Engineering and Education for Affordable, Sustainable Rainwater Harvesting in Paraguay

A Major Qualifying Project

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by

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Authorship

This report is the work of Katherine R. Picchione. Significant portions of Chapters 4 and 5 were adapted from an interim report written with the help of Ms. Brianna Fogal, who collaborated on the tank design as an Independent Study Project in B-Term 2015. Throughout, "I" refers to me, Katie, and "we" is inclusive of others who contributed to the project.

Graphics used in this report were created by me, primarily using Microsoft PowerPoint unless otherwise noted. Photographs are original, unless otherwise noted. Many of the photographs of rainwater harvesting systems were taken by me in Guatemala and are attributed to Engineers Without Borders-USA WPI.

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Thank you to all who supported and guided me throughout the course of this project and my time at WPI. This project is a testament to the WPI community that has nurtured my passion for appropriate technology in the developing world.

Abstract

According to the 2015 United Nations Millennium Development Goals Report, 663 million people still lack access to improved water sources. Rainwater harvesting, collecting and storing rainwater that falls on roofs, offers one solution to water challenges in developing areas, but is often unaffordable for poor families. In collaboration with the NGO Fundación Paraguaya, this project aimed to make rainwater harvesting more feasible through the design of educational materials and inexpensive water storage tanks. A learning module, developed for a Paraguayan agricultural high school, teaches rural youth the critical thinking and project management skills to design, build, operate, maintain, and repair rainwater harvesting systems using locally-available materials. The module also introduces a DIY rainwater storage tank made of repurposed tires. The Tire Tanks were 'ethno-engineered' for Paraguay's unique socio-cultural context, where an excess of discarded tires presents an environmental and public health hazard. Both the learning module and 'tire tank' design were piloted in Worcester and in Paraguay in April 2016, evaluated through observations and user feedback, and modified based on results. In the future, both the tanks and learning module can be utilized as a model, both in Paraguay and around the world, to inspire self-efficacy towards development.

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EXECUTIVE SUMMARY

Water is a keystone resource. Globally, 663 million people globally lack access to improved water sources, and a growing 40% of the world's population is affected by water scarcity (United Nations, WHO). Paraguay is an agrarian South American country that relies on rainwater to sustain agricultural production. Rain falls frequently in Paraguay, but seasonal drought can cause reduced agricultural yield, threatening the livelihoods of small-scale farmers.

Rainwater harvesting (RWH) is an elegant technology that can improve quantity, quality, and access to water. Rainwater harvesting offers water security, but is often unaffordable for poor families. Working with the NGO Fundación Paraguaya, the purpose of this project was to make rainwater harvesting more feasible in developing areas by reducing system cost and making knowledge more accessible. This project had three objectives:

Objective 1: Design inexpensive water storage tanks made of local recycled and repurposed materials.

Objective 2: Develop a learning module to teach RWH project management and critical thinking skills.

Objective 3: Pilot test the tank and learning module at WPI and in Paraguay.

The tank was iteratively designed to be made of recycled tires and inexpensive plastic lining, materials that are locally available and familiar to rural farmers. Tires also present a public health hazard where water that is easily trapped in the rims creates a breeding ground for disease-carrying mosquitoes. Both numerical and empirical methods were used to test the "tire tank," and a prototype was built at WPI. Findings informed the design and construction of a second pilot system at Fundación Paraguaya's St. Francis Agricultural School in Paraguay, where WPI IQP students worked with Paraguayan students to realize the system. While there is room for improvement in the design, both prototypes demonstrated that water can be stored for low cost using ingenuity and local materials.

The learning module was developed around clear learning outcomes and applied learning according to the Integrated Course Design and Project Based Learning approaches. The overall goals were articulated and conformed to four lessons that focus on system design, tailoring a system to meet needs, planning a build, and long-term sustainability. A practice class was held early on with members of the WPI chapter of Engineers Without Borders-USA, and again, findings informed changes that were implemented when the lessons were held in Paraguay. Approximately 20 Paraguayan students participated in the lessons, and 9 WPI students facilitated. The lessons engaged students in the engineering design process and encouraged them to be creative about the design possibilities presented by rainwater harvesting.

Initial feedback from the in-country pilot build and lessons indicates that both were successful because they were developed to be adaptable, accounting for cultural nuances. Further, the technology was made accessible through the learning module, encouraging students to explore design possibilities and project management strategies. Further analysis, evaluation, and revision will be ongoing through August 2016.

The main finding from this project is that accessible technology inspires innovation. Rainwater harvesting is not only culturally appropriate, but it is an adaptable technology that can be ethno-engineered to complement the nuances of a specific cultural context. In the future, the tanks and learning module promise to inspire locally-driven development, social entrepreneurship, and bettering of life in Paraguay and around the world.

Chapter 1. Introduction

Water is a keystone resource, integral to environmental, social, and political ecologies. It is critical for sustaining life and livelihoods: at minimum, people depend on water for drinking and cooking, bathing, cleaning, and agriculture. According to the United Nations' 2015 Millennium Development Goals Report, over 40% of the global population now faces water scarcity, a percentage that is expected to rise as renewable water resources are stressed and non-renewable sources are depleted, an ominous trend in light of global climate change.

Water scarcity is but one facet of ***water security***, contextually defined as having adequate quantity, quality, and access to water to satisfy needs. Elgert et al. (2015) explain that water must be available in a sufficient quantity and of an appropriate quality for each intended use. If water is scarce or too polluted for consumption, water security may be in jeopardy. Political, social, economic, environmental, or technological barriers can also bar Individuals, families, and communities from accessing water. These three dimensions, quantity, quality, and access, provide a framework for discourse about water security in the developing world.

As global climate change induces altered patterns in the magnitude and frequency of precipitation, water security is increasingly at risk, particularly in countries like Paraguay that rely heavily on seasonal rain. Paraguay is a landlocked, agrarian South American country where the agricultural sector accounts for 30% of the country's GDP and 97.8% of farms rely solely on rainwater to cultivate crops (World Bank Group, 2009). In a 2015 World Bank report, Paraguayan farmers, 86% of whom own small-scale family farms (225,587 farms) and rely on the land for both subsistence and cash crops, identified drought as the most serious threat to agricultural production. When rain is scarce, crop yields are significantly reduced or of poor quality, a damaging blow to farmers' livelihoods (Acre, 2015). With droughts predicted to become more severe as global climate change progresses (Benitez, 2014), adaptation strategies are urgently needed to protect agricultural and domestic water security.

A number of simple technologies exist to improve water security, including wells, biosand filters, and fog nets. Rainwater harvesting (RWH) is another elegant technology that can be locally tailored to meet water needs in a technically sound, culturally appropriate way. Nuanced environmental, geologic, economic, social, and political factors preclude a single universal solution to water problems, but customizable technologies like rainwater harvesting systems, can be adapted to diversity.

Rainwater harvesting (RWH) systems pragmatically supply water in areas of frequent rainfall during all or part of the year. RWH systems capture rainwater, often from roofs or other collection surfaces, and store it for later use in tanks typically made of plastic or concrete. Gutters and pipes channel water from roof to tank while filters and 'first flush' mechanisms remove contaminants. RWH systems can be installed on large buildings, such as schools or community centers, to provide water security for many people. They can also be implemented on an individual scale, providing water security for a family.

To best meet the needs of a family or farm, systems should be designed based on intended water use, daily rainfall, water consumption rate, available materials, spatial constraints, and budget. With site-specific considerations, RWH systems can be optimized for diverse domestic and agricultural settings. In developing countries, stored rainwater is pragmatic. In Paraguay, RWH promises a secondary water source to sustain crops during droughts. However, RWH is expensive; tanks alone typically account for more than 50% of the total system cost (EWB-USA WPI, 2015). Without financial assistance from governmental or nongovernmental organizations, rainwater harvesting is unaffordable for people living on $2 per day, making water security unattainable for many poor and marginalized populations. In order for rainwater harvesting to be an accessible and sustainable technology, it is imperative to reduce the cost of water storage and promulgate best practices in rainwater harvesting system design, maintenance, and repair.

This project aimed to make rainwater harvesting more accessible through collaborations with Fundación Paraguaya, a nongovernmental organization that works closely with rural farmers and indigenous communities, pioneered microfinance and social entrepreneurship in Paraguay, and runs several agricultural vocational schools that teach high school students practical skills in farming and business administration. With the support of Señor Martin Burt, social entrepreneur and founder of Fundación Paraguaya, the opportunity arose to work with Fundación Paraguaya's Saint Francis Agricultural School, located near Paraguay's capital, Asunción, where many of the 150 students come from small-scale farming families. The St. Francis School has close ties with WPI and annually sponsors several teams of WPI students completing their Interactive Qualifying Project (IQP). The school teaches students to become problem solvers and entrepreneurs themselves, and hopes that by integrating rainwater harvesting into the curriculum, students will be empowered to embrace management of their own water security.

This project advanced the accessibility of rainwater harvesting technology in rural Paraguay through the design of inexpensive water storage tanks made of repurposed tires, and through the creation of a learning module to spread the skills and knowledge needed to build and maintain a system. When coupled with educational measures, inexpensive, locally-made water storage tanks have the potential to transform the state of water security in developing areas. Furthermore, elegant technologies that are culturally appropriate, structurally sound, adaptable, and accessible—technologies that can be ethno-engineered to accommodate specific needs: these inspire people to innovate and to attain a better quality of life.

Chapter 2. Global Water Challenges and Socio-Technical Solutions

2.1. Water Poverty and Water Security

Humans depend on water in myriad ways. At a minimum, water is needed for drinking and cooking, bathing, cleaning, and agriculture. Water security can be contextually defined as the state of having reliable access to adequate quantity and quality water to satisfy these needs (Elgert 2015). In other words, there must be ***enough*** water to satisfy needs; that water must be of an appropriate ***quality*** to meet needs (for both potable and non-potable uses); and individuals must be able to ***access*** water unencumbered by social, political, environmental, legal, or economic barriers.

Water is one of the world's most serious challenges. The United Nations Development Program reports that, even with the achievement of the Millennium Development Goal to provide access to improved drinking water to people in need, over 40% of the global population is subject to water scarcity, defined as living in areas where non-renewable water resources are being drained more quickly than they are replenished. With global climate change and a growing population that depends evermore heavily on water-stressed food systems, that number is expected only to rise.

2.2. The State of Water in Paraguay

In Paraguay, an agrarian South American country, adequate water is essential for agriculture, the sector that accounts for 30% of the country's GDP. 86% of farms (225,587 farms) are family owned and 20 hectares or less in size (WHO, 2009). These people rely on the land for both subsistence and cash crops. Most (97.8% of farms) rely solely on rainwater to cultivate crops (Acre 2015).

In Asuncion, Paraguay's capital, the dry season occurs during the winter months (June - August), and rainfall is frequent throughout the rest of the year. Figure 1 shows the daily rainfall in Asuncion over the past five years. Annually, Asuncion receives 1200mm - 1800mm of rain (Dirección de Meteorología).

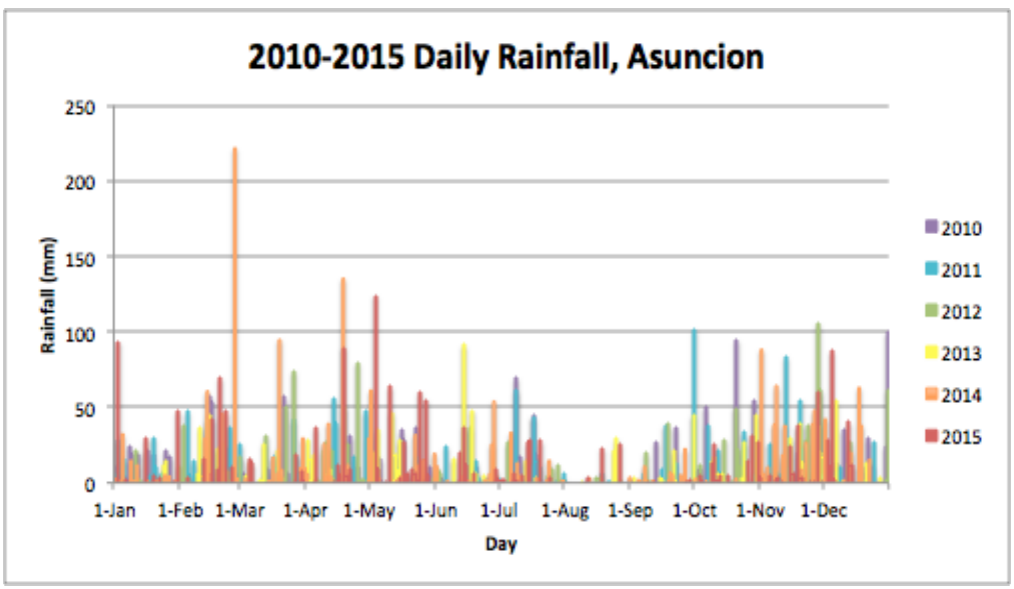

Figure 1: Daily rainfall in Asuncion over the last five years (data from the Dirección de Meteorología e Hidrología de Paraguay, Aeropuerto Pettiross meteorological station)

Rainfall is consistently lowest during August and the first half of September. Farmers know this and plan the growing season appropriately. However, as seen in Figure 2, lengthy droughts occur outside the dry season as well. The orange dots in this graph indicate the number of days since the last drought. In 2013, there were twelve dry periods that lasted over a week and occurred outside the regular dry season.

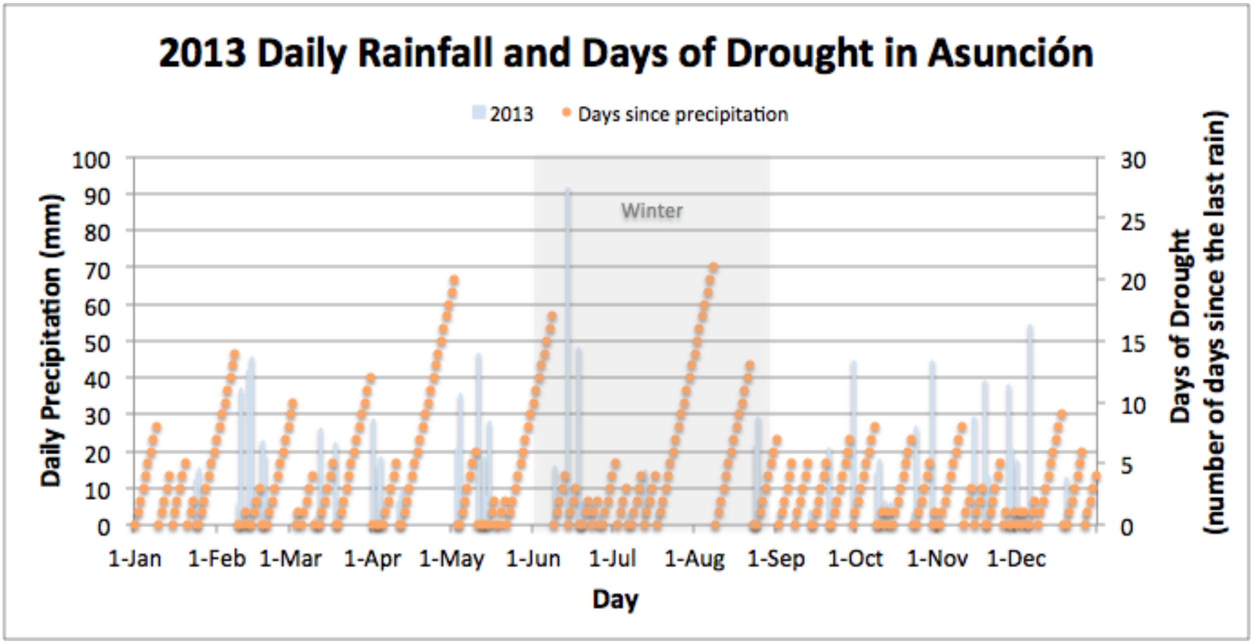

Figure 2: Daily rainfall overlaid with days without rain.

While crops usually survive these periods, crop yield and quality is dependent on the plant having consistent and sufficient water. Currently, crop quality is left to chance. In a 2015 World Bank report, Paraguayan farmers identified drought as the most serious production threat (Acre). With droughts predicted to become more severe as global climate change progresses, adaptation strategies are needed to ensure agricultural and domestic water security.

2.3. Rainwater Harvesting: A Solution to Water Poverty

Where water security is lacking, simple technologies can provide solutions. Water lingers underground, at great distances, and in the air, available to those who have the skills and tools to extract it. Respective to each circumstance, wells, water distribution lines, and rainwater harvesting systems are among the water-procurement technologies familiar to the developing world.

