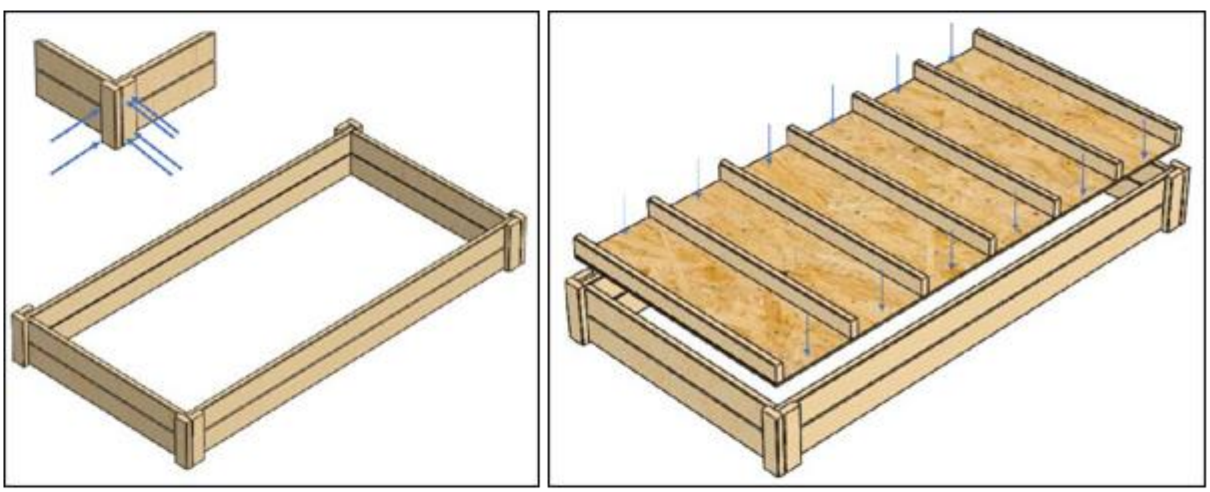

Figure 28: Construction sequencing of the raft bed frame included in the manual to be sent to: Construction sequencing of the raft bed frame included in the manual to be sent to students and teachers at LEAP 5.

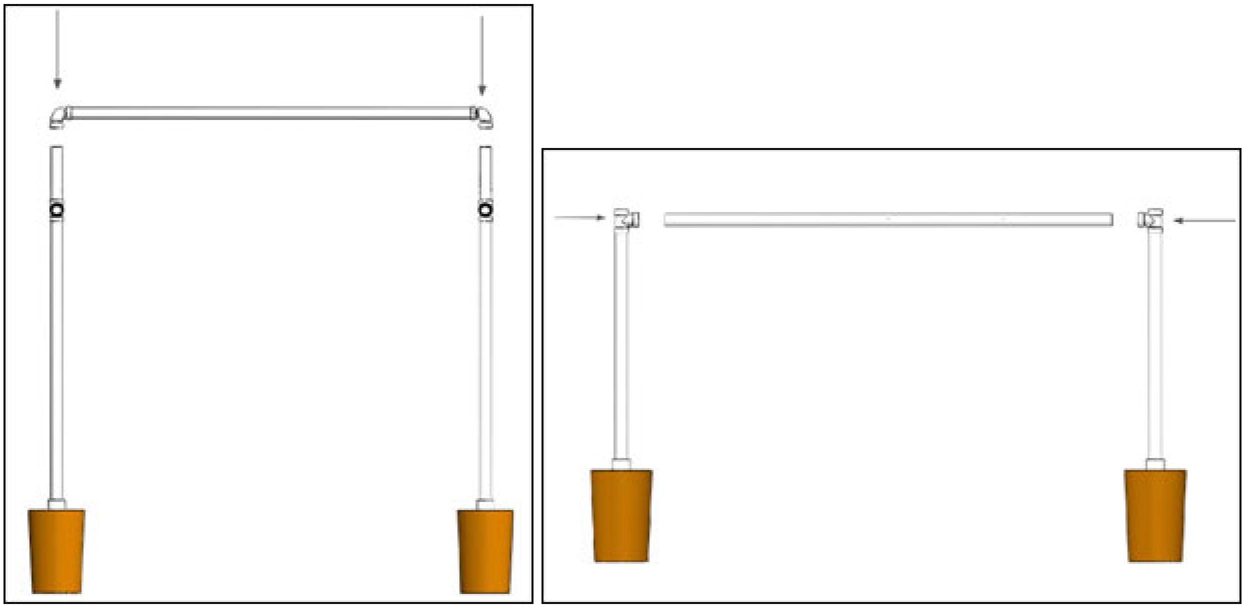

Figure 29: Construction sequencing of the shading structure included in the manual to be sent to students and teachers at LEAP 5.

6.5 System Pricing

The intended use of the system for LEAP 5 is as an educational tool for the students and teachers to learn about alternative farming methods that use less water than traditional soil farming. We are considering this a non-profit business model, but capital and annual operations and maintenance costs are projected as if the system was being used for profit. The value of the produce is assumed to be comparable to the benefit of education. The complete capital costs of the system in South Africa are shown in *Figure 30*.

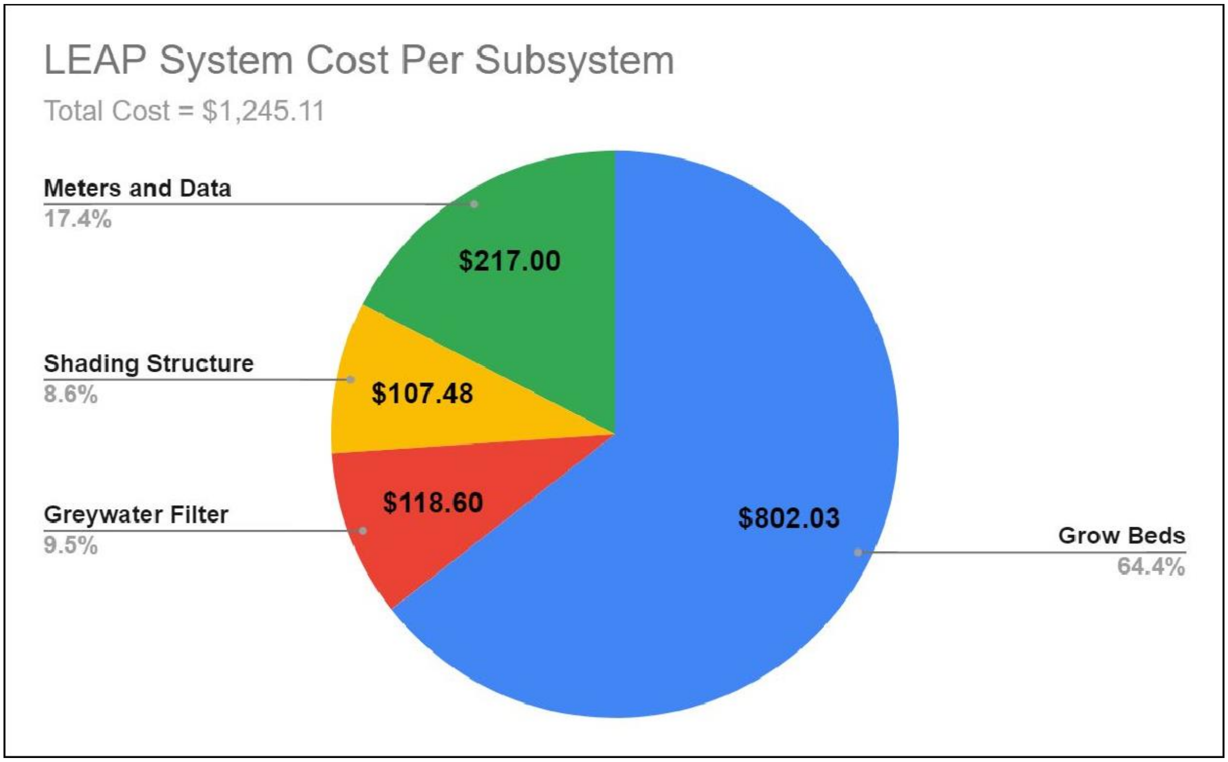

Figure 30: The total capital costs broken down per each subsystem.

Operations and maintenance (O&M) include electric for the air and water pump and seedlings. This total is projected to be $127.18 annually. Assumptions involved in the O&M include not having to pay for nutrient solutions or water due to the sustainable options associated with our system design. Payment for the land to build the system was also left out due to the space already available at the LEAP 5 campus.

In terms of servicing for the system, the areas of the system that will need it the most are the greywater filter and the grow beds. With our system's plan to create a healthy habitat for vegetative growth, clogs and decomposition will occur. The infrastructure of the system theoretically should be straightforward and the replacement of pipes or valves are the only expected servicing that will need to occur. The representatives from LEAP informed us of a couple handymen that are employed to tend to the garden and any servicing around the campus. They will be our target for bigger fixes of the system, while smaller upkeep items will be conducted by the students.

6.6 Financial Plan (ROI)

To investigate the sustainability and affordability of the system for rural South Africa, an economic analysis was performed to compare the LEAP 5 hydroponics garden design with traditional raised-bed agriculture. Even though the intended use of the final system is for educational opportunities and not for profit, this economic analysis is able to clearly compare the benefits of hydroponics to traditional soil farming.

Sustainable initiatives which decrease operations and maintenance costs (O&M) included with the hydroponics garden are the greywater filter and homemade compost nutrient solutions. Yield comparisons were documented using the same growth area and $1.25 as an average sale price of a head of lettuce. The results are shown in *Table 18*.

Table 18: Cost-benefit comparisons between the LEAP 5 hydroponics design and raised bed soil farming with the same grow area. The sustainable initiatives include constructing the Mulch Greywater Filter and using homemade fertilizer as a nutrient solution. As a result, the hydroponics garden employing sustainable initiatives had an 83 % return on investment and an annual profit of $1,245.21.

	Type of System			
	Raised Bed Garden - Baseline Model		***Hydroponics with Sustainable Initiatives***	
	Capital Costs	***Annual O&M***	***Capital Costs***	***Annual O&M***
Grow Beds	*$719.85*	*$240.53*	*$802.03*	*$127.18*
Shading System	*$173.00*		*$107.48*	
Data/Logging			*$217.00*	
Greywater Filter			*$118.60*	
Initial Start-Up Water			*$0.10*	
Total Cost	***$892.85***	***$240.53***	***$1,245.21***	***$127.18***
Annual Yield	***$431.05***		***$1,068.62***	
Return on Investment	***23.47%***		***83.17%***	
Payback Period (years)	***4.35***		***1.29***	

The Raised Bed baseline model had a 24% return on investment with a payback period of under 4.5 years. The LEAP 5 hydroponics design had a 83% return on investment with a payback period of under 1.5 years. Along with the added water savings per pound of produce, the hydroponics garden design is projected to yield $1,068.62 annually.

The main reason for a higher yield in the hydroponics system versus raised bed farming was the yield per square foot. The hydroponics system is able to produce four heads of lettuce compared to soil's one head per square foot.