Though technologies exist to remediate water challenges, nuanced environmental, geologic, economic, social, and political factors preclude a single universal solution. However, customizable technologies can be adjusted for use in a variety of scenarios.

Rainwater harvesting (RWH) is an elegant technology that can be locally tailored to meet water needs in a technically sound, culturally appropriate way. Rainwater harvesting is the sustainable process of collecting water from precipitation and storing it for later use. Rainwater harvesting systems can improve water security in developing and rural areas by providing access to an increased quantity of better quality water. Though RWH usually does not render water potable, contaminants can be removed where water for drinking and cooking is unavailable.

Over the past seven years, the Worcester Polytechnic Institute chapter of Engineers Without Borders-USA has been building rainwater harvesting systems with a rural community in Guatemala (Figure 3).

Typically, systems consist of the roof of a family's home, gutters, PVC pipes, storage tanks, a concrete base, and a "first flush" mechanism, which removes contaminants washed off the roof.

Figure 3: Rainwater harvesting system built by EWB-USA WPI in 2014

Rainwater harvesting (RWH) is only possible when there is a vessel that water can be stored in. Water storage technologies are often costly, making it difficult for families in developing areas to afford adequate water storage capacity to supply enough water year round.

Concrete is widely available around the world and is a familiar medium to unskilled laborers in developing countries where buildings are commonly built with cinder blocks and cement. The same technique can be used to make a water storage tank.

Figure 4: Concrete Block Tank in Guatemala (EWB-USA WPI)

The concrete block tank featured in Figure 4 is made of cinderblocks with an inner rebar frame. The tank is built into the ground and has a total water storage capacity of about 1000L. Cement is used to create an impermeable lining on the inside.

One of the advantages of these tanks is that they can be hand-built with locally available construction materials. However, there are some concerns that make them less desirable than other types of tanks. The cement lining needs to be re-laid every few years, and small fissures can lead to a significant amount of water being lost. Another disadvantage is that once built, the tanks are immovable. If a family moves, the tank stays. If the water is intended for agricultural applications, the water must be draw or pumped out of the tank and transported.

Plastic tanks exist around the world. Most are made of high density polyethylene (HDPE) and may have various linings to reduce microbial growth. Pictured in Figure 5 are tanks from the manufacturer Rotoplas found throughout Latin America.

Figure 5: Rotoplas tanks in San Cristobal, Guatemala

These tanks are lightweight, easy to transport, and can last 25 – 40 years. They are fairly durable and can usually be repaired with epoxy. New inlets and outlets can be cut into the plastic using tools as sophisticated as a hole saw or as simple as a machete. They have removable lids and can be cleaned with relative ease by turning the tank over or climbing inside and scrubbing the walls with chlorine.

The main disadvantage of plastic tanks is that, while they are the preferred water storage vessel, they are unaffordable for many rural families. Each tank costs around $300, a month's wages for a manual laborer in Guatemala. Consequently, the tanks are frequently subsidized by governmental and volunteer organizations, a model that is unsustainable, both economically and socio-politically. Families cannot afford to repair or replace tanks and, with little initial stake in the investment, may not feel ownership and responsibility for maintaining the system.

While rainwater harvesting is an adaptable technology that has the potential to transform the state of water security in developing countries, there are two major issues currently. Technologically, rainwater harvesting storage tanks are unaffordable for people in rural areas. Socio-culturally, affordable means of rainwater harvesting have yet to be discovered in many places.

Chapter 3. Project Strategy

3.1. Objectives

The purpose of this project was to make rainwater harvesting more feasible in developing areas by reducing system cost and making knowledge more accessible. This project had three objectives:

> ***Objective 1: Design inexpensive water storage tanks made of local recycled and repurposed materials.***
>
> ***Objective 2: Develop a learning module to teach RWH project management and critical thinking skills.***
>
> ***Objective 3: Pilot test the tank and learning module in Paraguay and at WPI.***

With background in both mechanical engineering and the social sciences (society, technology, and policy studies), I took an interdisciplinary approach to completing these objectives. Rather than designing the storage tank from an engineering perspective alone and basing the learning module solely on learning sciences, the tank and module were iteratively crafted with input from both fields.

Motivation for this project originated from my experiences in Guatemala with the WPI chapter of Engineers Without Borders-USA. However, I decided to pursue the three objectives in the context of another country, Paraguay, to gain experience working in another new culture, with people who weather water problems of a different flavor. WPI has a strong relationship with a non-governmental organization called Fundación Paraguaya, who welcomed the idea of promoting rainwater harvesting in Paraguay. Applying rainwater harvesting as a solution to drought-related agricultural vulnerabilities. Fundación Paraguaya provided a specific and unique socio-technical context for which the tanks and learning module were created.

3.2. Fundación Paraguaya and The San Francisco School

3.2.1. About Fundación Paraguaya

Founded in 1985, Fundación Paraguaya de Cooperación y Desarrollo (The Paraguayan Foundation for Cooperation and Development) is a self-sustaining, non-governmental organization that develops and implements practical, innovative, and sustainable solutions to eliminate poverty and create decent living conditions for every family.

According to its website, Fundación Paraguaya's main undertakings include a microcredit program, entrepreneurial and financial education programs for children and youth, self-sustaining agricultural high schools that train young people to become "rural entrepreneurs," and a separate NGO called Teach A Man To Fish that helps spread the self-sustaining school model around the world. Fundación Paraguaya has also developed a tool called the Poverty Stoplight that helps families identify areas of need and create a plan to overcome multidimensional poverty.

With 28 offices across the country and over 450 staff members, Fundación Paraguaya measures impact in the number of people reached. Its microcredit has served over 86,000 micro-entrepreneurs and, in the past three years alone, its programs have helped over 16,000 families overcome poverty. Fundación Paraguaya has been recognized as an innovator and leader in the microcredit industry and alleviation of poverty by a number of prestigious awards and organizations, including The MasterCard Foundation's Learn, Earn, and Save Program, The Skoll Foundation Award for Social Entrepreneurship, and the Nestlé Prize in Creating Shared Value.

3.2.2. The San Francisco Agricultural School

Fundación Paraguaya runs several self-sufficient agricultural high schools that teach students from rural families practical skills in farming and business administration. In 2002, the Escuela Agricola San Francisco, the San Francisco Agricultural School, was born as a first-of-its-kind school that is run like a business. Students learn skills for both running a farm and for making money by running a farm. Through several on-campus projects run by the students, including a cheese making, a hotel, and keeping fowl and livestock, the school teaches students agricultural and business administration skills, and students are able to afford their education by making money through these projects. Fundación Paraguaya now operates four self-sustaining schools in Paraguay. In 2006, Fundación Paraguaya initiated the non-profit ***Teach A Man To Fish*** to spread the model around the world. Teach A Man To Fish has reached over 80,000 students in the past ten years and has supported schools in over 100 countries.

The San Francisco school is located about two hours from Paraguay's capital, Asuncion, near a town called Benjamin Aceval in the Presidente Hayes province. The school houses 150 students (50 students per year) on its campus. The majority of the students come from poor farming families, many of which would not have been able to afford to send their children to school otherwise. The San Francisco school offers them the opportunity to overcome poverty by becoming "rural entrepreneurs" and turning their small farm into a profitable business.

The life of a student at the San Francisco School includes elements of both theory and practice. Students follow a biweekly schedule where, in the first week, half the class (25 students) spend their days in the classroom, and the other half apply their knowledge to run the school-business. In the second week the groups switch roles. They manage Hotel Cerrito, the hotel located at the school. They work with livestock (pigs, goats, chickens, quails, cows, horses, and rabbits), tend a fruit and vegetable garden, and cultivate a large field of yuca. Students run a dairy processing facility, where they make three types of cheese, dulce de leche, yogurt, and milk. They are responsible for both the maintenance of the school and for the marketing and sale of products. Through these activities, students both learn to run agricultural businesses and earn the money to pay for their education.

Figure 6: Hotel Cerrito at the St. Francis Agricultural School

3.2.3. Relationship with WPI

Since 2013, WPI students have had the opportunity to complete GPS, IQP, and MQP projects with Fundación Paraguaya and the San Francisco school (Great Problems Seminar, Interactive Qualifying Project, and Major Qualifying Project, respectively). In the past few years, a handful of GPS and MQP projects have aimed to tackle social and technological problems brought to light by Fundación Paraguaya. Thanks to the support of Mr. Martin Burt, social entrepreneur and founder of Fundación Paraguaya, and Dr. Robert Traver, the WPI Paraguay Project Center Director, WPI also sends students to complete their IQP in Paraguay through an extended stay at the San Francisco school itself. In D-Term 2016 (March – April), 23 WPI students completed their projects at and near the St. Francis School. Their projects included making the cheese processing cheaper, improving marketing of the dairy products, increasing tourism in the area, repairing the biodigester, improving the accounting and kitchen inventory efficiency, analyzing and redesigning the septic system, and improving the efficiency of the daily cleaning routine at the school.

In late August 2015, after speaking with Mr. Burt about rainwater harvesting as an inexpensive and practical solution to water challenges, he proposed that I develop the tanks and learning module in collaboration with the San Francisco school. The school teaches students to become problem solvers and entrepreneurs themselves, and hopes that by integrating rainwater harvesting into the curriculum, students will be empowered to embrace management of their own water security.

3.3. Stakeholders and Needs Analysis

A large number of people and groups are interested in and have affected this project. At the outset, a chart was made to consider each party that has some stake or influence. Many different groups and individuals were included in the chart, including the St. Francis School, members of the WPI project team, and other people and groups in Paraguay like materials suppliers. The complete chart can be found in APPENDIX X.

This section describes the main stakeholders, their perspectives, and their needs that were considered throughout the project process. This exercise helped focus the scope of and give direction to the project.

Students at the St. Francis School

The St. Francis School serves youths from rural agricultural families. The three-year program accommodates 50 students per class for a total enrollment of about 150. On a weekly basis, students alternate between classroom learning and application; one week, half the class spends time studying traditional subjects, like mathematics and writing, while the other half applies skills learned via various projects on the farm. They tend livestock and crops, run a cheese-making business owned by the school, etc. Many students come from rural families whose livelihoods are based on agriculture. Students learn to optimize crop production and profit, essential skills that they then bring home.

Inexpensive rainwater harvesting is another tool that can benefit students and their families. An on-site secondary water supply reduces stress on crops in times of drought, leading to better crop quality and larger yields. An elegant and accessible technology, rainwater harvesting can be adapted to meet the needs of a specific family or farm. Students who learn to manage a project from the planning phase through construction and long-term maintenance and repair will be equipped to realize rainwater harvesting systems at home. Additionally, entrepreneurially minded students can make a business leading rainwater harvesting projects at other farms nearby and/or by teaching the techniques to others.

Faculty at the St. Francis School

Señor Luis Cateura is the director of the school. He welcomed the idea of and made arrangements for building a rainwater harvesting system at the school and piloting the learning program. Another key faculty member was Señor Vergilio Borges. He is the Technical Director and is in charge of vocational training for the students. Together, Sr. Cateura and Sr. Borges will ultimately decide if and how to integrate rainwater harvesting into the school's curriculum. Therefore, both the technology and learning module needed to be compatible with—and tailored to—the school's pedagogy.

Fundación Paraguaya

Mr. Martin Burt, the Executive Director of Fundación Paraguaya, championed communications between my team at WPI and the St. Francis School. Fundación Paraguaya started the school as a place that would provide students with the skills they need to be successful. Ideally, they will be able to spread rainwater harvesting to their other schools as well. In addition, the project-based learning approach and curriculum guide developed for the learning module, described in Chapter 5. , is a method that the faculty can emulate to achieve more focused learning outcomes. Fundación Paraguaya hopes to see rainwater harvesting make a significant impact in the lives of the Paraguayan people.

WPI IQP Students at the Paraguay Project Center

In D-Term 2016, 23 WPI students completed their Interactive Qualifying Projects at the St. Francis School in Paraguay. During their time in-country, they volunteered to help implement the learning module and pilot rainwater harvesting system. Throughout the semester, I worked to keep the IQP class informed of my progress and the nature of the project through intermittent visits to their ID2050 class. A number of students increasingly expressed interest in helping bring this project to life.

It was initially unclear what the relationship between the IQP students and this MQP would be, particularly since they had their own projects to complete. As time went on, Karen Orton, a member of the Engineers Without Borders-USA WPI team and a Paraguay IQP student, took charge of overseeing the implementation of the lesson plans and system build in-country.

Dr. Robert Traver was a key team member as well. As a co-director of the Paraguay Project Center and advisor of this MQP, he was able to bridge the connection between my work at WPI and implementation of the deliverables in-country.

3.4. Limitations and Lessons Learned

Limitations and challenges helped focus the scope and goals of the project. With respect to working cross-culturally, managing a project remotely and in another country, coordinating project resources in an unfamiliar context, and accommodating a limited team size and timeline, the challenges faced also posed opportunities for learning and growth.

3.4.1. Working Cross-Culturally

One of the greatest challenges of this project was working cross-culturally in a Spanish-speaking country. Paraguayan Spanish is heavily influenced by Guarani, the country's second official language. Fortunately, due to time spent abroad in Guatemala and Costa Rica, I speak Spanish proficiently to communicate and translate documents. While the eloquence and vocabulary of the translations could be improved, they sufficed to convey concepts despite the language barrier.

Cultural norms did, however, impede communications at times. In Paraguay, engineering is still largely seen as a male profession, and concerns were raised that gender stereotypes would cause this project to be poorly received and ignored. For this reason, Mr. Burt facilitated communications with personnel at the St. Francis School until Dr. Traver and the IQP students arrived. It took several months to communicate the project objectives, but once proposed in this way it was warmly received.

Understanding the cultural context was crucial for this project, yet difficult to achieve at a distance. Originally, I was scheduled to travel to Paraguay but had to cancel due to extenuating circumstances. In order to design a learning module and tank that were culturally appropriate and adaptable, I needed to know what tools, skills, and materials were locally available, to grasp a sense of the customs, mentality of the people, willingness of students to work, and existing circumstances. During the first semester of the project, Mr. Martin Burt, Mrs. Dorothy Wolf, and Dr. Robert Traver helped guide my work to ensure that suggested activities would be culturally appropriate. In the last term, I worked closely with Karen Orton to make modifications to the tank design and learning module so that both could be implemented by the IQP students at the St. Francis School.

3.4.2. Project Management

Managing the project remotely was difficult at first. Once the IQP students arrived in country, many decisions were out of my hands. However, seeing the project unfold according to plans and resources I had spent months working on was rewarding. Most of the activities that took place in country came to fruition effectively and accurately because of measures taken earlier. I visited and spoke with the IQP class several times prior to their departure to ensure that they had as much knowledge about the project as I could impart. I met several times with Ms. Karen Orton to ensure that she understood the plans in detail. Further, Karen and I utilized Internet communications (email, WhatsApp, Facebook, WeTransfer) so that she could update me on in-country progress and we could collaboratively make decisions about adaptations and changes to the plans.

3.4.3. Timeline and Team Size

This project began taking shape in late August 2015. The final report was submitted on April 28th, 2016. Even though three quarters of a year were devoted to the work, more time would have allowed for deeper analysis of results, recommendations, and impact evaluation. Since the lessons and in-country build were not held until late April, there was little time to record results, let alone closely analyze and evaluate them. Because of this, I intend to spend time over the coming months interpreting and publishing findings.

I began this Major Qualifying Project as a one-person project. The difficulties of accomplishing an MQP without teammates are that the work cannot be distributed and ideas are coming from only one person. However, I found that as I became more and more passionate about the project, others were more and more likely to help. I may only have a one-person MQP, but the team working on the project is much larger. As mentioned in the Acknowledgements section, this project would not have been possible without the help of Brianna Fogal, who collaborated on my project in B-Term, 2015, Karen Orton and the IQP class, Engineers Without Borders-USA WPI, and WPI Facilities. These people voluntarily helped bring this project to life and were invaluable members of my team.

Chapter 4. Tank Design

4.1. Approaching the Opportunity For Better Tanks

While there are innumerable ways to store water from the rain (see Section 2.3), culturally appropriate options are not available in every context. In order for rainwater harvesting to be a viable solution to water challenges, storage tanks must be affordable, made of local materials, easy to use, maintain, and repair without years of study, scalable to provide sufficient quantity of water, and adaptable to address water needs different contexts. Objective 1 sprung from this opportunity:

> ***Objective 1: Design inexpensive water storage tanks made of local recycled and repurposed materials.***

A blended Systems Engineering/Engineering Design Process methodology was used to achieve Objective 1. Systems Engineering approaches projects from the perspective of stakeholder needs and functional requirements. The Systems Engineering process, portrayed in Figure 7, systematically encourages iterative design and revision at every step. The Engineering Design Process, shown in Figure 8, also follows an iterative design process, but takes a trial-and-error approach. Utilizing aspects of both approaches, design decisions were continuously tied back to the needs being met, but were also judiciously based on prototyping and testing.

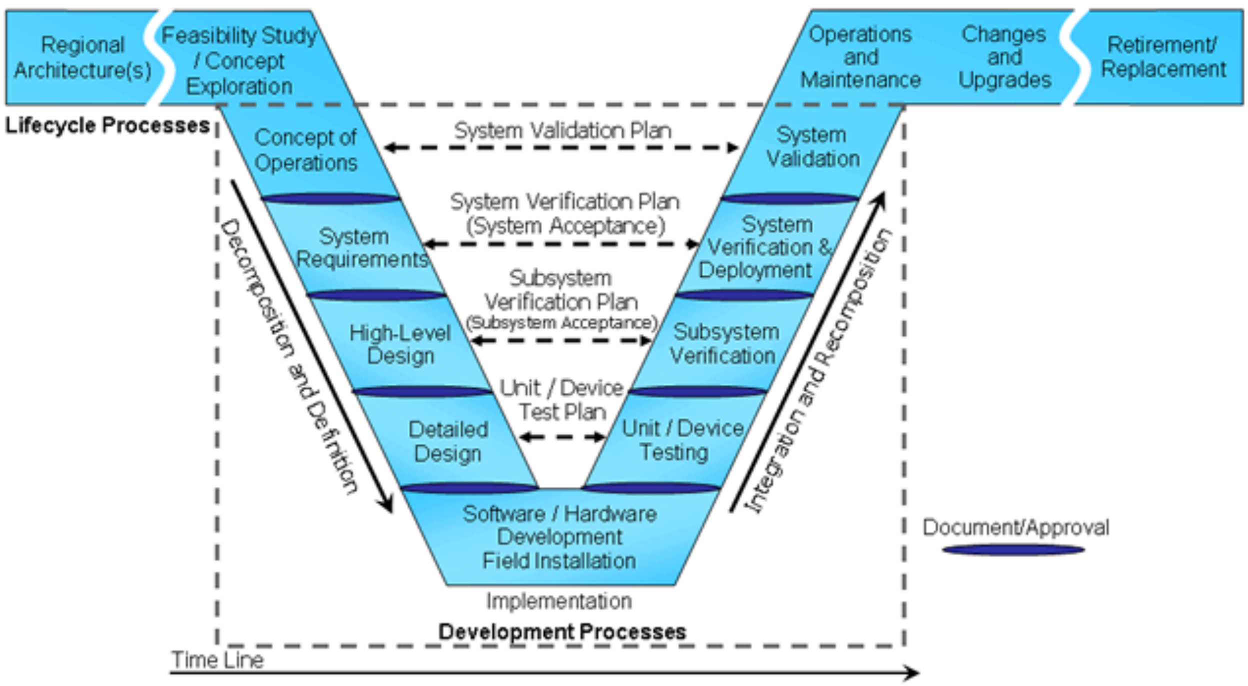

Figure 7: Systems Engineering Process (Federal Highway Administration)

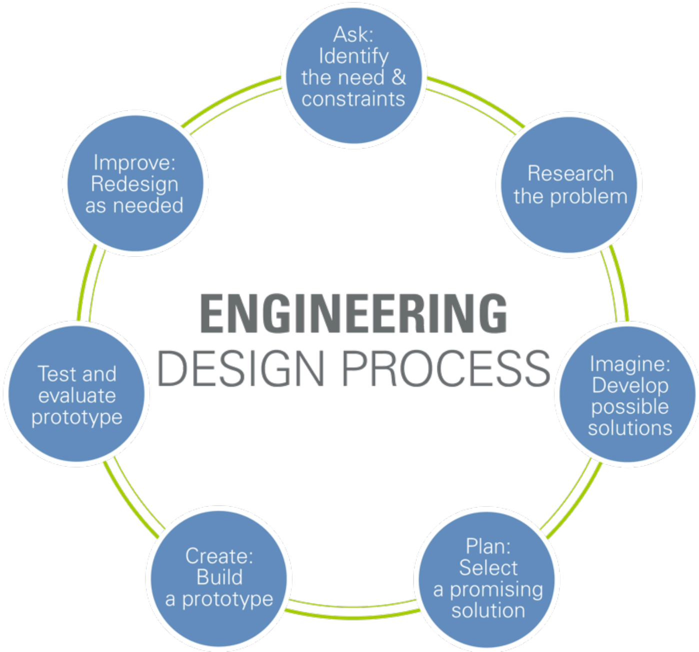

Figure 8: Engineering Design Process (Teach Engineering)

Overall, system design was completed through five steps that included elements of both processes:

1. Articulating System Functional and Physical Requirements
2. Identifying Materials and Developing the Conceptual Design
3. Analytically Improving the Conceptual Design
4. Creating an Excel Model to Design Specific Systems
5. Prototyping

Steps 1, 2, and 4 were completed with help from Brianna Fogal, who collaborated on this project as an Independent Study Project in November and December 2015.

4.2. Articulating System Requirements

At the outset of the project, a large number of ideas were generated for what a "tank made of recycled materials" might look like. To direct ideas, list of functional and physical requirements were developed. The following were considered in selecting an initial design for an inexpensive, culturally appropriate rainwater storage tank. The full tables are included in Appendix B:.

Functional Requirements:

- Supply adequate water quantity
- Supply adequate water quality
- Can attach to an irrigation system
- Culturally appropriate to operate
- Relatively simple to repair and maintain
- Does not cause negative social impacts or unintended consequences
- Made of locally-available materials

Tank and Material Physical Requirements:

- Inexpensive

- Strong
- Inert
- Weather resistant
- Transportable
- Locally Available
- Repairable

4.3. Identifying Materials and Developing the Conceptual Design

To begin the design process, we brainstormed ways that waste materials might be used to store water. With insights from my own experiences in Guatemala and those of Dr. Traver and Mr. Burt in Paraguay, we identified plastic and tires as two materials that are problematic, yet promising.

4.3.1. Tires: Environmental and Public Health Hazard in Paraguay

Tires, while commonplace, are complex composite parts. They have a wide variety of uses and are manufactured in a wide variety of sizes and shapes for different applications. Tire sizes range from 18-inch diameters for small passenger vehicles to 13 feet wide for heavy mining and construction equipment. Structurally, tires are made of several layers of rubber over a steel mesh frame. The combination of the flexible yet strong steel mesh and the bouncy rubber that does not degrade makes tires nearly indestructible.

That being said, tires are very difficult to dispose of. They do not breakdown in the natural environment, and equipment is required reshape or cut them. The rubber in tires is made from oil and natural rubber. The rubber can be melted down and incinerated to produce energy, but this also releases harmful fumes.

Tire recycling facilities in the United States freeze the rubber below the glass transition temperature and pulverize it to make astro-turf, rubber mulch, and other rubber-based products.

Paraguay has no tire recollection system and very poor disposal and recycling facilities. Spent tires are discarded into the environment where they stay until someone decides to do something with them. There is no demand for tires although they can sometimes be repaired by ***gomeros*** who also repair tire inner tubes for bicycles.

One of the most concerning issues with tires, however, is their role in the spread of infectious disease. Once water collects in the rim of the tire {be it from rain, from falling into a stream or pond, etc.} it is very difficult to get the water out. Tires can either be forcefully bounced to shake the water out, or they can be cut in half with a chainsaw. Otherwise, the water remains pooled in the rim.

This stagnant water creates a perfect environment for mosquitoes to breed. With a hot, tropical climate and regular rainfall, Paraguay is infamous for dengue and other mosquito-bourn illnesses. Programs that aim to reduce standing water have been effective in controlling mosquito populations. In remote rural areas, however, few people understand the relationship between standing water and the spread of these diseases. Even fewer care to do something about it.

Thus, tires were proposed as a sturdy, long-lasting, widely available material that could be used to make water storage tanks and, in the process, mitigate a public health hazard.

4.3.2. Storing Water in Tires

Storing water in tires is not a novel idea. There are several companies around the world that sell and install tire-based water troughs that ranchers can put in their fields to provide water for livestock

(University of Missouri Extension). Typically, these tire troughs are made of a single large tire, one with a diameter of 6' – 13', and is sealed to the ground with a concrete base. A pipe and pump system is used to deliver water to the trough.

Figure 9: Water trough made of a large vehicle tire (University of Missouri Extension)

We considered pursuing a similar design for the tire tanks to be used with rainwater harvesting systems, but quickly realized that these troughs rely on the large diameter of the tire to provide sufficient quantity of water. In Paraguay, most tires are from passenger vehicles and small trucks, not heavy equipment.

Several possible designs were developed for ways water could be stored in tanks made of tires for rainwater harvesting applications. Each idea was approached with leading questions:

- How can the tank be made watertight?
- How much water can be stored?
- What tools and skills are required for assembly?
- Will it be easy to clean and repair?

Figure 10 - Figure 12 depict some of the ideas that were considered but set aside.

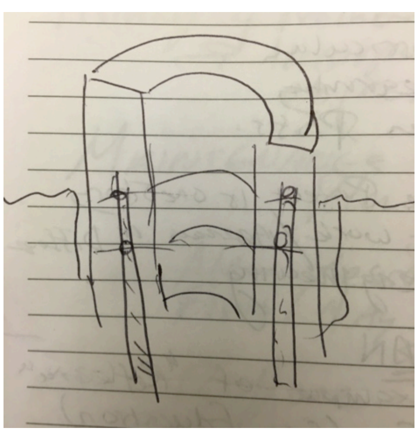

Figure 10: Tires with connecting rods

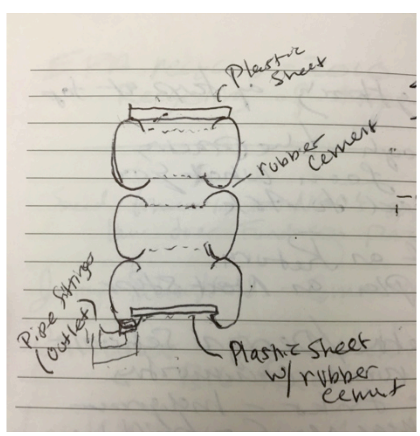

Figure 11: Tires cemented together

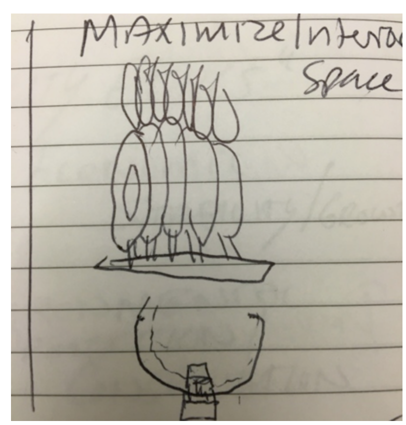

Figure 12: Horizontal configuration

The concept we decided to pursue further is a simple column of unmodified tires stacked like rings with water stored on the inside of the column. This design avoids the need to cut or reshape the tires in ways that might be time consuming and require skill. The tank can be sized by adding more tires vertically.

4.3.3. Lining the Tank With Plastic

One of the main challenges was figuring out how to make the tire tank watertight. Interfaces between tires are not flush. The edges of the tires are riddled with ridges and grooves that serve to improve traction for a vehicle but make it difficult to create a watertight seal. There are innumerable types of glues and sealants that could have been used to close the gap between tires, but most are expensive and we had difficulty discerning which ones are locally available. Sealing the tires together also would have made tank maintenance and repair difficult, so we began to look at other options.

We decided to pursue a design that uses an inexpensive or recycled plastic liner to make the tank watertight. An impermeable liner circumvents the need to create a seal between the tires. Plastic is frequently used in agriculture to protect crops and cover greenhouses. Waste plastics may also be available from agricultural or industrial packaging.

4.3.4. Selected Conceptual Design

The basic design we decided to pursue is a tank made of tires stacked in a column and lined with an interior plastic “bag”. The tanks connect to a gutter/downspout assembly to capture water off the roof of a building. In the original concept, the inlet and outlet tubes were sealed with gaskets and hose clamps. As seen in Figure 13 below, tire tanks could be connected in parallel to fill and drain at the same rate. The design was modular, so the system can be scaled to meet the needs of a producer or family.

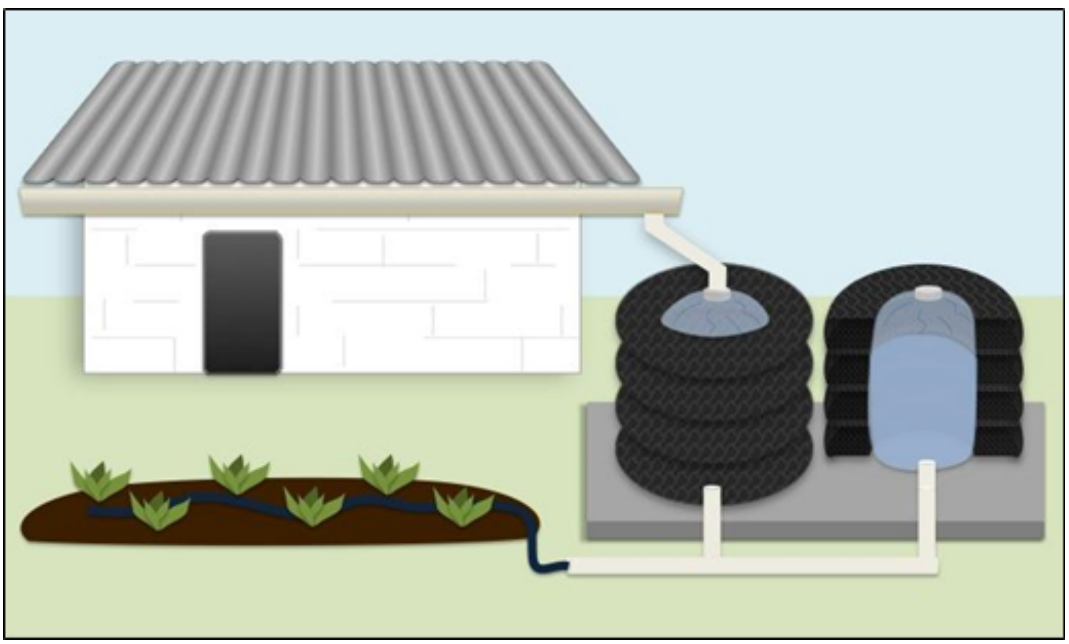

Figure 13: Idea drawing of RWH system, tire tanks with internal liner.

4.4. Analytically Improving the conceptual Design

4.4.1. Calculating the Water Pressure on the Inside of the Tank

In the design, we needed to ensure that materials used for the liner would withstand the water pressure in the tank. We determined that the critical points on the tire tank would be on the walls and the bottom. To determine the total force on the walls, we began with the basic pressure (P) equation (Equation 1). This takes the height of the tank (y), times the density of the water (ρ), times the Earth's gravity (g).

Equation 1: Pressure (P)

$$P = y\rho g$$

Next, to determine total force on the walls of the tank, we took the integral of this formal times the area of the amount of wall that is being considered. In this case, since our walls are round, we multiplied by the circumference, as shown in Equation 2.

Equation 2: Differential force exerted on the tank walls (df)

$$df = (y\rho g)(2\pi r)dy$$

Since we are taking the integral with respect to y, the variables become constants and can be pulled out of the integral as in Equation 3.

Equation 3: Total force over height (h)

$$\int df = \rho g(2\pi r)\int_0^h y\,dy$$

Once the integral from 0 to the height of the tank (h) is taken, the total force equation, Equation 4, is left. This is the Total Force on the walls of the tank.

Equation 4: Total force (Ftot)

$$F_{tot} = \frac{1}{2}h^2\rho g(2\pi r)$$

After calculating total force, we can use it to determine the average pressure on the walls (Pav), and simplify by substituting in the formula for total force as shown in Equation 5.

Equation 5: Average pressure (Pav)

$$P_{av} = \frac{F_{tot}}{2\pi rh} = \frac{1}{2}h\rho g$$

Finally, the last equation that we determined was the pressure on the bottom of the tank (Pb). This tanks the original pressure equation (Equation 1) and adds the initial pressure (Po). This is shown as Equation 6.

Equation 6: Pressure on the bottom of the tank (Pb)

$$P_b = \rho gh + P_0$$

From the equations we derived, we can determine the total force on the walls of the tank, the average pressure on the walls of the tank, and the pressure on the bottom of the tank.