6.7 Marketing

In order for a successful business plan, the marketing for this hydroponic project would be deliberately directed to specific audiences. Our team would market this product to two main types of clientele: Non-Government Organizations and Universities. There are countless numbers of Non-Government Organizations that provide humanitarian aid throughout the world. Some of these organizations focus on access to clean water as well as food security which fits perfectly with our team project. We would market our product to them for deployment in countries that are dealing with these issues. Additionally, our team envisions that our project can be marketed to universities across the country. We believe that many engineering institutions would want to provide innovative hands-on projects to encourage deeper learning for their student community. Overall, our team has decided that these two clienteles are essential to the business plan that we have set out in this section.

7. Ethical Analysis

The hydroponics system our team is completing is aimed at providing an educational tool for a rural high school in South Africa. The Limpopo region of South Africa which we are targeting is hugely impacted by the massive farms which dominate the province. The majority of households depend on some form of agriculture for financial support. As the global climate undergoes changes and weather patterns become increasingly strange and unseasonal, the farms are in jeopardy because of their weather-dependence. Offering a hydroponics system in this environment is very beneficial because hydroponics is not as weather dependent as traditional farming, and only calls for one-fifth the amount of water. Less water needs present in hydroponics also allows farms that were previously limited by water allocation, to expand and produce greater products and therefore revenue for them and their families. The tool we are supplying the school in South Africa with will hopefully enable the individuals who contact the system a learning outcome that they can then use for their own personal gain. Hydroponics is an expanding industry and rapidly becoming a major agricultural institution in urban areas because of its low water needs and efficient use of space.

The most critical outcome for our project is conveying the lessons we have learned when designing and manufacturing the project to the students who will possess and maintain the system at the high school. Communication is the heart of this outcome and will only be achieved if we form legitimate relationships with the students and present our materials in a clear and concise way. Emphasizing communications and the establishment of good working relationships is a fundamental soft skill that is very good practice in engineering. The skills our group will acquire from the communication and education emphasis in our project will lay the foundation for a career of good communication. An engineer could potentially design the best system of all time, but without proper communication, the design would be irrelevant. An important factor to consider when deploying and handing over ownership of the system is to consider the audience we are targeting. The students at the high school do not have much experience with engineering topics and cannot be assumed to have the capability of interpreting technical, engineering drawings. Additionally, concepts like fluid dynamics and pump cycles are also outside of their high school scope, so we must translate the information we have gathered into more digestible terms and bits.

Our project will be completely contained on the campus of the LEAP school, so in our case, the public at risk would be the students and school employees with access to the system. We will be teaching them about all aspects of the system during our time down there so they are aware of any risks from electric shocks and drowning due to the large amount of water in the raft beds. Both of the hazards associated with these risks are reasonably known to the community (electric shock from an outlet, drowning in local bodies of water, etc. The water risk is a minor-hazard since the water level is low enough for anyone of toddler age or older to stand in, so ethically the small magnitude of this risk means that merely making the public aware of its presence should be enough to mitigate the effects of the risk. As for the risk of shock, the public is informed of the presence of the electronics in the system. The ethics which we must consider is how to mitigate these risks by placing the electronic components in safe containers and in locations which are not dangerous (i.e,. don't have any live wires in the water of the system). Additionally, we must make the public aware of the locations of these components through signage. Doing so will ensure that the public is aware of the risks involved with our project and can reasonably avoid the associated hazards.

8. Future Considerations

Due to the COVID-19 pandemic, the project team was not able to travel to South Africa for the planned March 2020 implementation at LEAP 5 School. However, all instructional materials will be sent to LEAP 5, alongside do-it-yourself manuals detailing the system's structure, material selection, and construction sequencing. Incorporating students and the community in the construction of the hydroponics system is essential to the success and longevity of this project.

Our greywater hydroponics system was designed to augment their STEM curriculum and provide an avenue for water savings and food security. This system, designed to be sustainable and self-monitoring, can reduce freshwater use for farming and increase food security for the students and their community. This project was designed to serve as a pilot at LEAP School 5 in hopes that they can extend the knowledge of the system for implementation across the entire LEAP school system and beyond.

Due to the COVID-19 pandemic, there were a couple of tests that the project team was never able to run in their entirety. Although the quality of the filtered greywater was determined to be adequate for usage, the greywater filter was never connected to the hydroponics grow beds for their complete testing in a harvest of vegetables. Another item was the nutrient solution. In order to further the system's sustainable design, an organic-homemade nutrient solution using fermented chicken manure, straw, and water was to be tested for its effectiveness in the system. By using this at the LEAP high school, they could decrease their O&M costs significantly by not having to purchase and ship nutrient solutions each month.

The final consideration moving forward would be to test the effectiveness of the product in various climates. We were lucky enough to have a similar climate in Santa Clara to Jane

Furse, such that this system would work sufficiently all year in South Africa. However in order to expand its reach to the LEAP school system, this system may have to be adapted in order to fit different climate zones.

9. Conclusion

Hydroponics is a method of gardening that suspends plants' roots in a nutrient rich water instead of replacing new soil each harvest. This alternative to traditional, in-ground farming has the ability to significantly reduce pesticide usage, growing area, water usage per plant, and time between harvest and consumption. Greywater refers to wastewater that does not contain fecal matter. By employing filtered kitchen sink wastewater as the primary water source of the hydroponics garden, the water footprint is reduced and the sustainability of the garden is enhanced even further.

The greywater-supplied hydroponics garden system designed alongside LEAP 5 High School in Jane Furse, South Africa successfully utilizes sustainable materials, a self-monitoring temperature controls system, a shading system, and greywater input. It was used as an educational tool for students and significantly reduced freshwater use compared to traditional, in-ground agriculture. The educational material surrounding this system was critical to its success as an inspiration for adopting alternative agriculture for the students at LEAP 5 and the surrounding Jane Furse community.

When compared to traditional, in-ground agriculture, our hydroponics system was found to have a much higher payback period and return on initial investment. The final product also reduced the amount of freshwater usage while utilizing a successful greywater filter which removed harmful surfactants from kitchen wastewater. Along with a retractable shading unit that reduces the amount of leafy greens scorched from high temperatures, the prototyped project was a huge success when compared to its traditional farming alternative and will be utilized in the Forge Garden as an educational tool for years to come.

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Our greywater hydroponics system was designed to augment LEAP 5's STEM curriculum and provide an avenue for water savings and food security. This system, designed to be sustainable and self-monitoring, can reduce freshwater use for farming and increase food security for the students and their community. This project was designed to serve as a pilot at LEAP School 5 in hopes that they can extend the knowledge of the system for implementation across the entire LEAP school system and beyond.

References

[1] T. Khokhar, "Chart: Globally, 70% of Freshwater Is Used for Agriculture." World Bank Blogs, The World Bank, 22 Mar. 2017, blogs.worldbank.org/opendata/chart-globally-70-freshwater-used-agriculture.

[2] E. M. Akpabio, S. U. Eti-ido, K. Takara, "The nexus of water and socio-spatial inequality in sub-Saharan Africa: legacies, strands and agenda for research." (2017) Retrieved from WATERLAT GOBACIT.

[3] Mcgranahan, Gordon. (2002). Demand-Side Water Strategies and the Urban Poor.

[4] N. Bulled, "The effects of water insecurity and emotional distress on civic action for improved water infrastructure in rural South Africa," Medical Anthropology Quarterly, vol 31(1), pp. 133-154, 2017.

[5] Statistics South Africa (2012). Census 2011: Census in brief. Retrieved from: http://www.statssa.gov.za/?page_id=3955.

[6] "Water In Crisis - Spotlight South Africa." The Water Project. (2019) Retrieved from thewaterproject.org/water-crisis/water-in-crisis-south-africa.

[7] G. L. Barbosa, F. D. A. Gadelha, N. Kublick, A. Proctor, L. Reichelm, E. Weissinger, G. M. Wohlleb, R. U. Halden.. "Comparison of Land, Water, and Energy Requirements of Lettuce Grown Using Hydroponic vs. Conventional Agricultural Methods." International Journal of Environmental Research and Public Health, vol. 12 (6), pp. 6879–6891, 2015.

[8]"Limpopo."*Wikipedia*, Wikimedia Foundation, 23 May 2020, en.wikipedia.org/wiki/Limpopo.

[9] "What Is Deep Water Culture (DWC) Hydroponics." *NoSoilSolutions*, 19 Jan. 2019, www.nosoilsolutions.com/deep-water-culture-hydroponics/.

[10] "What Is Ebb And Flow Hydroponics?" *NoSoilSolutions*, 21 Aug. 2019, www.nosoilsolutions.com/ebb-flow-hydroponics/.

[11] "6 Gal. - AquaSprouts Fountain." *AquaSprouts*, www.aquasprouts.com/collections/grow/products/6-gallons-aquasprouts-fountain.

[12] Sharon, and Katz. "Harvest Elite." *AeroGarden Official Store*, 22 Oct. 2018,

www.aerogarden.com/harvest-elite.html.

[13] “General Hydroponics EuroGrower 8 Site Complete: HTG Supply.” *Hydroponic Store Shop Hydroponic Supplies LED Grow Lights Tents and More at HTGs Online Grow Store*, www.htgsupply.com/products/general-hydroponics-euro-grower-8-site-complete/.

[14] “Active Aqua 4' x 4' Ebb & Flow Hydroponic Flood Table Kit.” *Grow Lights, Hydroponics and Garden Supplies at HydroBuilder.com*, hydrobuilder.com/hydroponics/complete-hydroponic-grow-systems/ebb-flow/active-aqua-4-x-4-ebb-flow-hydroponic-flood-table-kit.html.

[15] “Botanicare 4' X 8' Hydroponic Drip System Flood Table Kit.” *Grow Lights, Hydroponics and Garden Supplies at HydroBuilder.com*, hydrobuilder.com/hydroponics/complete-hydroponic-grow-systems/drip-systems/botanicare-4-x-8-hydroponic-drip-system-flood-table-kit.html.

[16] Sawyer, Jonathan. “Aquabundance - Home Aquaponic Gardens.” *The Aquaponic Source*, 27 Apr. 2020, www.theaquaponicsource.com/shop/complete-systems/home-scale-systems/aquabundance-home-aquaponic-gardens/.

[17] Palomo, Eulalia. “Optimum Temperature for Growing Cabbage.” *Home Guides | SF Gate*, 7 Oct. 2016, homeguides.sfgate.com/optimum-temperature-growing-cabbage-67094.html.

[18] “How To Grow Salad Greens All Year: Gardener's Supply.” *Gardeners Supply*, www.gardeners.com/how-to/how-to-grow-salad-greens-all-year/7272.html.

[19] Albert, Steve, and Karin Williams. “Spinach Growing Tips.” Harvest to Table, 4 Sept. 2017, harvesttotable.com/spinach_growing_tips/.

[20] “Active Aqua Submersible Water Pumps.” *Active Aqua Submersible Water Pumps | Active Aqua*, www.activeaquahydroponics.com/pumps/active-aqua-submersible-water-pumps.

[21] “Eco-Sense Worm Biofilter.” *Eco-Sense Living*, 2012, ecosenseliving.files.wordpress.com/2010/01/wb-2012.pdf.

[22] Ludwig, Art. Create an Oasis with Greywater: Your Complete Guide to Managing Greywater in the Landscape. Oasis Design, 1998.

[23] Stewart, Crystal, and Natasha Field. “2018 Summer Romaine Lettuce Variety Trial.” Eastern NY Commercial Horticulture Program, Cornell Cooperative Extension, 2018.

[24] CES EduPack software, Granata Design Limited, Cambridge, UK, 2020.

[25] Budynas, R. G., Nisbett, J. K., & Shigley, J. E. (2011). Shigley's mechanical engineering design. New York: McGraw-Hill.

Appendices

Appendix A: Shading Structure Design Options

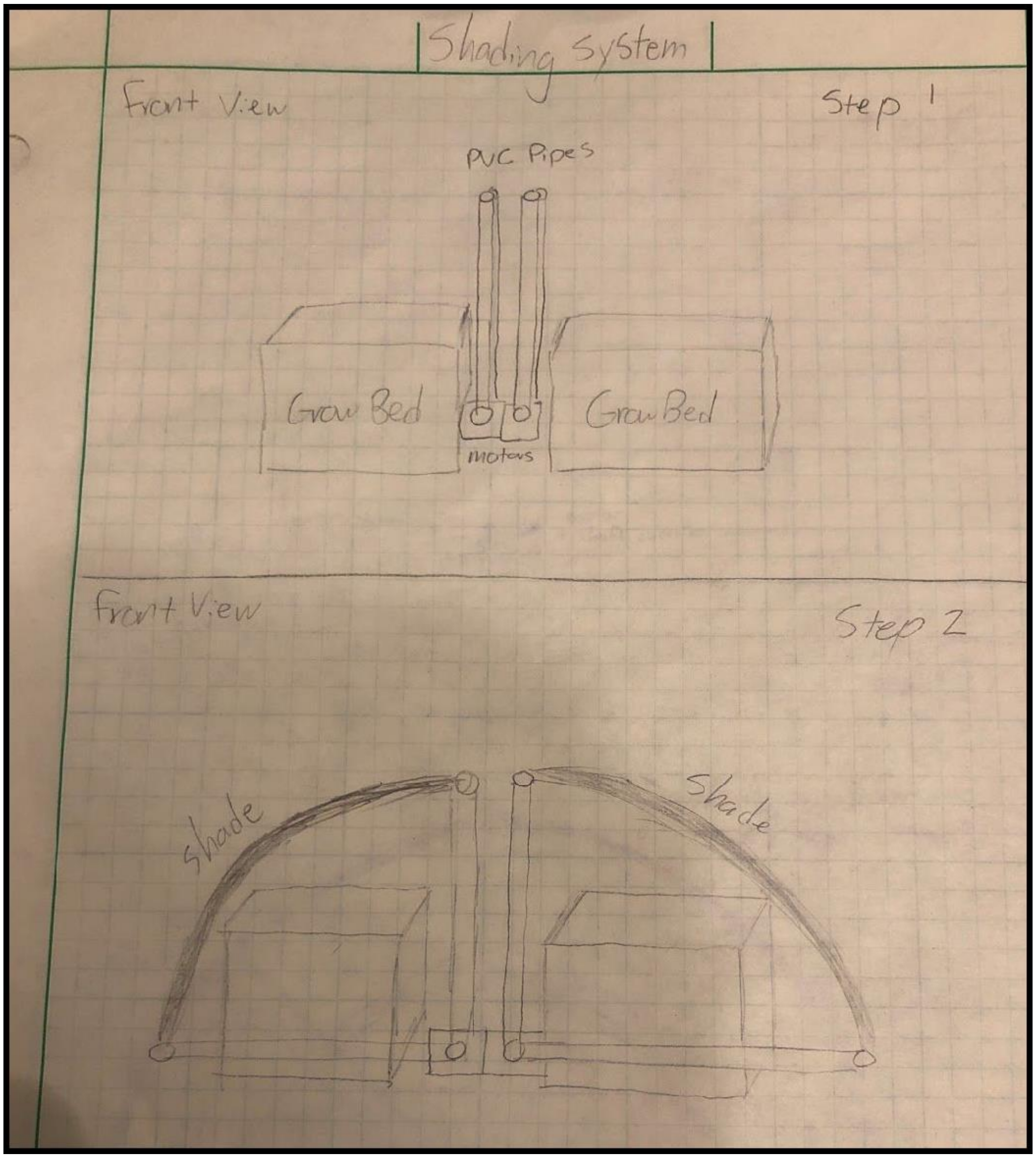

Figure A31: Hand Fan Shading Design

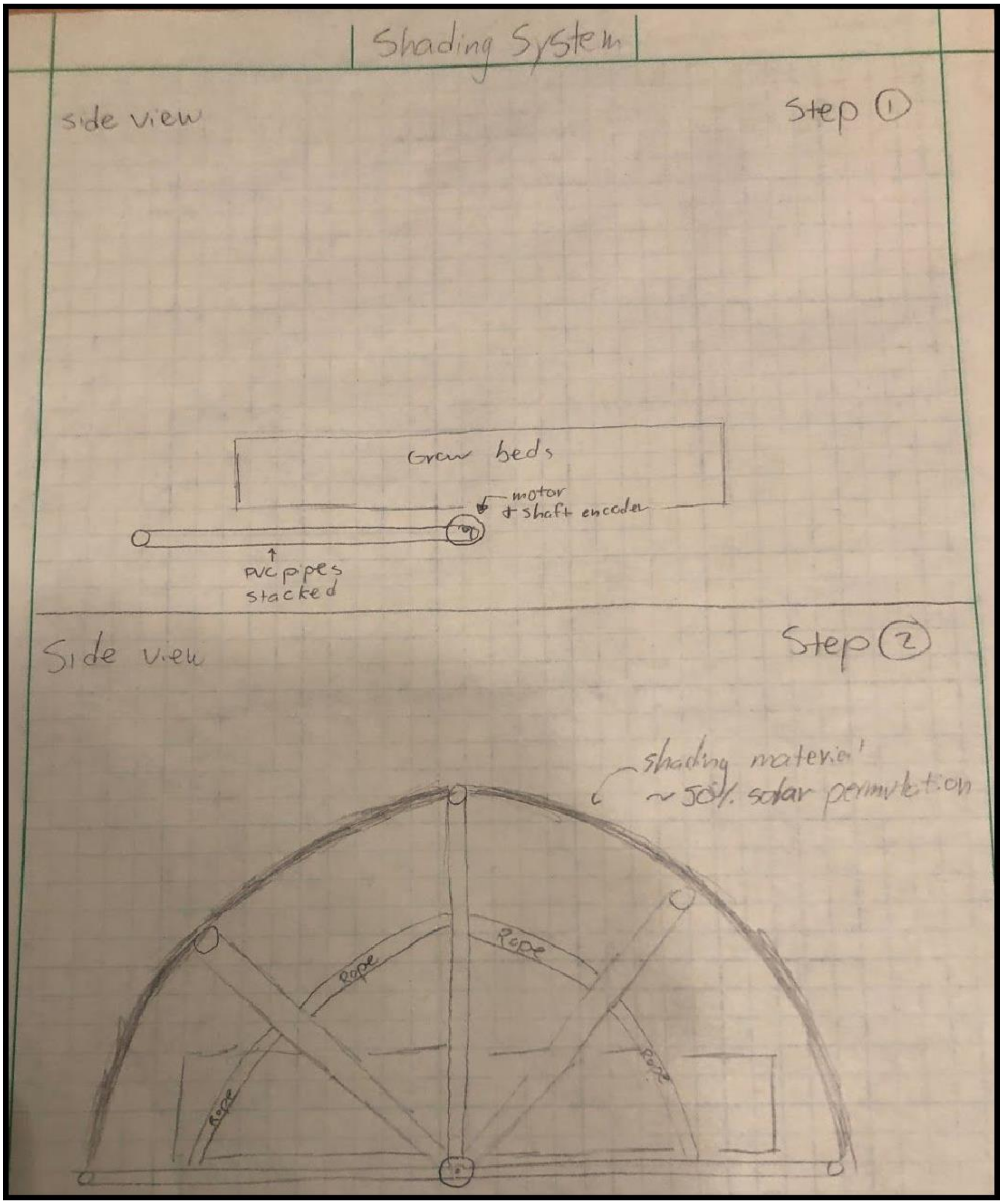