4.4.2. ANSYS Modeling and Design Optimization

To further anticipate the forces that will be exerted on the lining of the tank, ANSYS Workbench was used to model the stresses and deformation of the liner when the tank is filled with water. To develop the model, I incrementally increased the complexity of the part. Through five steps, the model evolved from a simple hollow cylinder to a 4-tire column with an internal liner. ANSYS Workbench has the capability to assign material properties to a structure, allowing for a more accurate model that accounts for the different material properties of the tires and internal liner.

Step 1: Static Cylindrical Loads

Approach:

I began with a very simple hollow cylinder and applied an internal pressure gradient to observe areas of deformation and maximum stress.

- Material: Polyethylene
- Fixed support on bottom surface
- Pressure gradient applied to internal surface
  - $P = pgh = (998\ kg/m^3)(9.81\ m/s^2)(2m)$
  - P(h=0): 19,580Pa;
  - P(h=2): 0Pa

Results:

Bulging was most significant near the bottom of the tank where the pressure was high. Because the bottom surface was fixed, bulging occurred slightly above, not at, the bottom.

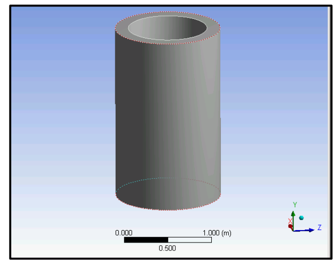

Figure 14: Solid Model 1

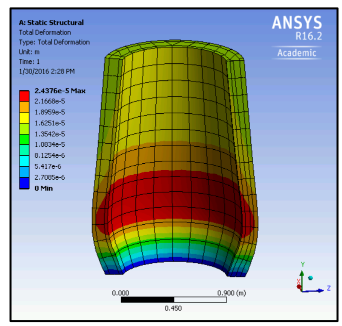

Figure 15: Internal Deformation Gradient 1

2: Sliced Cylindrical Loads

Approach:

- I sliced the cylinder into four segments, modeling tires stacked on top of each other, and applied the same internal pressure gradient.
- Fixed support on bottom surface.
- First, I applied elastic supports to the interfaces between segments. Results were very similar to the unsliced cylinder.
- When I changed the elastic supports to fixed supports, deformation was concentrated at the midpoint plane of each segment. I used a Multi-zone Prism mesh.

Results:

- Maximum stresses and deformation were concentrated at the center of each section.
- The top section experienced little deformation or stress while the bottom experienced the highest deformation.

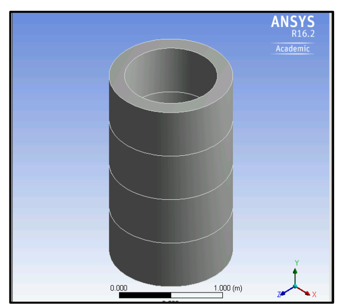

Figure 16: Solid Model 2

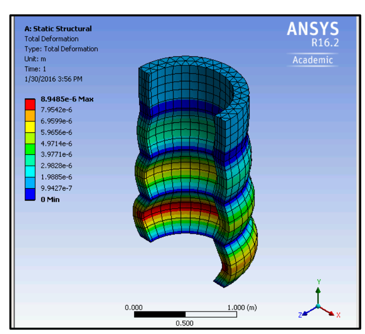

Figure 17: Internal Deformation Gradient 2

3: Tire Tower Static Structural

Approach:

- First, I created a simplistic solid model of a generic tire using SolidWorks 15.0. The model has slightly curved rims on the top and bottom, a cylindrical body, and a lip on the inside. It has thickness and dimensions similar to a real tire.
- I created a parasolid file of the solid model and uploaded it into ANSYS where I created a stack of 4 tires.
- I used Automesh to create a network of 19,238 elements, 38,840 nodes
- Using the same pressure parameters on the interior faces and a fixed support on the bottom tire, I was able to observe the deformation and stress gradients again.
- Originally, I added fixed supports to the faces where the tires meet. However, this prevented those faces from showing any deformation. I removed the fixed surfaces to improve accuracy, since they are only fastened at points by bolts.

Results:

- Maximum stress was observed at the midpoint of the bottom tire. The midpoint of each tire was the point on each tire that endured the highest stress and deformation.
- Deformation is highest on the top surface of the tank. In the animation, the top lip appears to curve in, likely because there is NO pressure applied to the inside surface of the upper rim of the top tire, and therefore the rim is a cantilever of sorts, hanging over open space. Other rims are supported by internal pressure.

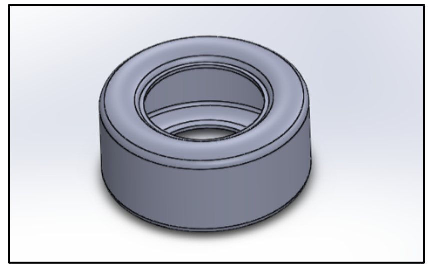

Figure 18: SolidWorks Tire Model

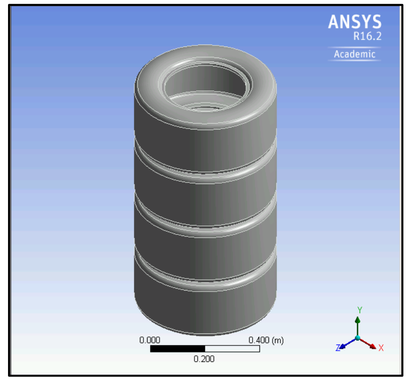

Figure 19: Solid Model 3

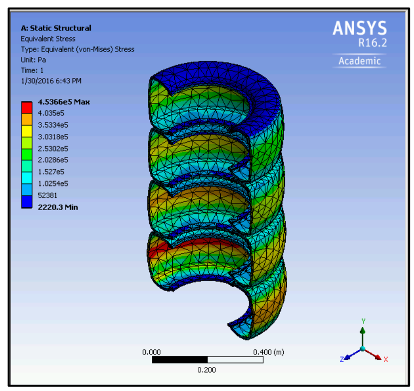

Figure 20: Internal Stresses Gradient 3

4: Modeling the Liner

Approach:

- First, a hollow, cylindrical feature was added to the interior of the tire assembly in ANSYS Workbench. The placement assumes that the liner will not be intentionally placed against the walls of the tires. This conservatively models the maximum stresses that might be applied.
- The bottom tire was fixed to the ground, but the liner was not fixed and had no friction applied.
- Separate meshes were created for the tire structure and the lining.

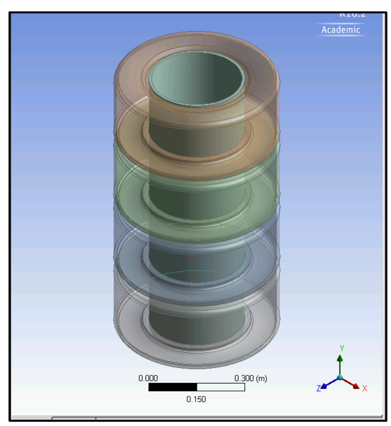

Figure 21: Solid Model 4

Results:

- The liner caved in, lifted off the ground, and shrunk from the top.
- Stress and deformation were highest at the midpoint of the bottom tire.
- Interestingly, the stress is highest in the curved parts of the liner, rather than on the points where the liner bends on the edges of the tire.

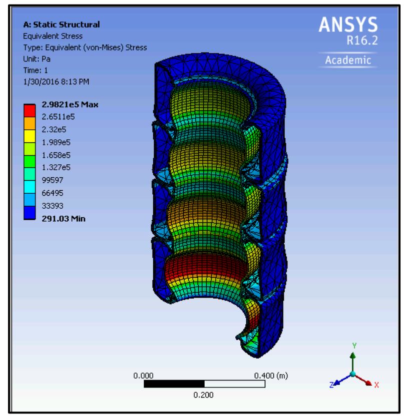

Figure 22: Internal Stresses Gradient 4

Step 5: Materials Selection

Approach

- Material properties for Natural Rubber with carbon black 60% imported from the CES Edupack materials universe.
- Steel was also used as the materials of the tires in some solutions.
- Hydrostatic load applied on the interior of the lining instead of a pressure gradient.

Results:

- More accurate representation of where the highest stress and deformation will occur (at the center of the bottom tire)
- Stress and deformation were highest at the midpoint of the bottom tire.

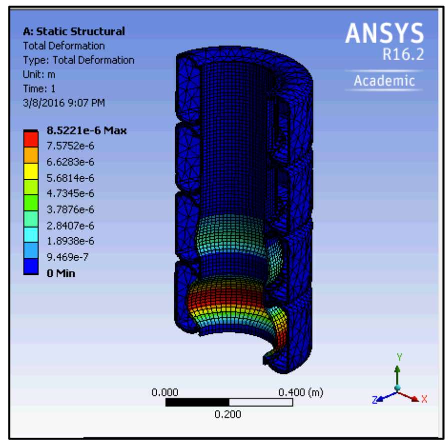

Figure 23: Internal Stresses Gradient 5

At step 5, I realized that tires are an incredibly complex composite material that is difficult to model accurately using numerical methods. Because the rubber in tires is layered around a steel mesh frame, the tire has properties of both rubber and steel, materials that have widely different properties. Tires have the strength of steel, but the flexibility and bulk modulus of rubber. They are durable yet forgiving. At this point, I decided to set aside further ANSYS analysis for future work. Empirical testing of the tires and tire tank structure can inform a more accurate model.

The numerical modeling using ANSYS Workbench FEM was useful for understanding where the tank lining will be most likely to fail. It was also an invaluable exercise in systematically thinking through the complexity of the design and materials. The system is far more complex than can be solved accurately using simple statics analysis because of the nonlinear and unknown material properties.

4.5. Creating an Excel Model to Design Specific Systems

We are constructing an Excel model that can help farmers and others design a RWH system that will satisfy daily water needs. The model determines the size and number of tanks needed based on daily consumption rate, capture surface area and efficiency, and daily rainfall. Calculations are based on Mun and Han's algorithms for defining RWH operational parameters.

We first agglomerated five years (2010 - 2014) of local daily rainfall data collected at the meteorological station in Asunción (the closest meteorological station to the St. Francis School). These data were entered into a single column in the Excel worksheet. In our calculations, we define daily rainfall with the variable Rd. Next, we defined the area of the collection surface (the roof area) as variable Ar in the worksheet. Using daily rainfall data and roof area, we configured the model to calculate the amount of rainwater collected each day. We denote daily water inflow as Qt. Daily inflow was calculated by multiplying the area of the roof (Ar) by the roof efficiency (Cr) and by the rainfall for that day (Rd). We divide by 1000 to convert mm of water to m^3.

Equation 7 Daily Water Inflow (Qt)

$$Q_t := \frac{\left(A_r \cdot C_r \cdot R_d\right)}{1000}$$

Next, to determine the volume of water in the tank on a given day (Vt), we set up an "if" formula in excel. The formula first queries whether the rainwater added that day (Qt) will cause the tank to overflow, or whether the water consumed that day (Dt) will cause the tank to be empty.

The formula sums: a. the quantity of water from the previous day (Vt-1); b. the volume of the added water (Qt); and c. water consumed that day (Dt). If the sum of these three is greater than the total volume of the tank, Excel reports that the amount of water in the tank is simply the maximum possible, the volume of the tank (V). If the sum of these three values is zero, it means that all water was consumed and the tank is empty. If the formula returns any other value, it means that the tank is not full, but nor is it empty. The sum of the existing water, plus additional water from rainfall, minus water consumed, is some real volume that fits within the tank.

Equation 8: Volume of Water in the Tank (Vt)

$$V_t := \left| \begin{array}{l} V \text{ if } V_{t-1} + Q_t - D_t > V \\ V_{t-1} + Q_t - D_t \text{ if } V_{t-1} + Q_t - D_t \le V \\ 0 \text{ if } V_{t-1} + Q_t - D_t < 0 \end{array} \right.$$

Once the formulas were set up, we experimented with the user-input variables: maximum tank volume (V), roof area (Ar), and daily water consumption (Dt). We input a tank volume of 5000 L, a roof area of 100 m^2, and a daily water usage of 100 L. Then, we graphed the amount of water in the tank each day of the year (Figure 24 shows an example graph using daily rain data from 2011).

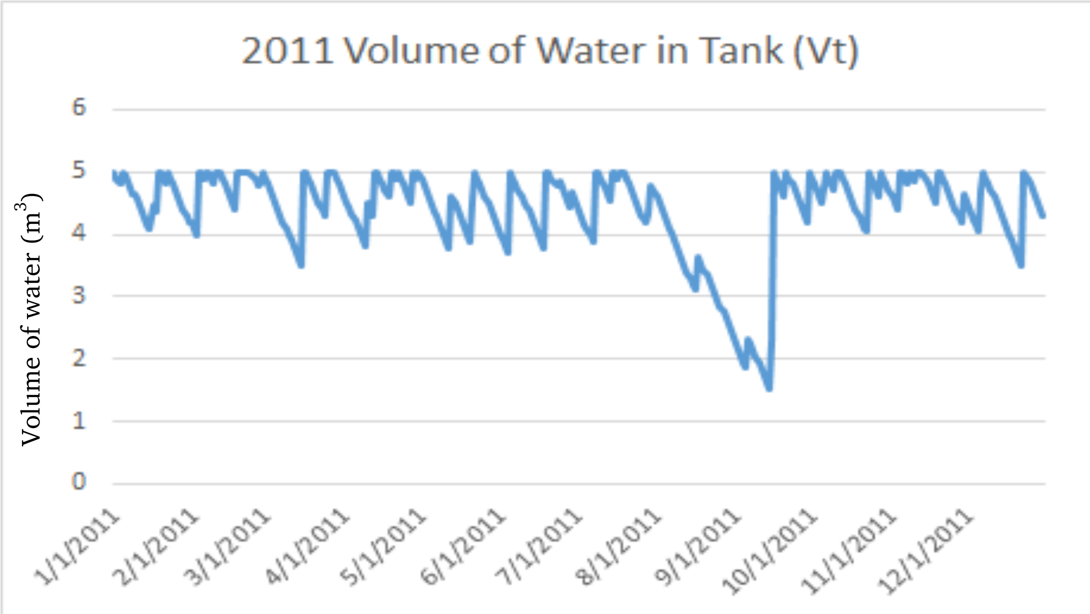

Figure 24: 2011 Volume of Water in Tank (Vt); during the dry season, water is partially depleted, but in this scenario, the tank is never completely empty

With these parameters, we were able to visually see that the tank would never empty. The blue line never dips to zero. Because the variables are all defined in the excel spreadsheet, the user can change the tank volume, roof area, or daily water usage, and the graph will adjust automatically. It is easy to adjust variables to determine what size tank is needed in order to have water everyday.

4.6. Materials Analysis and Tank Prototyping Methods

To assess the viability of the design, a prototype tank was built at WPI. This section explains the steps that were taken to first test the lining material and then build and assess the prototype tank. Findings were used to advise construction of a pilot system in Paraguay.

4.6.1. Liner Material Testing

The original idea for a tank liner was to use a tarp because these are relatively cheap and accessible. After some research, it was discovered that most tarps are only water-resistant and not water proof, meaning that the tarp would not be able to hold water in the tanks. With this information in mind, we spent time in the hardware store looking at the different types of tarps available. We found that the tarps that were water proof were expensive and flimsy. After searching the hardware store, we discovered scrap vinyl roller shades that we decided to test.

A full methodology of the tests we conducted on the vinyl, with step by step pictures, can be found in Appendix E:. Through Internet research, we discovered that heat can be used to weld plastic sheeting together. With one person using a heat gun and the other using a stainless steel roller, we melted two sheets of vinyl together to create a waterproof seal. We determined that the durability of the seal depends on proficiency in the technique of heat welding. We used this technique to make a small vinyl bag and partially filled it with water to test the seal. After many attempts, we concluded vinyl can be heat-welded to produce water-tight seals, but better materials may exist. We discovered that vinyl becomes rigid and brittle when cold. A picture of the vinyl sealed bag is shown in Figure 25.

While testing the vinyl heat seal, we observed small fumes. After further research on vinyl, it was found that the production of vinyl consumes 40% of the United States' chlorine gas and releases dioxins when burned; there is no "safe" dosage of exposure (Morrison, 2009). We also found that standard vinyl is laden with anti-bacterial and fungicidal agents and because of this, it is not safe for storing drinking water (Web Sweeper, 2015). Even though the tanks in Paraguay will not be used for human consumption, it would be unsafe for livestock and could possibly have harmful effects on crops. Because of vinyl's toxicity and high glass transition temperature, we decided to investigate different materials.