Figure 32: Reinforced Hand Fan Design

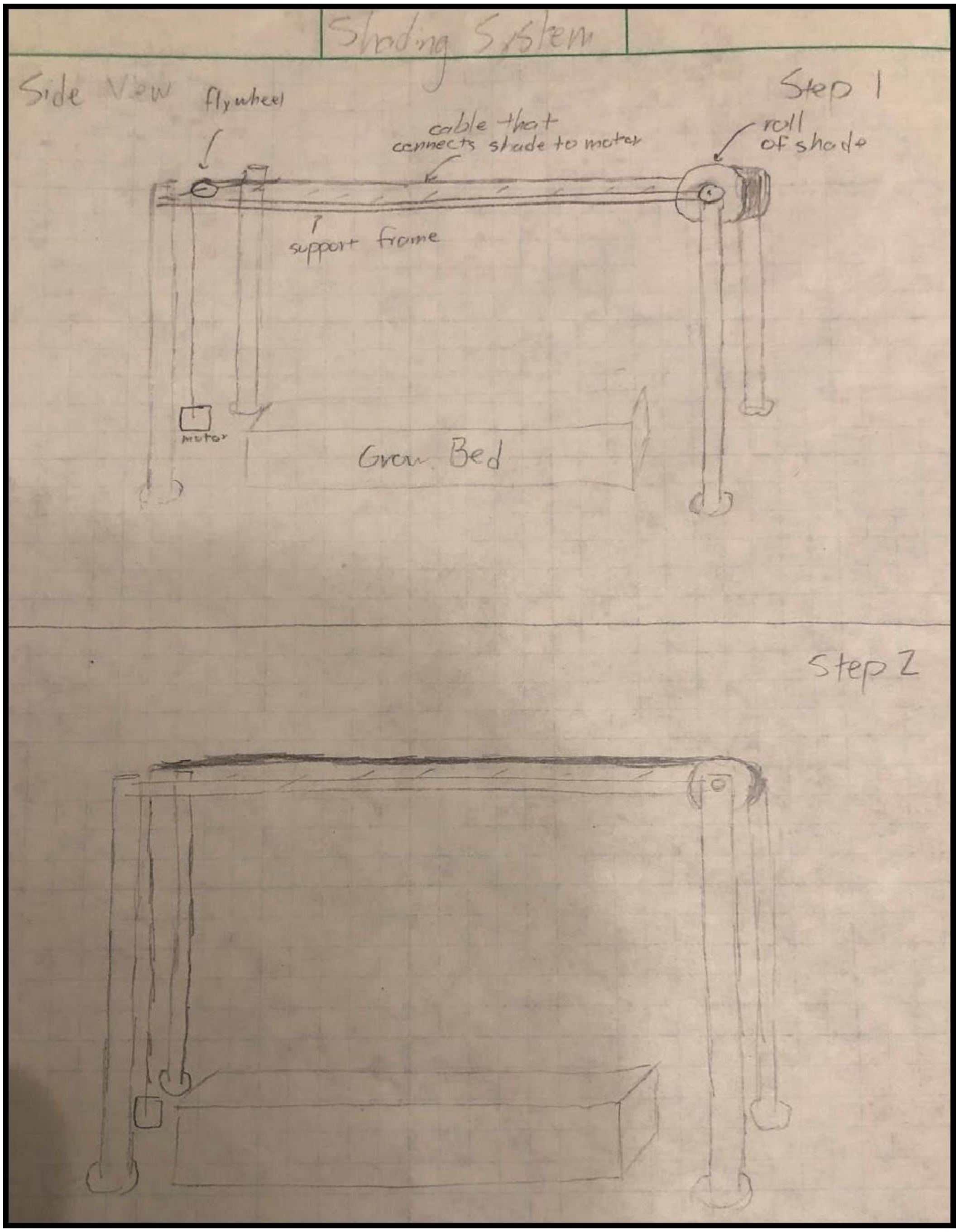

Figure 33: Square Frame Design

Appendix B: Shading Structure Hand and FEA Calculations

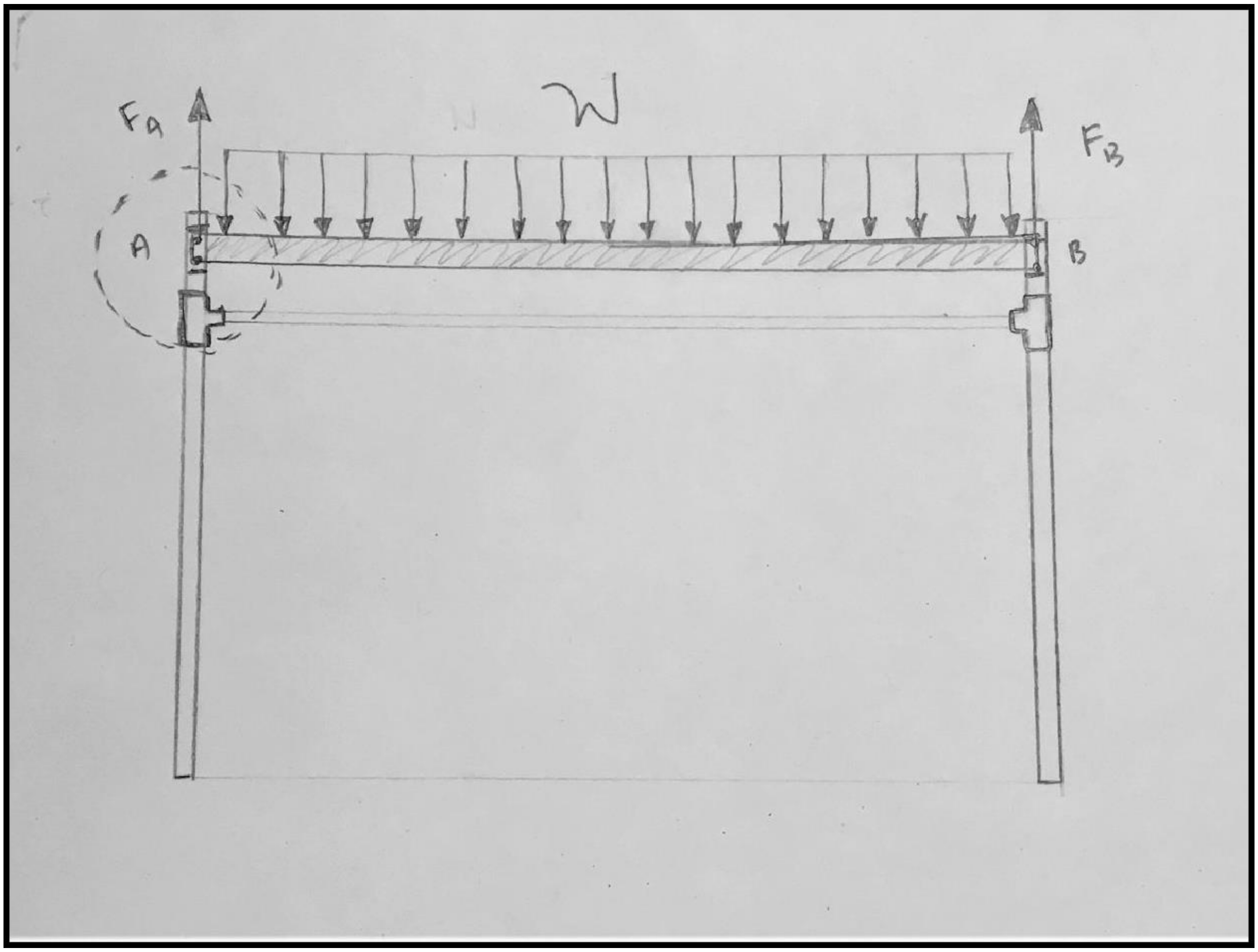

Figure 34: Horizontal tubing (shaded) with equally distributed weight and resultant forces from each bolted bracket.

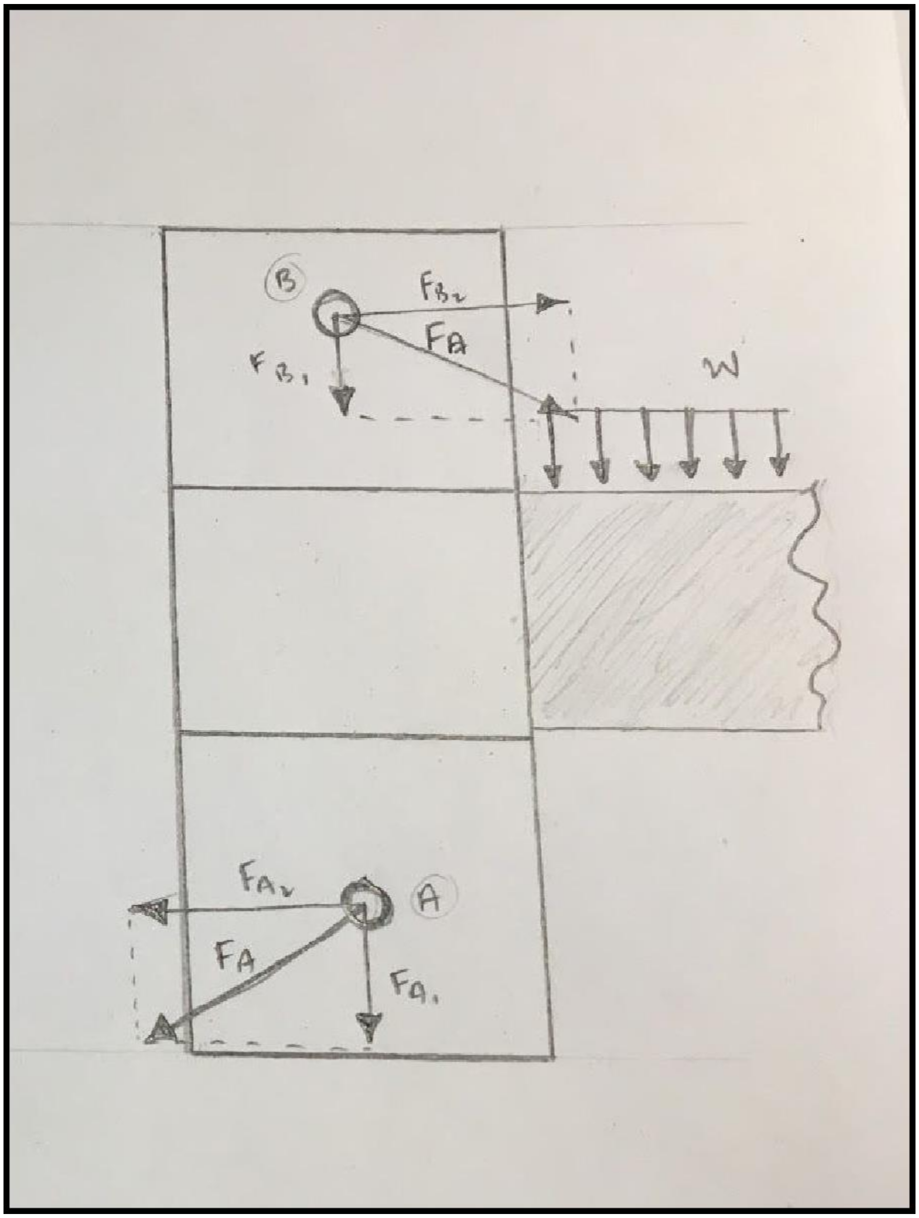

Figure 35: Shear forces observed in bolts on ABS piping.

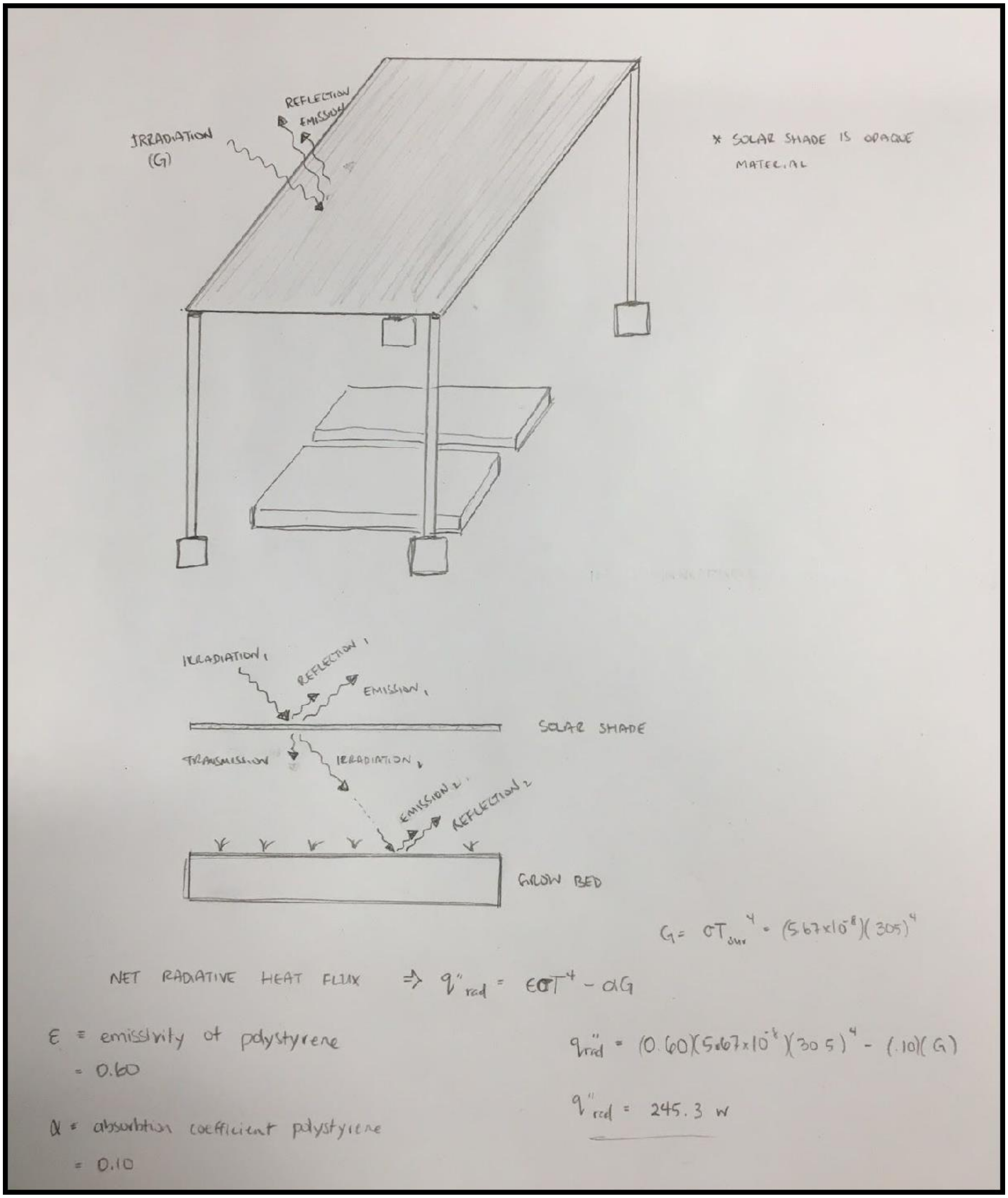

Figure B36: Diagram depicting solar load experienced by grow bed and shading structure. Calculations for the radiative heat transfer seen by the grow beds also included.

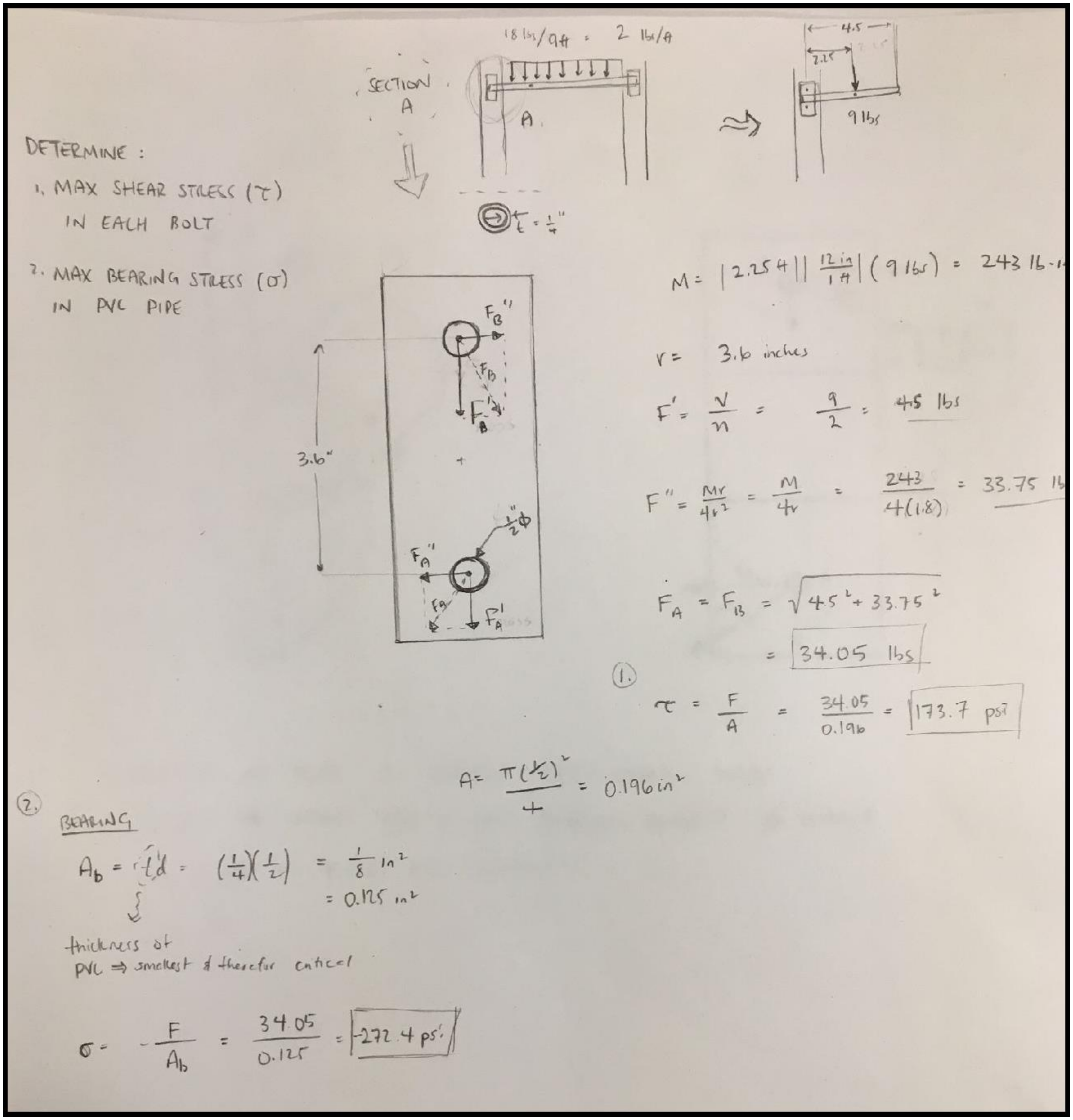

Figure 37: Hand calculations to determine maximum shear stress and bearing stress in ABS given load of motor and tubing assembly [25].

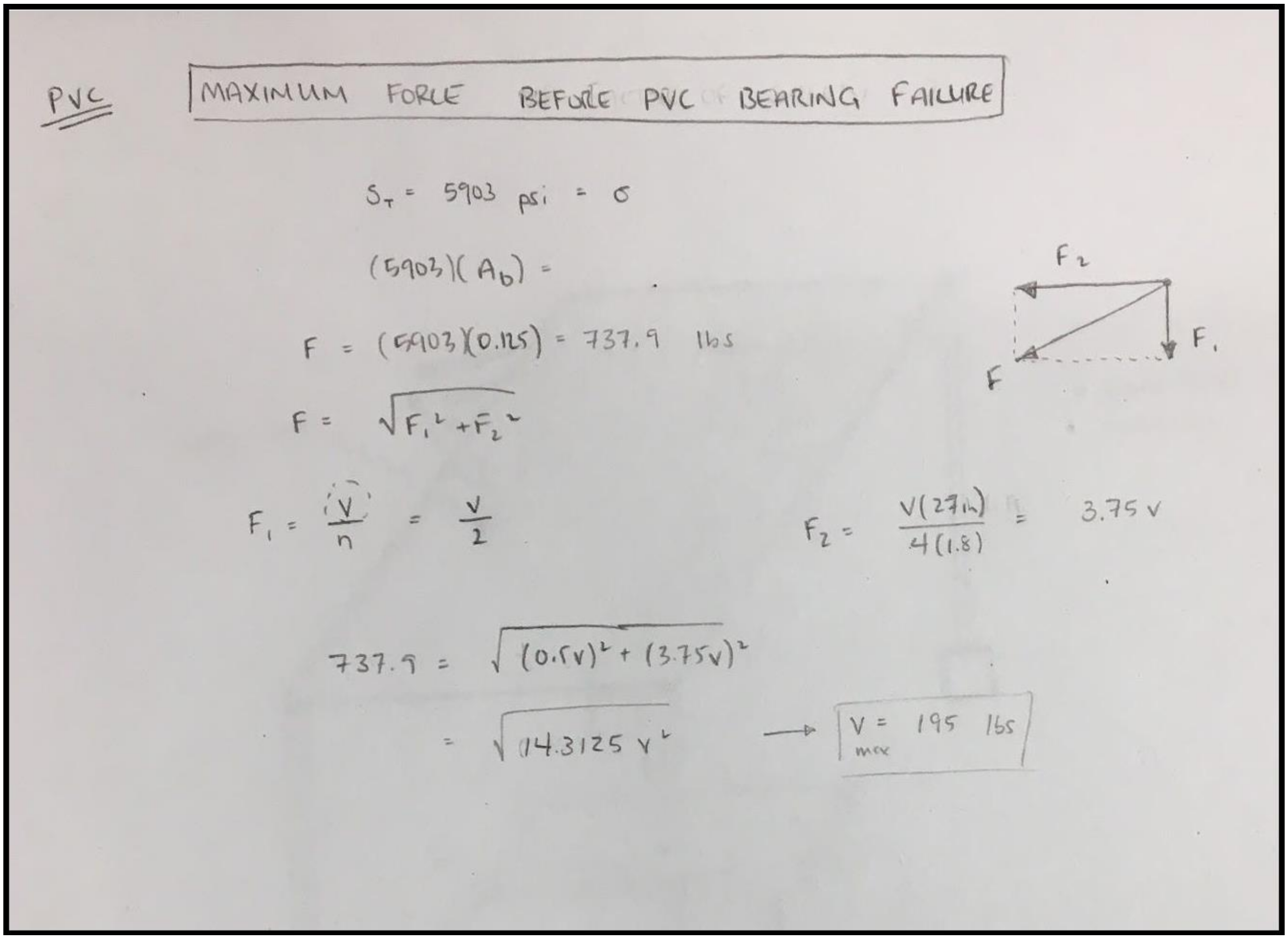

Figure 38: Calculations to determine the maximum vertical force capable of being withstood by the solar shade until critical bearing failure occurs in ABS.