After considering many types of tarps, tent covers, and water proofing spray, we decided to explore different plastics (Bond, 2004). There are plastics that we use everyday to contain our milk, water, juice, yogurt, trash and groceries that are cheap and accessible around the world. Specifically, high density polyethylene (HDPE) is commonly used in food packaging and is readily available. In Paraguay, HDPE is also used in greenhouse covers and may be available at agricultural supply stores.

Using the same heat sealing technique, we used the stainless steel roller and heat gun again to create a waterproof seal. A picture of the bag we made using this method is shown in Figure 26. Though it did eventually create a waterproof seal, there were many leaks and the heat gun created an uneven seal. Next we tried using a propane torch instead of a heat gun and used the roller in hopes of creating a cleaner seal. After making another bag, shown in Figure 27, we discovered that a propane torch creates a thin, even waterproof seal that is stronger than the seal created by the heat gun.

Figure 25: Vinyl Bag

Figure 26: Polyethylene w/ Heat Gun

Figure 27: Polyethylene w/ Torch

However, in the time available we were unable to establish a technique that created uniform, reliable seals. Heat sealing is promising, and further development of the skill a theme that should be investigated in further projects. For the tank prototype, we decided instead to procure a single sheet of polyethylene from Home Depot and fold it into the column of tires. Using a single sheet simplified the design and minimized the number of interfaces, connections, and seals that could have caused problems.

4.6.2. Tire Testing

The next step in developing the prototype was figuring out how to secure the tires together. We obtained several old tires and tried to cut one apart using a jigsaw, as seen in Figure 28. We found that tires are structurally weaker once cut and so should be used whole. Additionally, the wire mesh made the tire difficult to cut without power tools, which many not be available in rural areas. The mesh was directional and also was easier to cut in some directions than in others.

Figure 28: Tire cut with jig saw

Figure 29: Tires have steel mesh under layers of rubber

We also found that it was easy to drill holes in the tire; the rubber melted away under the force of the drill bit. While the holes were not uniform in size, the drill was effective. It may also be possible to heat up a nail or sharp object and puncture holes in the tires. While we did not have the right tools to try this method out during initial testing, creating holes in the tires made it possible to bolt tires together.

4.6.3. Assembling The Tire Tank

In late March, 2016, a prototype tank was built at WPI behind the Ellsworth apartments. I was able to coordinate with Mr. William Spratt, the head of WPI Facilities, and some of the other gentlemen in the WPI Facilities department to arrange a time and location to build the prototype. Appendix F: contain documents presented to the Facilities department to describe the project and the proposed prototype. With their help, a water source and access to electricity were made available on-site.

Figure 30: Map of WPI showing location of the prototype tire tank

The tank was assembled in about 45 minutes with help from the Engineers Without Borders-USA WPI team. First we drilled two holes on one face of the first tire, each on opposite sides of the rim. The tire was flipped over and laid on top of the second tire. A key was used to mark the locations for the holes on the face of the second tire, and then those holes were drilled as well. Two bolts were used to secure the tires together. This was done three times to secure four tires together in a column. The column was placed on a wooden pallet for support.

Figure 31: Drilling holes in tires

Figure 32: Tire tank prototype assembled

The next step was to arrange the lining. A 10’ x 25’ polyethylene sheet was purchased at Home Depot. The sheet was laid over the top of the tank and slowly pushed inward. It was large and difficult to maneuver around the complex interior geometry of the tank. After about 15 minutes, the lining reached the bottom of the tire column and was somewhat pressed into the rims of the tires. It was, however, thickly bunched around the top of the tank.

Water was pumped into the tank from a water truck provided by WPI Facilities. As it was filled with water, the lining stretched and settled into the tire rims a little bit, but less so than anticipated. There was a significant amount of friction between the plastic and rubber that prevented the lining from being pulled entirely into the rims. The tank held about 40 gallons of water, but might have held more if the plastic was inlaid more smoothly inside the tire rims.

Originally I had hoped to use a rubber gasket, hose clamp, and PVC pipe to seal the opening at the top of the tank, but the bunched plastic made this option impractical in the prototype. Instead, I left the top loosely covered by folding the plastic over and placing a metal garbage can lid, borrowed from WPI Facilities, on top of the tank. I laid bricks on the ends of the plastic to prevent it from blowing around.

4.6.4. Tire Tank Disassembly and Results

The tank stood for three weeks, from March 23, 2016, to April 13, 2016. In that time, Worcester saw two days of snow/ice storms and several nights with sub-freezing temperatures. While I was not able to observe it every day, I took notes several times throughout the trial.

The most obvious finding was that the plastic retained water. There was not a noticeable difference in the level of water in the tank from beginning to end, implying that no water was lost. This was expected, since no holes or seams were made in the plastic, but confirms the idea that a plastic sheet inside a column of tires can be used to hold water for an extended period of time.

Figure 33: Interior of tire tank filled with water

Figure 34: Tire tank with metal garbage can cover at the end of the 3 week trial period

To disassemble the tank, I first tried to push it over while it was still full. I found that the two bolts at each tire interface added elasticity in the structure of the tank, making it sturdy yet flexible. The tires were free to move, but were soundly connected; they resembled the vertebrae of a spinal column, bolts acting like connective tissue between. Because of this, it was quite difficult to overturn the tank. I had to push the top tire over and pull the lower ones up at the same time. Ultimately, the lining slipped through the bottom of the tank, the weight of the water pulling it down as I pulled the tires up.

Figure 35: Katie Picchione attempting to overturn the prototype tire tank at WPI

After emptying the water out of the tank, I noticed that there was water pooled in the rims of the tires. This was curious since the tank was covered and no water appeared to be lost from the tank. It is possible that rain and snow leaked in among the folds of the liner, but water was found in the rim of each tire, not only the ones near the top, the location that rain would most easily pool. Based on earlier observations, I suggest that the water came from condensed water vapor from the air. Water has a high specific heat, and it takes longer to cool down and warm up than air does. In the mornings, air warms with the rising sun and is able to have a higher concentration of water vapor. What likely happened is that the water in the tank was still cool as the air warmed, causing dew to form on the outside of the lining between the plastic and the walls of the tank. Over time, this condensation pooled up in the rims of the tires. This was an unexpected, but incredibly important finding, since the pooled water could harbor insects and bacteria. To remove the water from the tire rims, I rolled and bounced the tank around for several minutes.

Figure 36: Water condensed on the outside of the plastic and pooled in the tire rims

The final step of disassembly was to unfasten the tires. I was able to pull some apart without unscrewing the nuts and bolts but had to remove the bolts eventually on all of the tires. The pieces came apart completely and were in the same condition as when they had been assembled three weeks earlier. Even the plastic, once dried, was folded up and could be used again.

4.7. Tire Tank Recommendations

Based on these findings, I made several recommendations for the next iteration of the tank and future research:

Try making a heat seal and/or a better technique for folding the lining

The bunching of the lining significantly reduced the storage capacity of the tank and increased the surface area for condensation to form between the plastic and tire rims. By arranging the lining more deliberately, space in the tank will be optimized and the plastic will be less cumbersome to work with.

Using heat seals, the bag can be sized to fit the tank. Testing the technique in-country might be a good way to figure out what works and what does not.

Folding the lining before inserting it into the tank may also help reduce bunching. Like origami, the plastic sheet can be folded so that the excess plastic lies flat, rather than bunching up in the rim.

Avoid power tools by using heated nails to punch holes through the tires.

For the prototype built in Worcester, we used an electric drill to make holes for the bolts that held the tires together. Power tools may not be available in all areas, but holes may be made using heated nails instead. Nails are also less expensive than bolts and are probably more commonly available. By heating nails and driving them through the two layers of tire, holes can also be aligned more easily. The tails can be bent under on the inside of the rim to reduce the likelihood of damaging the lining.

Punch many holes in each tire to allow water to drain from the rim.

It is crucial to allow condensate to drain from the tire rims in order to avoid creating conditions in which mosquitoes and other insects can breed. The easiest way to do this is to create a large number of holes in the bottom of each tire. The same hot-nail technique can be used to melt/puncture holes in the tire rim.

In the future, it may be possible to capitalize on the collection of condensate in the rims. A system that directs this condensed water to a secondary or tertiary storage unit could provide additional water quantity. Rather than wasting the condensed water, capturing and utilizing it creates additional opportunities for improved water security.

Test an inlet/outlet design

While it could not be tested in Worcester, Figure 37 shows a design that was developed for a sealed inlet/outlet for the tank. It uses PVC piping, a PVC T connector, and a hose clamp to create a sealed connection to the bag. A flexible rubber hose and sealant create a combined outlet and overflow.

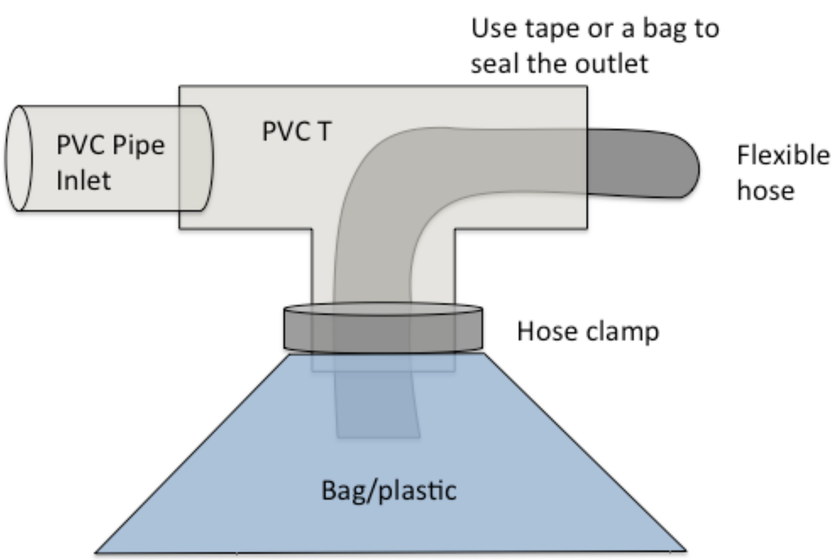

Figure 37: Proposed Inlet/Outlet for Tire Tank

4.8. Prototype in Paraguay

On April 27th, 2016, a pilot tire tank was built at the St. Francis School in Paraguay to test the idea on the ground. Several weeks were spent coordinating between Worcester and Paraguay to prepare for the build. A small building with existing gutters was selected as the build site, and materials were located in Asunción, about 2 hours away from the school. The build was successfully led by Karen Orton and executed with the help of several IQP students and students from the St. Francis School.

4.8.1. Planning the Build

The Excel model, described in Section 0, was used to design the system. Since the system is a pilot, the water will likely be used for low-demand chores such as watering houseplants; we estimated a daily demand of 5L of water. Using the measured roof area (16 ft x 15 ft) and daily rainfall data for 2011 – 2014, graphs were generated that show the level of water in the tanks at each day of the year. As seen in Figure 38, a tank of 200L was sufficient to provide water year round. We estimated that this is the volume of 5 – 6 tires, depending on the size.

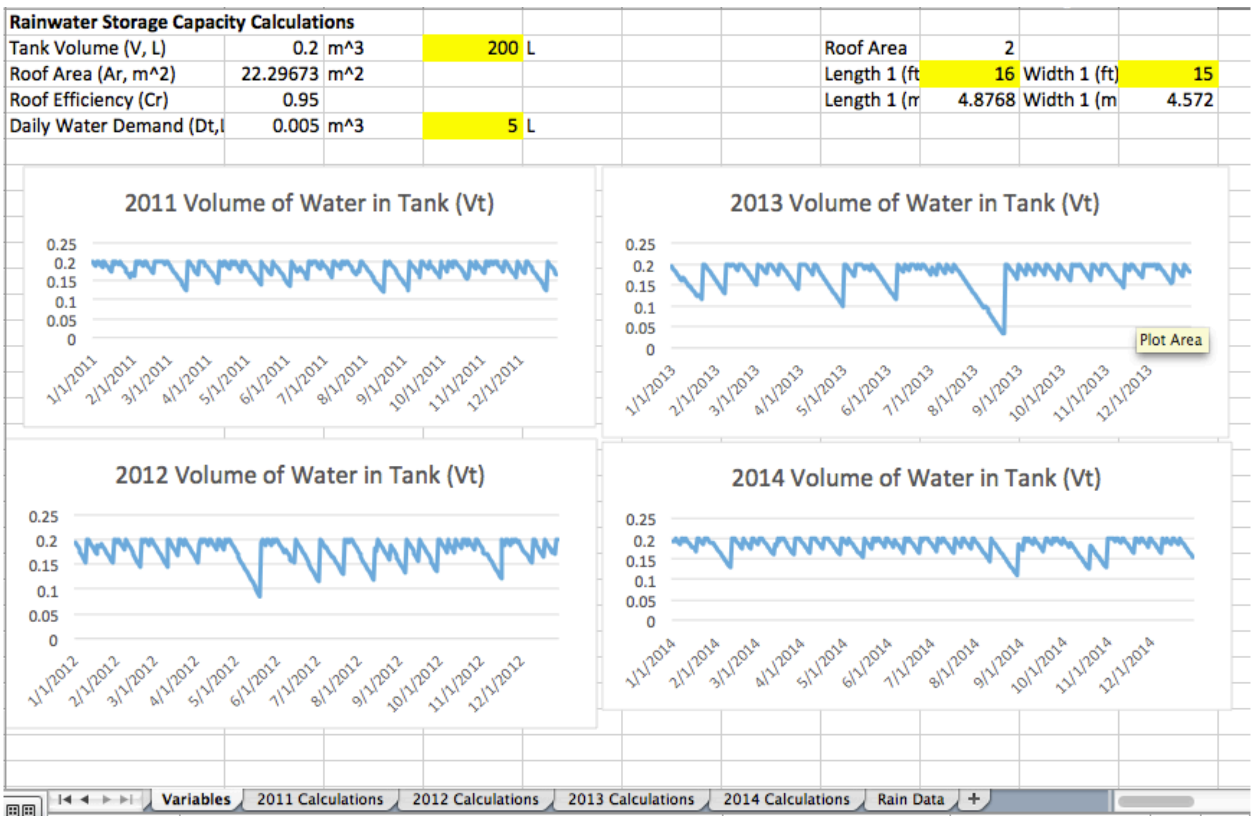

Figure 38: Excel Model Used to Design the Paraguay Pilot Tank

To advise the process of sourcing and purchasing materials, I created a preliminary materials list that details what materials were necessary and what their intended purpose was. The spreadsheet was written in Spanish, as seen in Figure 39.

A final materials list was created by Sr. Vergilio Borges and includes the quantity of items purchased, the cost in Paraguayan Guarani (the conversion to USD is approximately 5534.95:1), and the location where the items were purchased (Figure 40).