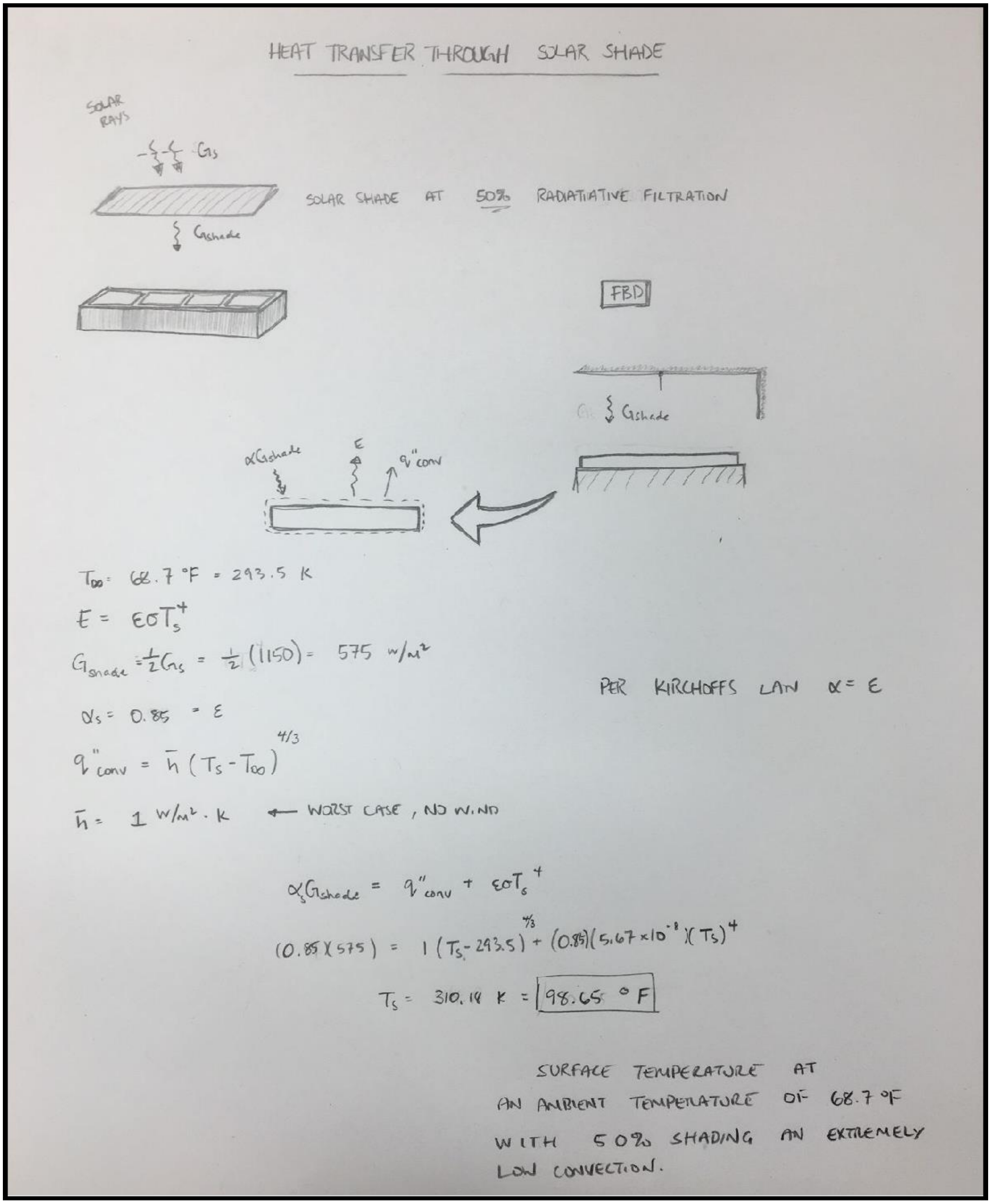

Figure 39: Calculation for surface temperature of grow beds given 50% shading at an outside temperature of 68.7 °F.

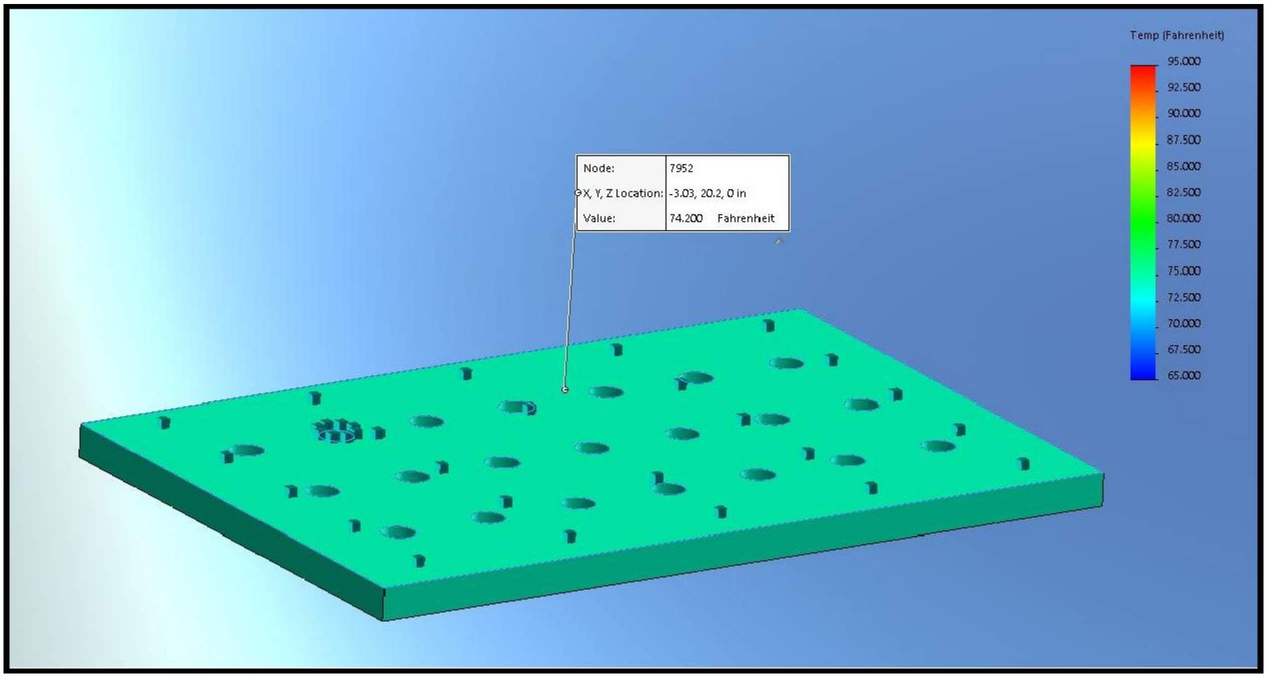

Figure 40: Styrofoam grow bed surface temperature test (through SolidWorks) with a 50% solar shade experiencing 74.2°F surface temperature with ambient temperature of 95°F.

Appendix C: Pump Selection Calculations

Component	Water Volume (L)		Fittings	Equivalent Straight piping (ft)	Equivalent Straight piping (m)		
Reservoir	190		3/4" 45 degree elbow	4.5	1.37195122		
Raft Beds	785.8		3/4" right angle elbow	1	0.304878049		
Media Beds	77.0988928		Total	5.5	1.676829268		
Total	1052.898893						
Total in gal	277.8097342						
Flow Rate (kg/s)	Flow Rate (gpm)		Density (kg/m^3)	1000		Component	Head Loss (m)
0.292471915	4.630162237		dynamic viscosity (Pas)	0.00089		1/2" PVC	0.316722846
						3/4" PVC	0.167774948
PVC			3/4" Diameter				
Length 1/2" (ft)	2.083333333		Diameter (m)	0.019050038			
Length 1/2" (m)	0.635162602		Area (m^2)	0.000285024		**Total Head Loss (m)**	**0.484497794**
Length 3/4" (ft)	2.166666667		Velocity (m/s)	1.026130484		**Total Head Loss (ft)**	**1.589152764**
Length 3/4" (m)	0.660569106		Reynolds Number	21963.84811			
Absolute Roughness (mm	0.0015		Relative Roughness	0.00007874			
			Darcy Friction Factor	0.025479098			
1/2" Diameter							
Diameter (m)	0.012700025						
Area (m^2)	0.000126677			GPH			
Velocity (m/s)	2.308793589			277.8097342			
Reynolds Number	32945.77216						
Relative Roughness PVC	0.00011811						
Darcy Friction Factor	0.023309226						

Figure 41: Pump Head Loss Calculation Spreadsheet.

Appendix D: Temperature Data Logging Materials

```
hydroponics_temperature_sensor §
#include <BlynkSimpleEsp8266.h> #include <ESP8266WiFi.h> #include <SimpleTimer.h> #include <OneWire.h> #include <DallasTemperature.h>
char auth[] = "Ict046_r8TBhqvPsi9ocE1Y9yY24h57S";
char ssid[] = " Wifi network ";
char pass[] = " Wifi password ";
SimpleTimer timer;
#define ONE_WIRE_BUS 2 // DS18B20 on arduino pin2 corresponds to D4 on physical board "D4 pin on the ndoemcu Module"
OneWire oneWire(ONE_WIRE_BUS);
DallasTemperature DS18B20(&oneWire);
float temp;
float Fahrenheit=0;
void setup()
{ Serial.begin(115200);
  Blynk.begin(auth, ssid, pass);
  DS18B20.begin();
  timer.setInterval(1000L, getSendData);}
void loop()
{ timer.run(); // Initiates SimpleTimer
  Blynk.run();}
void getSendData()
{ DS18B20.requestTemperatures();
  temp = DS18B20.getTempCByIndex(0); // Celcius
    Fahrenheit = DS18B20.toFahrenheit(temp); // Fahrenheit
  Serial.println(temp);
  Serial.println(Fahrenheit);
  Blynk.virtualWrite(V3, temp); //virtual pin V3
  Blynk.virtualWrite(V4, Fahrenheit); //virtual pin V4}
```

Figure 42: Arduino code for Node MCU wifi chip.

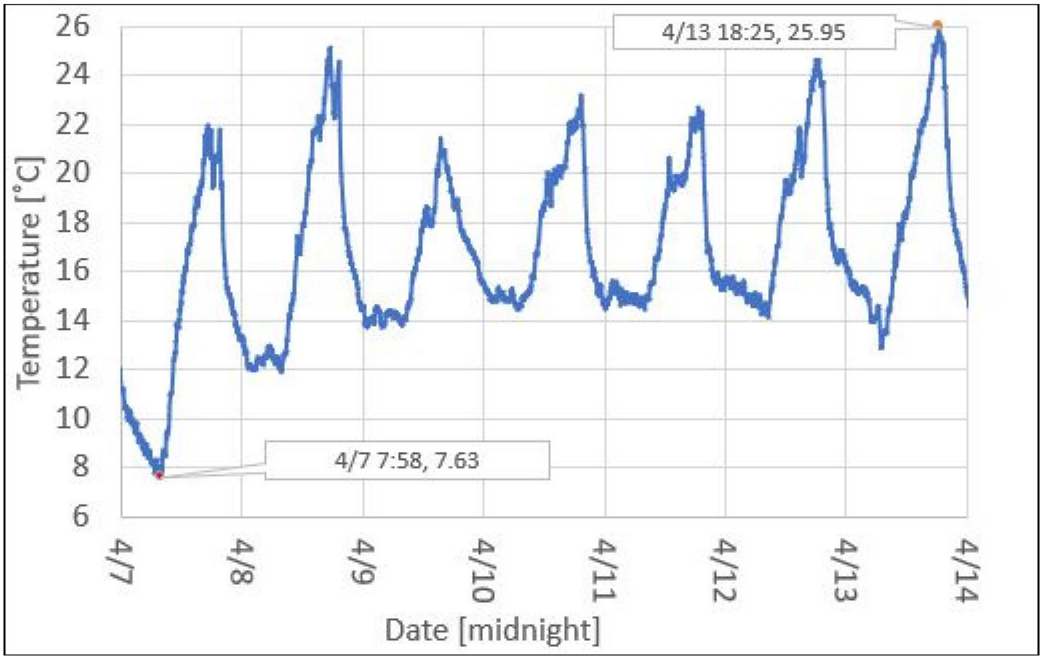

Figure 43: Template of excel spreadsheet for weekly temperature histogram reports.

Figure 44: QR code to access the temperature reading app. Note, users must first download Blynk on their mobile device before scanning code in the app.

Appendix E: Location Photos of LEAP 5 High School

Figure 45: Existing Conditions Photos at LEAP 5 High School in Jane Furse, South Africa.