	Material	Cantidad	Como usarlo
Tank	Tanque		
Tires	Llantas		Hacer la frama del tanque
Bolts	Percos		Usarlos para juntar las llantas
Nuts	Tuercas		
Plastic sheet or bag	lamina o bolsa de plastico		Liner for the tank
Wooden pallet	plataforma de madera		Apoyar a los tanques
Tank inlet/outlet	**Entrada/salida del tanque**		
PVC T connector 2"	Conexion T PVC 2"	1	Entrada y salida del tanque
Hose clamp	abrazadera de la manguera	1 o 2	Sellar la entrada del bolsa y posible la salida donde esta puesto la manguera
Flexible hose	Manguera flexible	6 metros	salida del tanque y rebalse
Plastic bag or tape	bolsa plastica o cinta de ductos	1	sellar la salida acerca de la manguera
Downspout and piping	**Bajada de canal y tubos**		
Square to round adapter	Adaptor para convertir el parte rectangular a una conexion circucular como la tuberia		
PVC Pipe 2"	Tubo de PVC 2"	6 metros	
PVC T Connector 2"	Conexion T PVC 2"	1	Conectar la bajada de canal a la primera lluvia
PVC 90 elbow 2"	Codo 90 PVC 2"	3	Dirigir los tubos desde la bajada de canal a la entrada del tanque
First Flush	**Primera Lluvia**		
2" - 3" Reducer	Reductor 2" - 3"	2	Conectar la primera lluvia al sistema y tapar el tubo
3" Tube	Tubo PVC 3"	1	El cuerpo de la primera lluvia que capta agua
2" Cap	Tapadera de 2"	1	quedar el agua al dentro del tubo y vaciarla llenosamente
Empty bottle	Botella vacia	1	Tapar la primera lluvia cuando esta llena

Figure 39: Preliminary Materials List with Descriptions

	ESCUELA AGRICOLA SAN FRANCISCO.				
	PRESUPESTO DE MATERIALES				
Cantidad	**Materiales**	**Prc. Unit.**	**TOTAL (Guarani)**	**USD**	**Proveedor.**
8	Cubiertas viejas (Old Tires)	20,000	160,000	29	Gomeria
30	Bulonas de 3¨x 3/8 con arandelas. (Nuts and bolts)	950	28,500	5	Com. Alfred.
1	Kg. de plastico tubular (Plastic bag tube)	28,000	28,000	5	Plasticor
1	Plataforma de maderas (a buscar) (wood pallet)		0	0	
1	T de dos pulgadas PVC (PVC T 2")	27,500	27,500	5	Com. Alfred.
6	Metros de manguera de 1 pulgadas (buena) (1" hose)	8,000	48,000	9	Com. Alfred.
2	Abrazaderas para la manguera, (hose clamps)	4,000	8,000	1	Com. Alfred.
1	Cinta para sellar (dasy) (duct tape)	19,000	19,000	3	Com. Alfred.
1	Tira de 6m de caño de 2 ¨ PVC (PVC pipe 2" 6m)	180,000	180,000	33	Com. Alfred.
2	T de 2 pulgadas PVC (PVC T 2")	27,500	55,000	10	Com. Alfred.
3	Codos de de dos pulgadas PVC (PVC 90 Elbows 2")	26,000	78,000	14	Com. Alfred.
2	Reductor de 3¨a 2¨ 9PVC Reducer)	15,000	30,000	5	Com. Alfred.
1	Tira de 6 m de de tubo PVC de 3¨ (PVC Tube 3")	240,000	240,000	43	Com. Alfred.
1	Tapa de 2 pulgadas. (PVC Cap 2")	6,000	6,000	1	Com. Alfred.
	TOTAL		908,000	164	
	Conversion Rate		5534.95	1	

Figure 40: Final Materials Budget (Annotated in English)

The most expensive components were the PVC pipes and connectors, specifically those used to make the First Flush. For this build, the tires were purchased from a ***gomero***, a rubber worker, for convenience. In total, the First Flush, piping, and tank cost $164. The tire tank built in Paraguay has approximately 1/10th of the storage capacity of the systems built by the EWB-USA WPI team in Guatemala. If the tires were found or free, the volumetric cost would be approximately $0.05—half the volumetric cost in Guatemala.

4.8.2. Build Logistics

The build took place throughout the day on April 27th, 2016. WPI IQP students and students from the St. Francis School worked together to realize the system. The morning was spent divided into two groups, one focused on connecting the tires and one focused on building the First Flush.

St. Francis School students took the lead on the tank. They used an electric drill to put drainage holes in the tires and for connecting the tires together. Nuts and bolts were purchased instead of nails, so the tanks were connected in the same fashion as in the WPI prototype. It took about three hours to drill all the holes assemble the structural component of the tank.

Karen Orton led the group that was working to assemble the First Flush. St. Francis School students innovatively found a way to connect round PVC pipes to the existing square gutter downspout by using a 3" – 2" PVC reducer. They then built and connected the First Flush, placing a 3" cap on the bottom end. The plan for maintaining the First Flush is to manually remove the cap after rainstorms.

In the afternoon, the liner and inlet/outlet were configured. A single piece of large, tubular plastic was procured for the internal liner. The students were familiar with the plastic, the same used to make the school's biodigester. The students used a familiar technique to close the bottom end of the tube, making a bag. They folded, rolled, and taped the plastic to create a seal they anticipate will be waterproof.

At the top end, they again used tape to create a seal around the inlet/outlet pipe. They used a flexible hose to make the overflow, as recommended, and curled it on top of the tank to prevent a siphon from forming unintentionally when the tank overflows. They experimented with inducing a siphon to draw water from the tank, and found that it was difficult with the 1" hose. There is room for improvement, yet, the basic design was successfully implemented.

Figure 41: Students after connecting the tires

Figure 42: Karen Orton posing with the completed tank

Chapter 5. Learning Program Development

At the beginning of the project, Mr. Burt requested that a module be developed to incorporate learning of the new tank design into the curriculum at the St. Francis School. At the same time, the EWB-USA WPI team set out to develop a training program for teaching rainwater harvesting system maintenance in Guatemala. Meanwhile, I have spent the past three years developing ideas for a sustainable social enterprise based around rainwater harvesting that depends on the employment of local skills and knowledge. Innumerable opportunities for development and bettering of life become available with a vehicle for spreading knowledge. Thus, rather than focusing the learning module on tire tanks, I expanded the scope to include rainwater harvesting system design, construction, maintenance, troubleshooting, and repair. The goal of the learning program is that students are able to employ critical thinking skills to manage a rainwater harvesting project from the inception of the idea through a long-standing, sustainable system that provides water security.

While I have experience as a teaching assistant and instructor in the WPI Hass Technical Education Center in the Washburn Manufacturing Laboratories, and as a former tutor in WPI's Academic Resources Center, I have little formal background in education. To begin developing the curriculum for the learning module, I turned to literature on pedagogical approaches and utilized examples of lesson plans to create my own.

5.1. Background on Experiential Learning

Traditional approaches to learning employ lectures, memorization, and practice problems to present knowledge to students and help them develop skills. Pedagogical research and the development of "flipped classroom" and "Project Based Learning" frameworks, among others, have begun to reshape education to encourage higher orders of thinking, student-driven learning, and real world application.

Bloom's Taxonomy is one tool that, originally developed in 1956, has been to articulate learning objectives that engage students in higher orders of thinking (Vanderbilt University Center for Teaching). The lower taxa deal with the recall of information and increase in complexity and difficulty to where students are generating their own knowledge and skills.

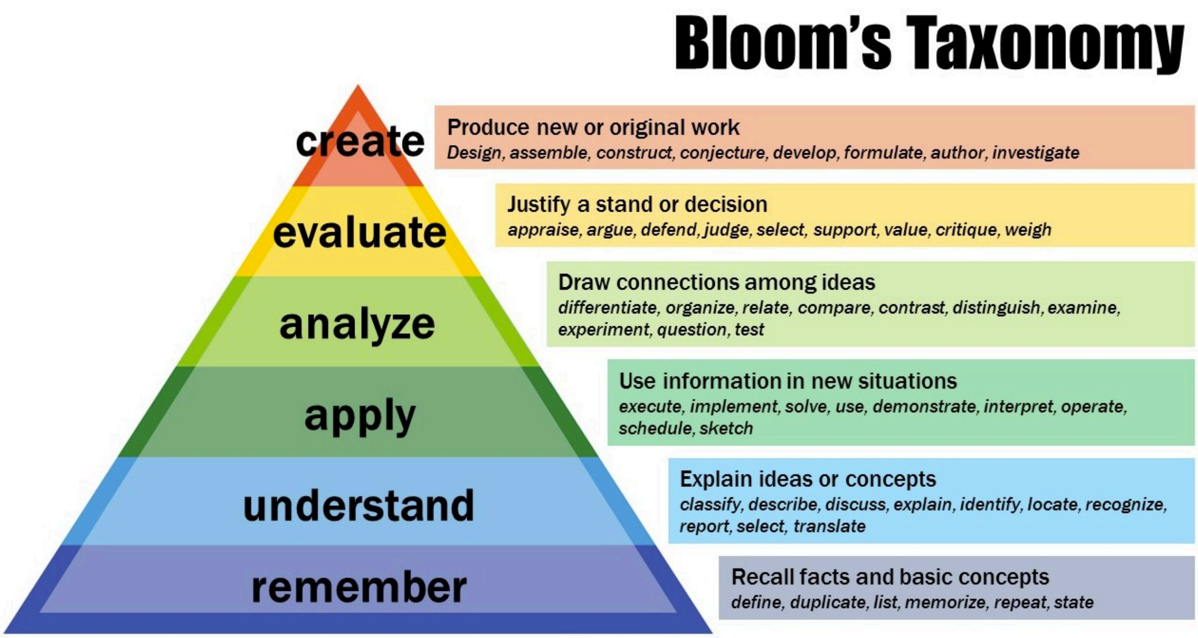

Figure 43: Bloom's taxonomic hierarchy of cognition (Vanderbilt University)

Since the development of Bloom's Taxonomy, another framework that has received increasing attention is the Integrated Course Design approach. Pioneered by Dr. L. Dee Fink, the founding director of the Instructional Development Program at the University of Oklahoma and a nationally recognized expert on college teaching, Integrated Course Design considers the learning goals, assessment and feedback, and teaching activities as interdependent and inseparable components of curriculum design that must be tailored to the situational factors in which a class is being taught (Fink, 2014).

The Project Based Learning (PBL) model is another framework that has started new pedagogies in curriculum design. Project Based Learning approaches learning from a similar approach: first identifying learning objectives, then determining assessment criteria, and finally developing activities that engage students in discovering knowledge, self-driven exploration, and development of skills.

Harry Torrence, director of the Education and Social Research Institute at Manchester Metropolitan University, UK, urges teachers to tailor assessment techniques to evaluate ***what*** the student has learned, rather than simply ***if*** the student has achieved specific learning objectives. By narrowing the scope of learning assessment, a whole curriculum might be "convergent" to specific content and omit opportunities for unanticipated and/or student-directed learning.

The Buck Institute for Education promotes the PBL model and has created an online community for educators to provide and share resources related to PBL. Their database was particularly useful during the development of the learning module. BIE provides guidelines, worksheets, frameworks, and examples to help teachers develop effective activities for engaging students and promoting student-driven learning.

Another resource I drew on in the development of the learning module was Project WET. Project WET (Water Education for Teachers) is an initiative to make and promote water-related classroom activities for elementary, middle, and high school educators (Brody, 1995). Sponsored by the Western Region Environmental Education Council and Montana State University, Project WET has published several curriculum guides that provide activities for teachers. Project WET lessons provided examples that I emulated when designing the rainwater harvesting curriculum guide. Interestingly, though Project WET based its 80-item learning framework on input from educators at all levels, natural resource managers, and university researchers (Brody, 1995), rainwater harvesting was not included.

5.2. Developing the Curriculum

The goal of the learning module was to equip students with the knowledge and skills to achieve water security at their home or farm through rainwater harvesting. The two sub-goals of the curriculum were (1) that students gain the project management skills to design, build, maintain, troubleshoot, and repair a rainwater harvesting system, and (2) that students think critically and employ the faculties of innovation, teamwork, planning, and problem solving. I took a student-driven and outcome-driven approach to developing the learning module, specifically defining what it was that I intended for students to learn. In retrospect, I realize that I also built flexibility into the framework so that the lessons could be adapted to be most effective when delivered in a different culture by a different person.

To develop the module, I systematically began by identifying the overall learning objectives and then breaking them down into specific "content standards" that I could use as a framework for the lessons. The next step was to determine criteria upon which learning could be evaluated. Finally, I wrote a curriculum guide that details four lessons and provides supporting materials (PowerPoint presentations, handouts, and worksheets).

5.2.1. Defining Learning Objectives

Articulating learning objectives required careful thought and foresight. With my experience building rainwater harvesting systems, I began by writing down all the steps taken from the initial decision to build a system through planning, construction, and maintenance. While the list was not exhaustive, it gave me the space to reflect upon the level of attention to detail required to build a sound system, the project management skills applied throughout the process, and the difference between knowledge-based and skill-based learning.

After brainstorming, I summarized the overall learning objectives of the learning module into seven specific statements:

By completing this learning module, students will be able to…

1. ***Explain Rainwater Harvesting as a means to improve water security***
2. ***Assess site-specific functional requirements for a rainwater harvesting system***
3. ***Design a site-specific rainwater harvesting system***
4. ***Make a construction plan***
5. ***Work on or lead a team to build the system***
6. ***Create an individualized plan for system operation and maintenance***
7. ***Troubleshoot problems, develop solutions, and make repairs***

These learning objectives were further broken down into 23 specific standards that articulate, with more specificity, what students will be able to achieve. Standards are coded based on the topic to which they pertain (Water, Building Planning, Operation & Maintenance, etc.). A few examples are included in the table below, and the complete listing of standards is available in Appendix G:. The first column indicates the lesson in which the content is presented. The second column codes the content based on the category, which is indicated in the third column. The final column explains what students will be able to achieve.

L	Code	Category	Standard
1	W1	Water	Articulate the concept of Water Security and explain how quantity, quality, and access affect water security
1	D3	Design	Draw a preliminary schematic for a system.
2	BP1	Build Planning	Make a list of needed materials and tools based on the revised system schematic.
4	OM2	O&M	Estimate the frequency with which roofs, gutters, and tanks should be cleaned based on the surroundings (trees etc.)
4	OM3	O&M	Create an inspection checklist and timeline
4	T1	Troubleshooting	Identify problems and their causes

The standards are written as verbs, indicating what students are able to achieve. While it was easy to state facts, turning that knowledge into measurable actions took time. As I began to work the standards into lessons, however, the action-driven objectives helped frame activities in the lessons.

5.2.2. Assessment Criteria

After the initial content was outlined, but before the standards were fully written, I developed a list of criteria for assessment. The guiding question was, “WHAT will be assessable and HOW will it be assessed?” I developed a list of artifacts that students who complete the module could create and criteria that an instructor might use to assess student learning through the artifacts.

Artifacts

Preliminary site drawing – this is a first attempt at designing a rainwater harvesting system, intended to engage students in creative thinking and problem solving.

Documentation on deciding the number of tanks/roof adjustments – this document includes calculations to determine the needed size of a tank depending on roof size, rainfall, consumption rate, and storage capacity.

Final drawing of system layout – this document is the final design and should demonstrate progress when compared to students' initial designs.

Materials list – a critical tool for planning a system build, the materials list (bill of materials) is a comprehensive list of all the parts needed to build the planned system.

Plan for materials supply and transportation – this documentation briefly explains where materials will come from and how they will be transported to the construction site.

Cost estimate/budget – Students should include the cost of materials, materials transport, and labor.

Complete system/photos of the realized system – For students who are able to actually build a system, this is the most critical activity. The built system is not only a learning implement, but continues to reinforce learning as it is used.

Personal maintenance plan – Each group or individual should develop a maintenance plan for their system that accounts for the nuances of the specific location.

Plan (or decision matrix) for troubleshooting – Students will create a plan for troubleshooting problems that are outside the scope of normal maintenance so that they can sustain the system long term.

Plan for making a repair – This document details the steps that students will take, generically, to solve a problem; it should include the process for buying and transporting materials and logistical considerations for making repairs (labor, time, etc.)

Criteria for Assessment

- Attention to detail: Accuracy, precision, thoroughness
- Functionality/Usability of the Deliverables
- Project Management: Identification of tasks, discipline in creating/following a timeline/budget
- Teamwork: Conflict resolution, collaborate well
- Professionalism
- Dedication and Interest

The original goal was to make rubrics for each artifact that would allow an instructor to compare student work upon the assessment criteria. With little sense of what student work in Paraguay might look like and no cultural context upon which to rank criteria like Professionalism and Teamwork—skills that are highly context and culturally dependent—I decided to postpone creation of rubrics until the learning module had been pilot tested in-country. Due to time constraints, no rubrics were ultimately created. However, these criteria were elemental in structuring lesson plans to present information in a way that would guide students to apply the skills identified in the assessment criteria.

5.2.3. Writing the Lessons

Originally the learning module was going to have seven lessons, one focused on each of the overall learning objectives. The number was reduced to four after several conversations with Mr. Burt about timing at the St. Francis School and the availability of the students.

The lessons were written iteratively. Several times, significant portions and entire activities were switched from one lesson to another or lessons were merged together. After the first draft of the curriculum guide was written, it was suggested that was made to provide PowerPoint presentations that the instructor can use to supplement the lessons. The PowerPoint slides were designed to be primarily visual. Text on the slides was originally written in Spanish and has not been translated, but images have been included in the report body to show the pictures and diagrams referenced.

While the PowerPoints were being made, further modifications were made to the lesson plans themselves to accommodate the visuals. Making the slides also helped visualize how the lessons would unfold and advised further development of the lessons. The rest of this section describes the content, format, and reasoning behind the structure of each lesson.

Lesson 1: Overview of Rainwater Harvesting and Intro to System Design

The first lesson brings students from a broad worldview of water issues to a specific solution and the design of a rainwater harvesting system. It was designed so that students understand why they should care about rainwater harvesting systems, are introduced to the different system components, and take the first steps to designing their own system.

Lesson 1 is structured to rhetorically bring students from a broad view of a common problem (water) to developing a solution (rainwater harvesting systems). It begins with questions about water security and ways students use water. The lesson plan encourages the instructor to ask questions like, "What are ways we use water? What happens if there isn't enough?" The lesson introduces the multidimensional idea of water security as a function of quantity, quality, and access, emphasizing that lack in any is an issue.

Figure 44: L1, Slide 4 presents various water needs and distinguishes between potable and non-potable uses

Figure 45: L1, Slide 5 introduces quantity, quality, and access as three dimensions of water security

Rainwater harvesting is introduced as a solution to water poverty, and students are asked to volunteer ideas for what kinds of systems or parts of systems could be built to capture the rain. The PowerPoint has a slide with a graphical representation of a rainwater harvesting system that has all the components labeled (roof, gutter, pipes, first flush, tank, base). A photo of a Guatemalan rainwater harvesting system is also included to provide different perspectives in case either the photo or graphic are pictorially misunderstood.

Figure 46: Labeled graphic of a RWH system

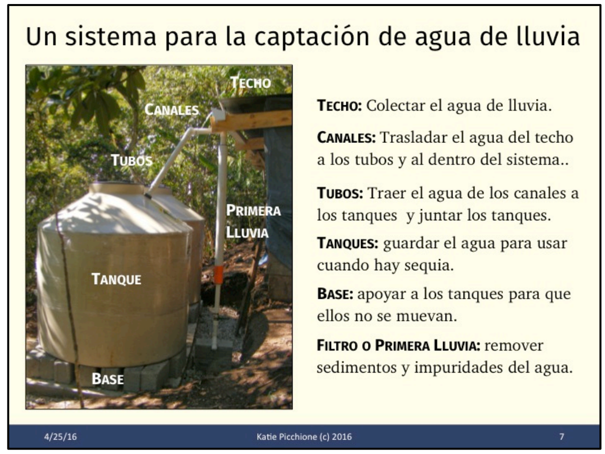

Figure 47: Photo of a RWH system (EWB-USA WPI) with descriptions of components

At this point, students break up into groups and use creativity to design their own rainwater harvesting system. Each group is given a ***Building Schematic***, found in Appendix H:, for which they are asked to design a system. The purpose is that students have the opportunity to explore design options based on a concept and minimal knowledge. It encourages innovation and imagination from the beginning. Each group may be assigned a different system component. Students then are asked to share their ideas with the class.

As each component is discussed, the teacher can show slides that detail the design of each and pass out handouts from the ***Rainwater Harvesting Guide Book*** (Appendix J:). Both the slides and handouts have labeled photographs and drawings or graphics of the component being discussed. These documents also show conventions I developed for ***field drawings*** so that systems can easily be designed and modified in the field with nothing more than a pencil and eraser.

The field drawings include two views of each building, a top view and a side view. The top view includes a birds-eye view of the markings for the direction of the roof angle, dimensions of the roof, and notes about the surrounding area. The side view allows a designer to visualize one or more sides of the building and arrange pipes, tanks, and gutters with the height and spatial relationship in mind.

A combination of shading and shape is used to distinguish different components. Gutters are portrayed as hatched rectangles, pipes are lightly shaded, and tanks are darkly shaded or filled in. The base can be represented by a speckled rectangle or a gridded rectangle, indicative of concrete or concrete blocks. Having and using these conventions allows someone to quickly and easily sketch systems in the field without being skilled at architectural or perspective drawing.

After each component is discussed, students are to be given time to revise their designs. A key part of the learning module is engaging students in the iterative cycle of design and revision. Since each group has a different building they are working with, each group's solution and ideas should be unique. Each group will encounter different nuanced situations they need to think through in terms of gutter placement, tank placement, tank size, and system layout.

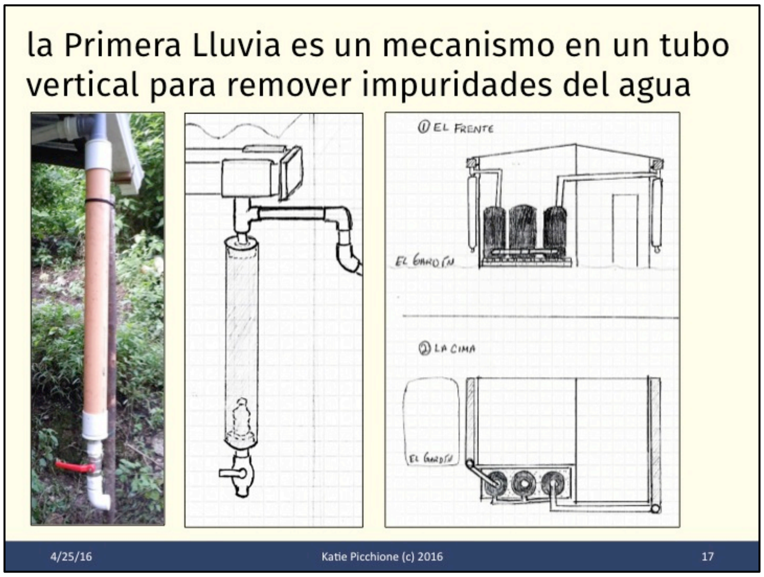

Figure 48: L1, Slide 17 shows a photo, perspective drawing and field drawing indicating the first flush

Lesson 2: Assessing the Site and Sizing the Tanks

The second lesson focuses on ensuring that a system will have adequate storage capacity to meet needs. This is primarily accomplished through an exercise that brings students through logic similar to that used to create the Excel model in Section 0.

The lesson begins by reviewing the main components of the system. The same diagram that is used in Lesson 1 is shown with the labels replaced by numbers so that students can fill in the blanks.

Next ensures a discussion about what factors affect the amount of water available in the tanks. This is a key part to understanding and being able to effectively implement rainwater harvesting. The amount of water collected is a function of rainfall, roof area, consumption rate, and tank size. It is crucial that students understand both what factors affect water quantity and which of those factors they can alter.

Figure 49: L2, Slide 9 notes the variables that affect water quantity and which ones can most easily be altered

Next, the lesson introduces the idea that the designer can decide how large to make the tank and may want to consider tanks of different sizes. To determine the appropriate tank size, students need to understand the relationship between roof area and volume of rain captured. The simple geometry is reinforced with a concrete application: collecting rain that falls on the roof.

Using a week's worth of sample rain data and the dimensions of a sample roof, the lessons guide students through the mathematics of determining the amount of rain captured and the water available with tanks of different sizes. The slides include an example of when the tank overflows and then runs dry because the storage capacity is not sufficient and an example of a tank that is appropriately sized.

Students are then given a rain data sheet that guides students through calculating the data for a week using the buildings they worked with in the previous lesson, and they are asked to calculate the amount of water in three differently sized tanks each day. Additionally, twelve weeks of average rain data are provided to show how, though imperfect, the mathematics can be simplified and scaled to estimate the size tank needed. The leading questions are, "Which tank will provide the most water for the longest time? Will you run out of water? When? What size tank will ensure that there will be enough water in the tank year round?" The worksheet can be found in Appendix I:.

Most of Lesson 2 is meant to be students working in groups to figure out the math and determine which tank is most appropriate. The teacher should spend time working with each group to ensure that they are on the right track and doing the math correctly. The final part of the lesson is to once again redesign the system from the day before, making modifications based on the new understanding of how tank size can be appropriately determined.

Lesson 3: Planning the Build

In the third lesson, students learn to plan a build by thinking about construction techniques, materials needed, and the processes for acquiring those materials.

The lesson opens with the guiding questions of "What quantities of materials are needed? Where will they come from? How will they be transported? How much will they cost?" A sample materials list is provided to guide student thinking first about what materials are needed and in what quantity. Students are given time to think about these questions in their groups and then discuss in the class.

Next, the teacher explains, in great detail, the method for building each component of the system. Ideally, an existing rainwater harvesting system could pose as a demonstration so that specific techniques can be discussed in an applied way. The PowerPoint slides list main points of concern and general methods for construction each component. The overall goal is that students think about the details and the level of detail required for building a system. Careful attention to detail will determine the success or failure of the system, and this lesson cultivates that skill.

After thinking through the detailed process for constructing each component, the materials list is revisited and revised. Prices are introduced and students will calculate the cost per material and total material cost of the system. This is an important skill for students who wish to actually build a system. Creating an accurate budget is essential for ensuring that a system can actually be built.

Lesson 4: Operation, Maintenance, Troubleshooting, and Repair

The final lesson is much less structured than the others. It aims to make students plan for short and long term maintenance and create troubleshooting and repair protocol.

System maintenance is crucial to ensuring water security. If a system is neglected, not only could it leak or break, but also it could harbor pathogenic microorganisms and insects, an unintended consequence. However, rather than impressing maintenance and repair methods, students are invited to predict the main problems that will occur in the short and long term and then generate their own suggestions for how to care for the system. Some systems may need more frequent maintenance thanks to externalities like overhanging trees, for example.

The second part of the lesson presents symptoms of problems (e.g. “there is water around the base”) and asks students to present possible root causes (“there is a hole in the tank lining,” “the tank overflowed,” “a tube became disconnected”) Various scenarios are presented and stimulate a discussion about how to identify the root cause of a problem. Further, students are asked to make a repair plan, including purchasing and transporting new materials if necessary and arranging for logistics with time and labor.

Part of the reason this lesson was left open ended is that I, having never been to Paraguay, do not have a good sense of the scope of problems that could occur. Rather than having one fixed set of answers, students could create a unique maintenance and repair plan for each building in the country. Rather than promoting a one-size-fits-all maintenance plan, the lesson is designed to promote the nuanced planning for adaptable appropriate technology.

5.3. Testing and Evaluating the Learning Program

I conducted a preliminary test of the lesson plan in February 2016 with a group of volunteers from the WPI chapter of Engineers Without Borders-USA.

Thanks to Karen Orton, Dr. Traver, and the WPI IQP students in Paraguay, the learning module was piloted in full at the St. Francis School in the evenings from April 18 – 21, 2016. Approximately 20 students from the school took the class. Taught by Ms. Orton and facilitated by 8 other IQP students, the class was held for approximately an hour each evening after regular school activities had ended. The first lesson was conducted in full with minor changes made prior to and throughout the lesson. The second lesson had to be conducted twice due to poor attendance at the first session and more difficulty than anticipated with conveying the mathematical concepts. The third lesson was then held in the fourth session, leaving time for only a brief discussion related to maintenance and repair. It was hoped that students who participated in the construction of the pilot system would have an in-field experience in which they would gain at least a basic understanding of the maintenance, troubleshooting, and repair process.

The lessons were originally planned to take place earlier in the month to allow more time for evaluation and revision. The timing was pushed back to accommodate the students’ schedules around the Easter holiday and the IQP project timelines. While I did receive feedback from Ms. Orton and Dr. Traver, the time constraints have made it difficult to truly assess the learning module. Upfront, one of the recommendations is to use more simple demonstrations to convey the mathematical concepts (the most challenging part of the module). In the future I intend to flesh out these recommendations and update the learning materials accordingly.

Over the coming months, I plan to closely watch the videos taken of the lessons and critique the efficacy of the lessons both through the students’ engagement in the material and by how well the lessons could be delivered. I intend to interview several of the IQP students when they return to the States and carefully review notes and feedback from Dr. Traver. I hope to analyze and publish these findings in the near future.

Chapter 6. Next Steps

As with any significant work, the endeavors we become passionate about are never quite finished. This Major Qualifying Project, extensive though it was, is certainly not exhausted. Fist and foremost, the pilot tank and learning module implemented in Paraguay need to be evaluated. Over the next three weeks, I plan to closely review video footage, interview the IQP students who helped facilitate the learning module and build the tank, and analyze the observations made by Dr. Traver. I hope to qualify what worked well, what areas could use improvement, and how the learning module and tank design could be made more adaptable. Publishable findings from this evaluation will both guide future work and allow other researchers and practitioners to learn from the successes and shortcomings of the module and tank.

There are several technical areas that need further attention. The pilot system needs to be tested and monitored over a more lengthy time period to identify technical problems that arise with use and maintenance in the long-term. A more technologically sound mechanism needs to be developed for ensuring that water can be drawn from the tank without creating opportunities for the lining to leak. Deeper analysis of materials available in-country could advise design improvements to further lower the cost of the tanks. Finally, an empirically tested computer model to numerically analyze the tank design could prove useful in adjusting and experimenting with new designs that utilize tires and/or the plastic linings in new ways.

The curriculum guide, with improvements, has the potential to promulgate rainwater harvesting in areas it may not be culturally appropriate, affordable, or technologically feasible. By promoting an open attitude towards adaptable technology, the learning module invites students to be creative and innovative in developing their own solutions to problems. A key question that will drive further development of the learning module is, how can we develop a curriculum that is structured for flexibility? How can the design of the lesson plans and learning materials promote exploration, innovation, and self-driven learning among students? To promote an adaptable technology, the learning module itself must be able to adapt to cultural and technical nuances.

Coupling an affordable, culturally appropriate technology—that is desperately needed in many areas—with a flexible learning module also springs opportunities for social entrepreneurship. Students who successfully complete the learning module and are able to build tailored rainwater harvesting systems now possess a marketable skill set. With both technical and educational tools in hand, these students can become teachers, promoting self-efficacious sustainable development among their own people. Rainwater harvesting offers opportunities to create jobs, build local economies, ***and*** provide water security. To date, I have written several grants that align with this theme of spreading rainwater harvesting through social entrepreneurship (see Appendix L: Kalenian Award Proposal). I plan to continue improving water security and access to other basic human needs through my life and career.

Chapter 7. Conclusion and Reflections

Through this project, an inexpensive water storage tank was designed and built out of recycled tires and inexpensive plastic; a learning module was crafted to teach Paraguayan students the project management and critical thinking skills necessary to build and sustain a rainwater harvesting system. Both the tank and learning module were preliminarily tested in Worcester, MA, at Worcester Polytechnic Institute, then piloted in Paraguay at the St. Francis Farm School. Based on preliminary evidence, both the tanks and the learning module were not only effective, but also impactful.

In the timeline of the project in Paraguay, the learning module was implemented first, followed by the construction of the pilot system several days later. The Paraguayan students who participated in the build had already completed the learning module. Realizing the system was a final step in ensuring that students had the skills and knowledge to build a system. Here, there is a story to be told.

At the start of the build, the Paraguayan students were shy. Nobody answered the question posed about how to connect a round pipe to a square gutter downspout. Nobody seemed to have ideas. When the WPI students walked away for a few minutes to investigate other options, the Paraguayan students came to life. They began to talk amongst themselves, ideate and plan. The WPI team came back to find the students bursting with ideas, requesting paper for drawing their designs, and collaboratively innovating a solution.

This is but one anecdote that illustrates the main finding of this project: ***accessible technologies inspire innovation***. Perhaps a group of high school-aged Paraguayan farmers creatively coming up with feasible solutions to a technical problem in which they have been trained is a modest example, but throughout the course of this project, I observed this phenomenon again and again. My peers at WPI took interest—and many ultimately helped with this project. Mr. Burt was quick to come up with technical suggestions. When I first brought home the idea of a tire tank to my family, everyone from my seventy-year old grandparents to my thirteen-year old brother was intrigued. The first question asked was, “How on Earth are you going to store water in ***tires***???” This was almost always immediately followed by suggestions. I could use glue, or spray-on rubber coating, or a wooden cover for the tank. The suggestion of a concept that was simple, yet previously unimagined, stimulated generation of ideas.

Through my work with Engineers Without Borders-USA WPI in Guatemala, I found the same situation. Men and women, who had little to no formal education, living in a poor rural community in the mountains of Guatemala, living in destitute conditions, became project leaders in building rainwater harvesting systems once the muse had struck. These people were frequently put in positions where they had to modify designs in the field and find solutions to minor technical issues that the EWB-USA WPI team overlooked or was not present to fix. Many times, the community members stepped up to the plate and solved the problem.

Accessible technologies inspire innovation.

Fundamentally, the tank design and curriculum are not “one size fits all.” There are not perfectly crafted to suit every need; both required modification when applied in Paraguay. However, they were designed iteratively, and, through the iterations, they were designed to be adaptable. In order to achieve culturally appropriate technologies and educational programs, adaptability is key.

If a technology is not compatible with the socio-political, cultural, environmental context in which it implemented, the technology will fail. There are countless examples of development projects gone wrong. Lack of cultural congruence is frequently the cause of failure. When a technology is adaptable, it can be ***ethno-engineered*** to accommodate and conform to the specific context in which it is implemented. The term ***ethno-engineering*** is seldom seen in literature, but currently has a negative connotation regarding the implementation of traditional local technologies in new ways. But developing communities do not want to revert to old technologies, studies show. Rather, people desire new and improving technologies, technologies that they can own, control, and tailor. And so, I propose we turn this term in a new light. Rather than the resurrection of traditional technologies in indigenous cultures, ethno-engineering can be more widely applied when framed as the adaptation of new technologies based on situational knowledge, available resources, and cultural norms. Rather than ethno-engineering a technology ***for*** a cultural group, let us suggest technologies that cultural groups can ethno-engineer for themselves, technologies that can be shaped ***within*** a culture.