Figure 46: Bathtubs that will be reused for wicking grow beds.

Figure 47: Scrap metal yard with material at hydroponic team's disposal.

Figure E48: Hydroponic system planned implementation location.

Figure 49: LEAP 5 greywater catchment system.

Figure 50: Location of overflow basin that waters lawn.

Appendix F: Greywater Filter Hand Calculations and Design

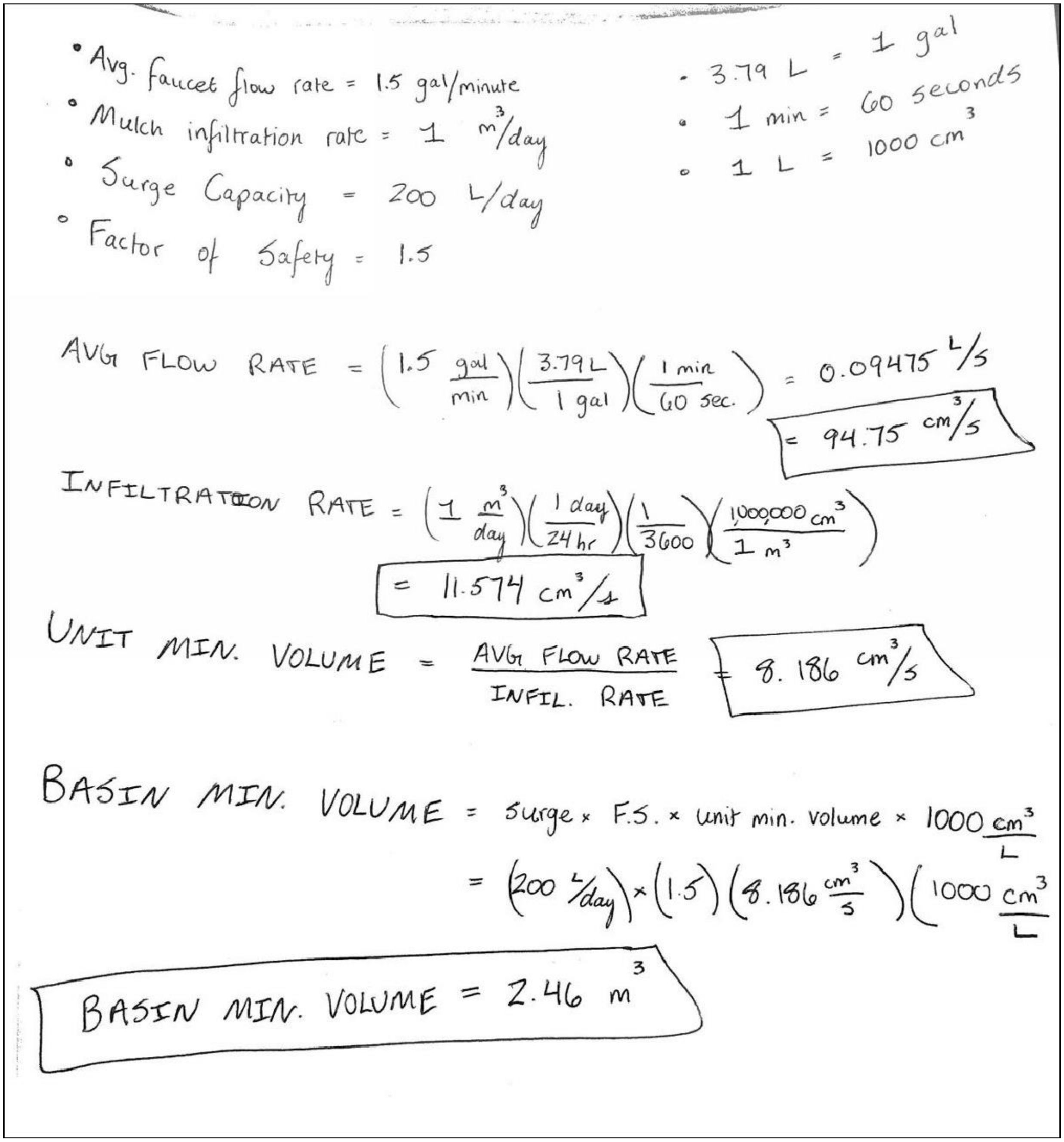

Figure 51: Hand Calculations for Sizing of Greywater Filter.

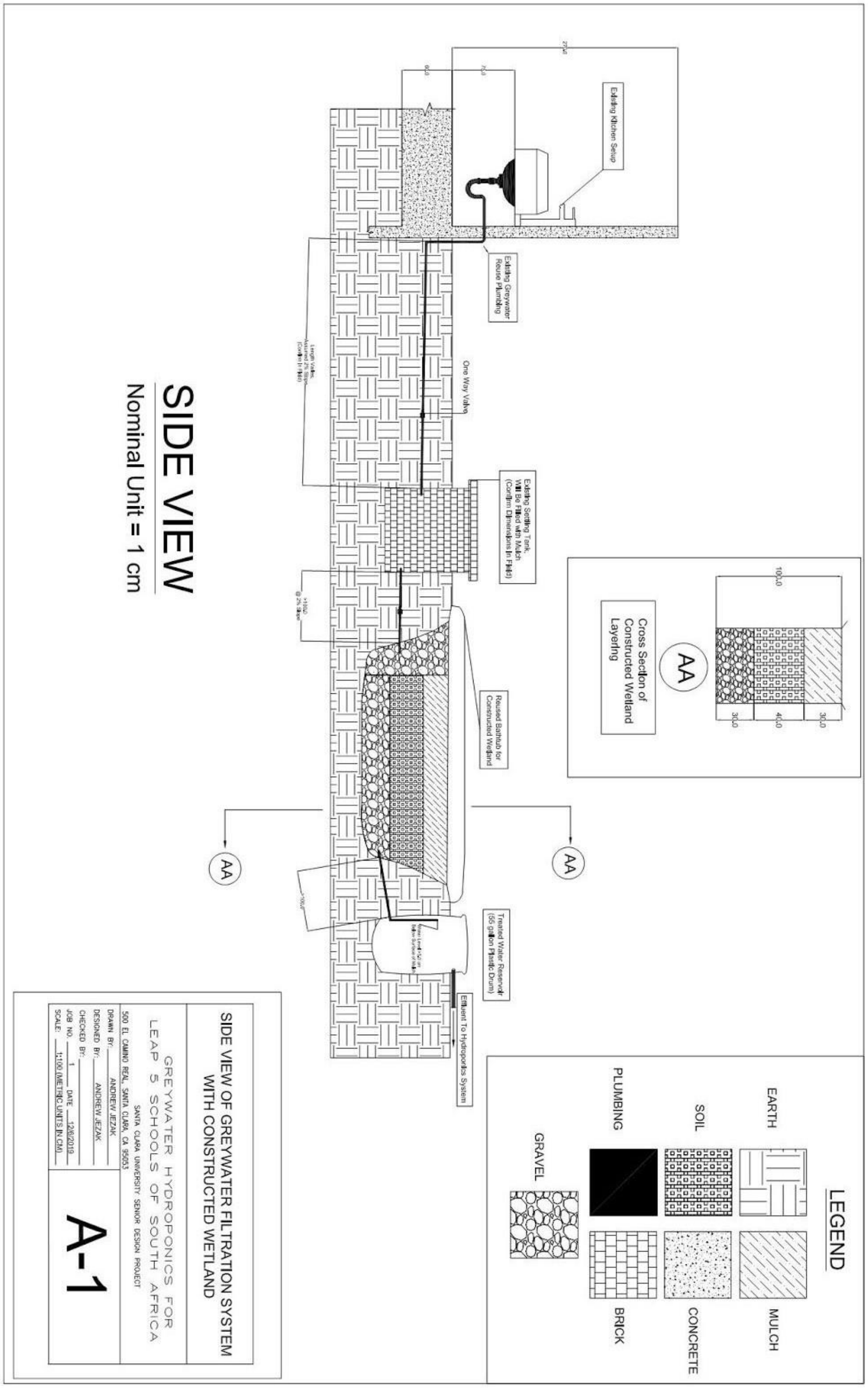

Figure 52: Preliminary Design of Constructed Wetland Greywater Filter.

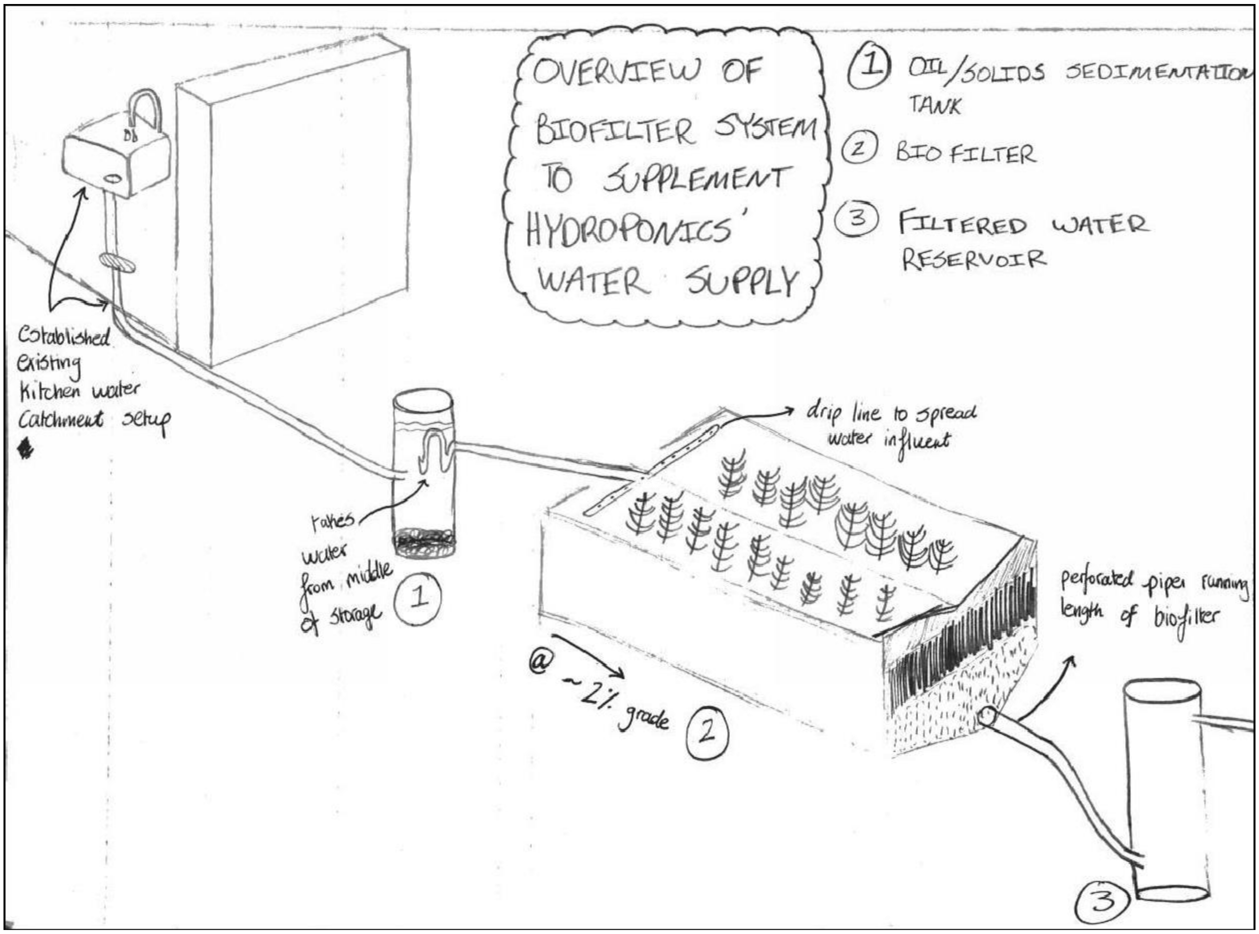

Figure 53: Hand Sketch of Biofilter Design for Greywater Filtration.

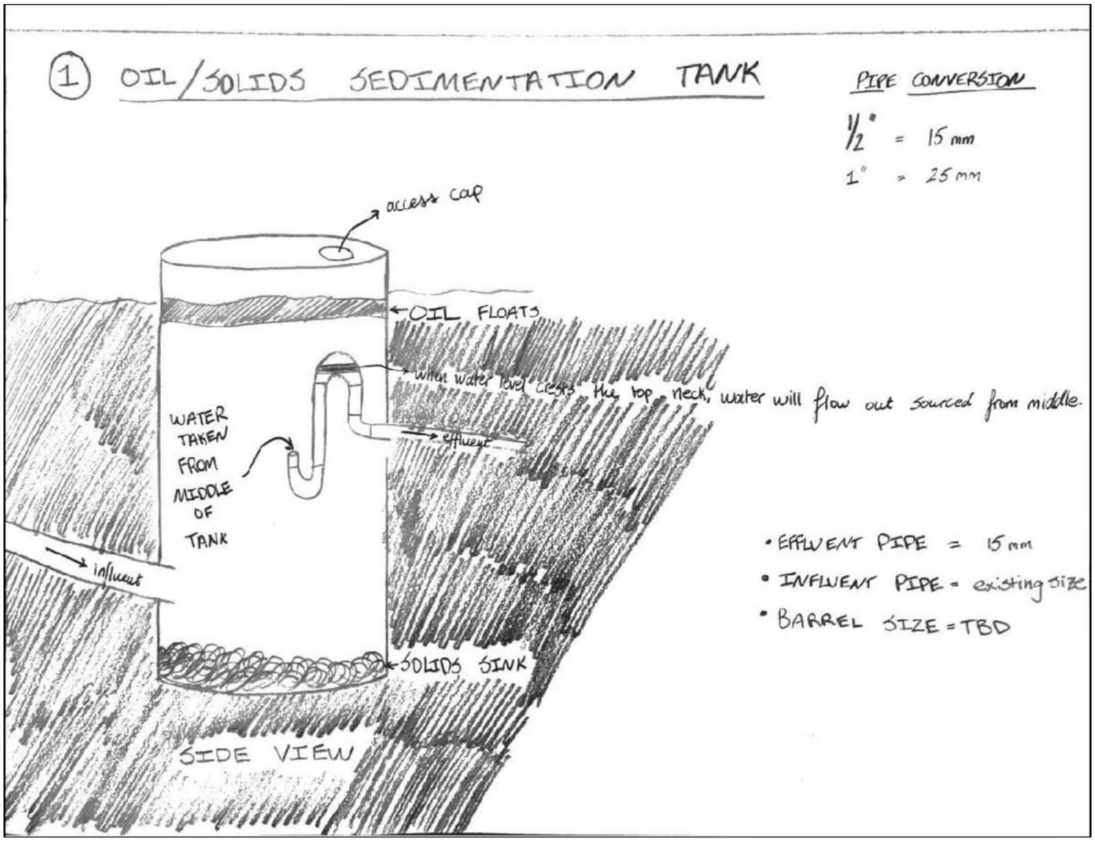

Figure 54: Sedimentation tank hand drawing reference for design.

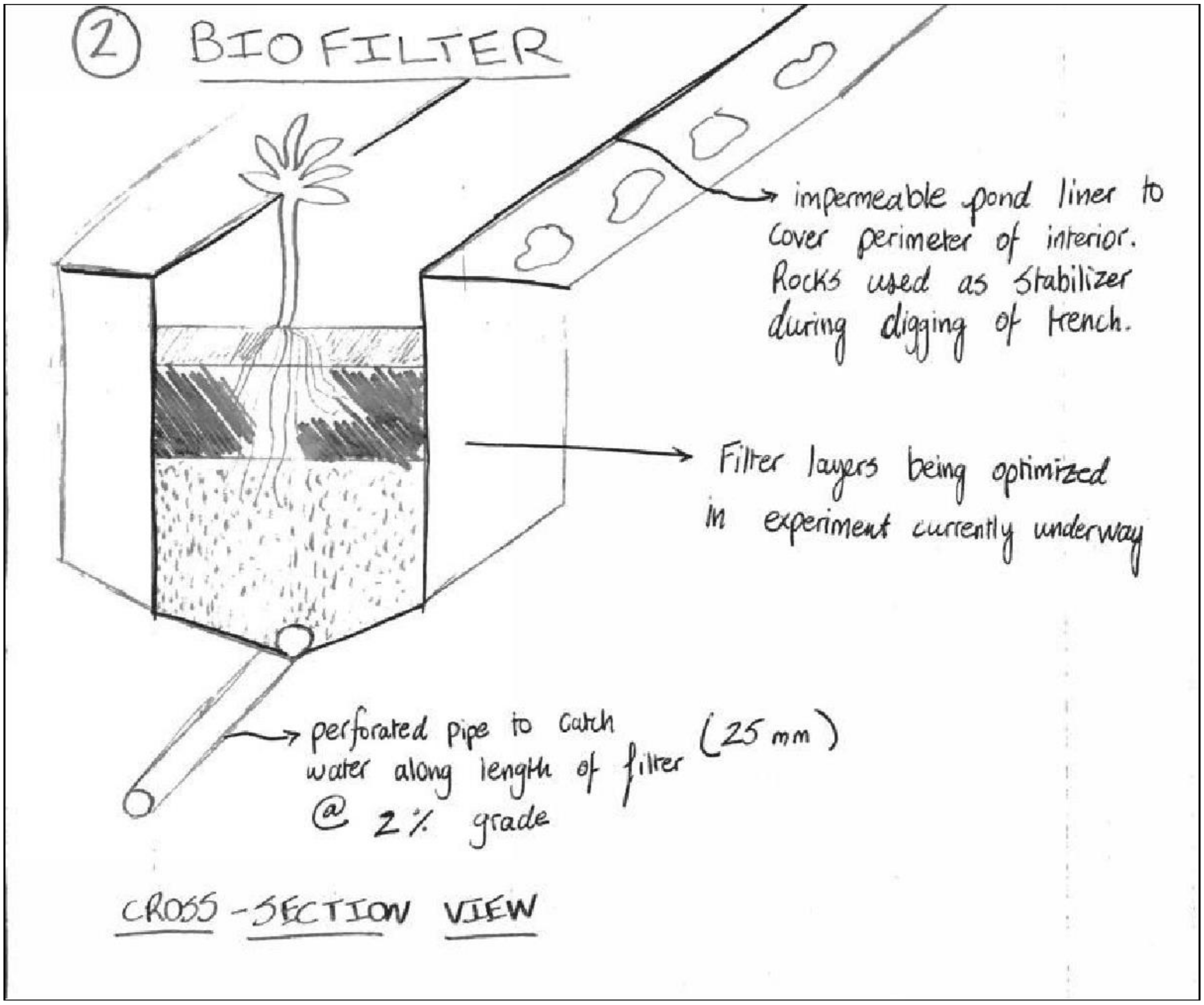

Figure 55: Biofilter layers shown as a cross-sectional view.

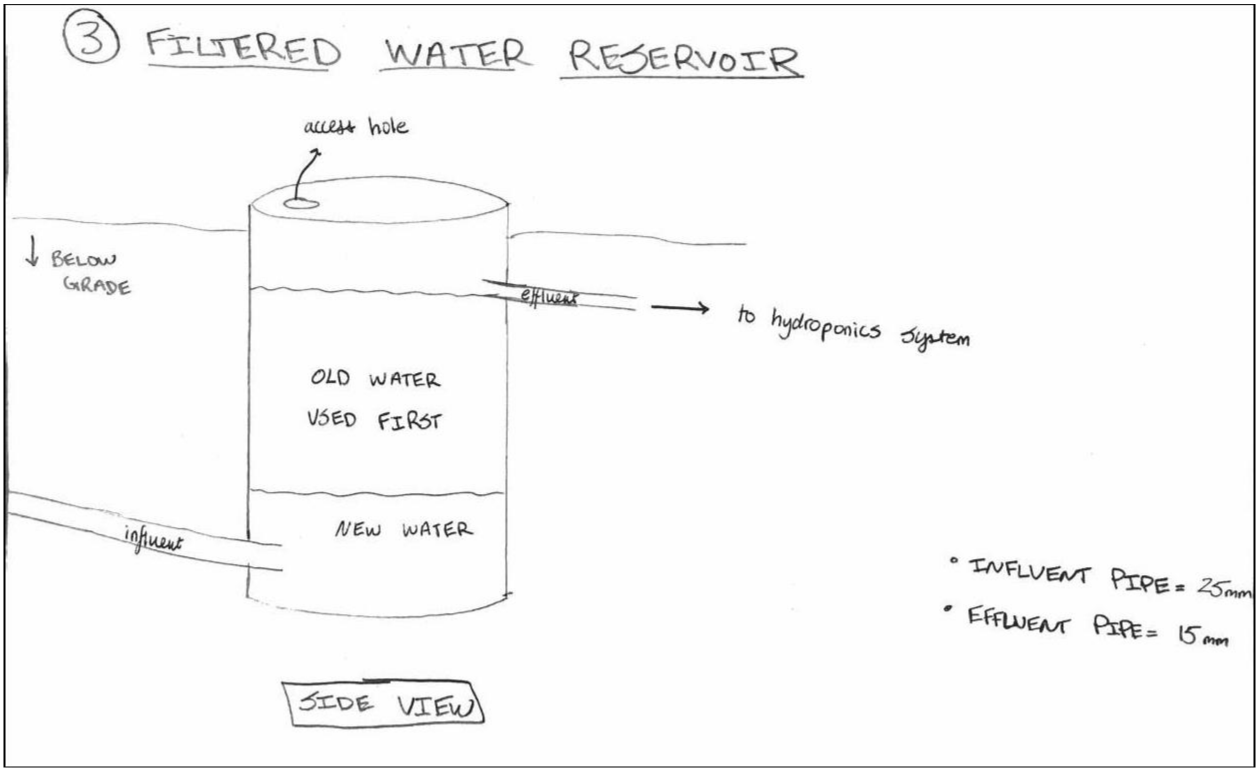

Figure 56: Hand sketch of filtered water reservoir.