Accessible technologies inspire innovation. Let us make technologies accessible.

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APPENDICES

Appendix A: Stakeholder Needs Analysis

Name	Description	Role/Needs	Communication	#
Escuela St. Francisco	Place of Learning	Infrastructure for sharing knowledge students need, maintain project later	Email/Skype	2
WPI	Authority/Framework	MQP Required	paperwork	1
Katie	Graduating Senior, EWB President	MQP that she's passionate about	Daily Meetings, phone/email/google	1
Brianna	Junior, ISP	Design project that she's passionate about	Daily Meetings, phone/email/google	3
Dr. Traver	SSPS Advisor, Paraguay Project Center Director	perspective on socio-cultural aspects, interested in agriculture	Weekly Meetings-email	3
Dr. Apelian	ME Advisor, Materials Processing Institute	Specialized in recycled materials, close with Martin Burt	Bi-weekly Meetings	3
Martin Burt	Former Mayor, businessman, founder of F.P.	Advisory Role, contact to the school/country, wants to see this succeed	emails, phone, skype	3
Students/Farmers	users, learners	Empowered to live better and snare knowledge -> empower others	Burt, email, skype	2
Paraguay's Environment	Land, water, air, animals, society/culture	sustainability & equilibrium, cultural appropriateness	one-way: accessed through library/Internet	4
Materials Suppliers	local hardware stores, businesses	profitable, early notice of large orders	email, in person	4
Standardization organization	Set standards for water quality, env. contamination	Guidelines for tech specs, testing, M.S.D.S/ Reference materials	One-way: info accessed through library/internet	5

Appendix B: System and Material Functional Requirements

Needs/Requirements

Requirement	Description/Factors	Way to Measure	Stakeholder
water quantity	must be sufficient to meet needs, depends on rainfall, capture area (roof), consumption rate, storage capacity	(L) empirical measurements, calculated based on daily rainfall data, interview users	farmers/student users
water quality	Must be adequate for agriculture. Air pollution, roof contaminants, tank materials	water quality testing, materials testing for tanks, interview user	farmers/student users
irrigation system	cheap, repairable/maintainable, culturally appropriate		
Knowledge	Design, instruction, maintenance, repair		
Knowledge about knowledge: learning about learning, training the trainers	teaching (sharing knowledge with others), research (obtaining knowledge with self), institutional knowledge transfer, improving/expanding/retaining knowledge within an organization	end goal of sustainability	

Tank Materials

Requirement	Description/Factors	Way to Measure
Strong	withstand force of water	tensile strength
Inert	can't leach toxic chemicals into the water	materials testing
weather resistant	storms/force, solar degradation, hail, temperature	materials testing, M.S.D.S/References
Transportable		
Locally Available		
Repairable		

Appendix C: Project Questions for Mr. Martin Burt

Questions:

- How will a RWH system benefit the school? What do the school and the students **need**?
- Are the students **interested** in learning about RWH? How can it benefit them and their families?
- How can the RWH training be integrated into the school's existing **instructional framework**?
- How does **drought affect the business** operations of the school? Are there certain times of the year when droughts are most prominent?
- What are the various **ways water is used** on the farm? (Irrigation, animals, human consumption, washing things, fish ponds, etc. - materials must be suitable for all uses)
- What are the technical and water needs of the old church/RWH system and the cabins
- What do you think about having us work with a group of students, a **project team**, from the school? These students would be involved in designing the specific system for the school and become experts. This team may also be involved in the upkeep of the system after the project is complete and/or be key players in starting a sustainable social enterprise to teach others how to build inexpensive rainwater harvesting systems.
- General information we need:
    - **Daily rainfall data** from the past 5-10 years for the school or surrounding area
    - **Blueprints** or a map of the school with the farm and buildings
    - **Topographical maps** available of the area
- Information about the farm:
    - What is the **size of the farm** at the school?
    - What **crops** are typically cultivated and how much water do they need? Are they cultivated year round or are they seasonal?
    - Is there an irrigation system or are crops sustained from rain alone?
    - Logistical information about the infrastructure:
    - How far is the farm from the other buildings? Can we run a hose from the tank to the fields, or is it be more effective and efficient to transport water another way?
    - What materials are the **roofs** made of?
    - Are there **already gutters** attached to the buildings?
- Project Process
    - What time and resources can Mr. Virgilio Borges and his students will dedicate to building and maintaining a systems? Is it worth their time?
    - Discussion about current ideas: water storage tanks made of used tires and recyclable plastic. There is a technique, but it is definitely a viable possibility.
    - What are possible **places to put water storage tanks**?
    - What **skills** are the students taught, specifically?
    - What **tools** are available at the school that we can use?
    - Let's come up with a plan for learning about what materials are available in-country.
- Leading questions:
    - Where are hardware stores located?
    - How can we obtain inventory information about what hardware stores sell? Catalogues? Photographs?
    - What are other, unconventional places we may be able to find materials?

Answers:

1. A rainwater harvesting system benefit the school in two ways: it will strengthen the current learning-by-doing curriculum for our high school students and will provide an alternative water source for agricultural production in case of drought. It will also be an opportunity for students and faculty to see how a RWH system works. We will insert this project into the "Rural Construction" class. Students will be able to transmit this new skill to their families back home.
2. Although Paraguay has good rainfall all year round, sometimes there are dry months, particularly in the winter months of June-July. Also, we are getting ready for another El Niño crazy-weather cycle, so we might have either a lot of rain or no rain. I am not sure.
3. As I mentioned, water is used in the school for human and agricultural use, both crops and animals. There are 150 boarding students living on campus and some 25 faculty members. The school hotel also is quite busy and it can house some 70 people...The school has grid electricity and has a generator in case of blackouts. The school has a few wells and in general has no water problems.
4. I understand that we have a few options for you. (1) you could build, with student help, a small RWH system for one of the small hotel cabins; (2) you could fix the old RWH system that 20 years ago existed on the school Church; or (3) you could help with the large reservoir that the school is thinking of digging to provide water for the new 50-acre eucalyptus plantation on campus.
5. Once we have a clear idea of the best alternative, we can assemble a group of students to work with you and Prof. Virgilio.
6. As I mentioned, the school sits on 65 hectares of land, 45 km from Asuncion, our capital city. Some 30 hectares are used for animal grazing and the rest is for growing crops, the vegetable garden, and the new forestry plantation. There is sufficient water year long for most needs, although as I said, there are some dry months. The vegetable garden has a drip irrigation system. We don't have information on the rainfall of the past 5/10 years nor a topographical map of the area, unfortunately.
7. In general, depending on what you want to do (use recycled material such as old tires, tarps, fiber glass water tanks, etc) we can find suitable tools in local hardware stores.

Appendix D: Project Information for Mr. Martin Burt

These materials were given to Mr. Burt to succinctly summarize the project in December of 2015. The intention was for them to be used in presenting the idea to the Mr. Cateura, the principal of the St. Francis School. We prepared a one-slide PowerPoint, a 2-page paper, and a letter to Mr. Cateura.

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1. One-slide presentation summarizing the main project activities at the St. Francis School (learning module and pilot system)

2. Two-Page Project Proposal and Draft Timeline:

Rainwater Harvesting Opportunity

A proposed project and learning module for inexpensive and sustainable capture of rainwater

December 3, 2015

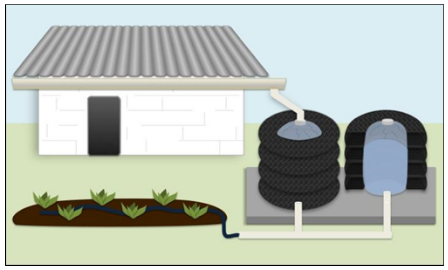
Project Plan

Water is a fundamental resource, used for drinking and cooking, bathing, cleaning, and agriculture. In Paraguay, agriculture accounts for 30% of the country's gross domestic product (GDP), and rainwater alone hydrates 97.9% of its cultivated land. While rainfall is non-uniform across the country, Asunción, the capital of Paraguay, located in the southernmost portion of the Presidente Hayes department, received over 1850 mm of rain in 2014. Cumulative rainfall was, and typically is, sufficient to irrigate crops year round. However, lengthy droughts, which occur unexpectedly throughout the growing season, threaten crop yields.

Technology and Training

Rainwater harvesting (RWH) offers an elegant solution to drought-related agricultural vulnerabilities. In general, RWH systems capture rainwater from roofs and store it for later use, typically in plastic or concrete tanks. Gutters and pipes channel water from roof to tank while filters remove contaminants. With proper knowledge, RWH systems can be locally tailored to meet water needs in a technically sound, culturally appropriate way. However, with current methods, RWH is expensive; tanks alone often account for more than 50% of total system cost.

Engineers at Worcester Polytechnic Institute are developing cost-effective ways of storing rainwater using recycled materials. As seen in the figure below, storage tanks are made of repurposed tires. An interior lining, made of recycled plastic, holds water securely. The design is adaptable, allowing tanks to be sized appropriately for the intended use of the water and to be connected in series if more space is needed. Water can be used for consumption and non-consumption domestic applications, raising livestock, and irrigating crops. These new tanks offer farmers inexpensive ways to store water on-site, reducing drought vulnerabilities and sustainably improving crop production.



Working with Fundación Paraguaya's Escuela San Francisco, we hope to beta test the new RWH storage tanks and develop a learning module that can be incorporated into the curriculum. The training has both theoretical and practical components. A pictorial manual, with descriptions in both Spanish and Guaraní, will be a reference and guide to understanding the general form of a RWH system and methods for customization. Through team-based, hands-on workshops, participants will design a RWH system to meet needs, learn proper RWH maintenance and repair strategies, and ultimately realize a system. Through this process, students will be inspired and empowered to take key concepts back to their family farms and build their own sustainable RWH systems to spread individualized small-scale agricultural water security.

Proposed Timeline

This timeline lays out the main events of the project. If all parties approve of the suggested dates, we can proceed with the plan as it is put forward here:

December 5-15, 2015: Present idea to the leaders of la Escuela San Francisco and open communication with the WPI project team.

By January 1, 2016: Have a team of 5-6 students identified who will work with Katie Picchione in January and February

January 1 - February 1, 2016 (start of classes): Work with students and faculty to design a site-specific system [create a parts list, budget, blueprints, implementation plan]

February 1 (start of classes) - March 9, 2016: Order materials, arrange transportation of materials (if needed), prepare other students/prepare and implement learning module to teach other students? Make sure everything is ready to build upon arrival.

March 12, 2016: Katie Picchione arrives in Paraguay; meet with student team in person

March 12 - 14, 2016: Gather materials at the school (should be ready/pre-ordered/located), prepare land area, and finish any final logistical arrangements

March 14 - 18, 2016: Construct RWH system with project team

March 21 - April 8, 2016: Interview students about the experience, interview other farmers about their potential interest in the RWH systems, coordinate student

April 9, 2016: Katie Picchione leaves Paraguay

3. Letter to Mr. Cateura

100 Institute Road
Worcester, MA 01609-2280 USA

Señor Luis Cateura December 5, 2015

Director de la Escuela San Francisco

Estimado Sr. Cateura:

Espero que esta carta le encuentra bien. Me llamo Katie Picchione, estudio al Instituto Politécnico de Worcester de donde vienen los estudiantes quienes trabajan con Dr. Robert Traver, Señor Martin Burt y Señora Dorothy Wolf. Originalmente soy de Albany, Nueva York, y estoy ahora en el último año de los estudios en las carreras de ingeniería mecánica y la sociología de tecnología y póliza.

He estado en comunicación con Señor Burt acerca de una tecnología nueva para la captación de agua de lluvia que pueda beneficiar a los estudiantes a la Escuela San Francisco y los agricultores de Paraguay. Desarrollamos un método para el guardado de agua con el uso de materiales comunes y reutilizados (como llantas viejas y plástico reciclado) para bajar el costo de la cosecha de agua de lluvia. A usted me gustaría proponer la oportunidad de hacer un módulo de aprendizaje con los estudiantes y con ellos construir un sistema a una casa en la escuela como una pilota en Paraguay. En el espíritu de los métodos de la Escuela San Francisco y de WPI, seria una capacitación de teoría y práctica.

Estoy entusiasmada de la posibilidad de hacer este proyecto con ustedes. En el pasado, yo he trabajado en el tema de sistemas de agua de lluvia en una comunidad en Guatemala con el grupo de Ingenieros Sin Fronteras de WPI ya en que viajé a Guatemala cuatro veces y ayudé con la construcción de 34 sistemas. En el año pasado, tenía la oportunidad de ir a Costa Rica y trabajar con el Ministerio de Agricultura y Ganadería en un proyecto de la agricultura orgánica. También, he estudiado en la carrera de ingeniería mecánica desde hace tres años y media. Tengo la pasión de usar los conocimientos de ingeniería para el mejoramiento de vida a través de proyectos así, y me encantaría colaborar con ustedes para aumentar la sostenibilidad de agua para los productores en Paraguay.

Con esta carta se encuentra un plan que explica los detalles del proyecto y de la implementación. Por favor me puede comunicar por Sr. Burt y con la información de contacto proveído aquí.

Cariñosos saludos,

Katie

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Appendix E: Liner Testing: Procedure and Findings

1. Vinyl Testing

On November 11, 2015, we attempted a first prototype of the tarp-style tire tank.

Materials and Tools

Used:

- Various vinyl curtain scraps
- Heat gun
- aluminum foil (used for nozzle)
- small hose clamp (used to secure aluminum foil)
- Stainless steel rolling pin

Bought:

- 6 Tires
- [2”] of 1½” PVC
- [2] 2” rubber couplings
- [2] 1½” hose clamps

Methods

Instead of tarp, we found scraps of vinyl roller shades for free at Home Depot. Using a heat gun with aluminum foil shaped into a funnel, we melted the 3 inches of overlapping vinyl together in hopes of creating a waterproof seal. As one person moved the heat gun, the other used a rubber mallet to force the vinyl together, removing air bubbles.

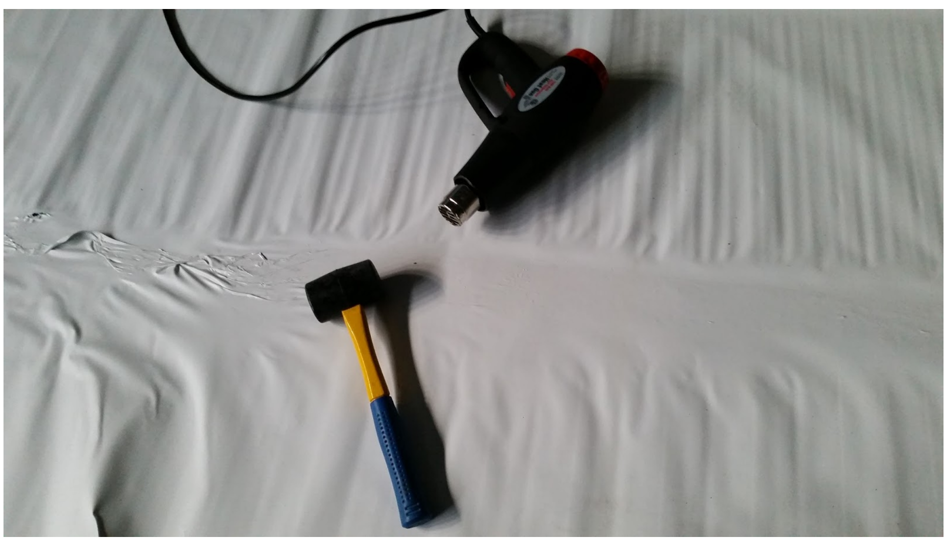


Figure 8

After a few attempts, the rubber mallet was not removing all air bubbles and was not creating a waterproof seal. The seal created with the rubber mallet can be seen in Figure 9. Next we tried a stainless steel, non-stick roller instead. With the heat gun between the two layers of vinyl, moving slowly along the seam, the roller is used to press these heated layers together evenly. This roller created a seal as shown in Figure 10.

Figure 9 *Figure 10*

After the seam was cooled, we tried to rip the seam apart to ensure the melting was successful. Any holes that were created from ripping or that were found after cooling were mended by using the heat gun and the roller. This mended seam can be seen in Figure 11.

Figure 11

Next we tested this sealing technique on a smaller piece of vinyl and tried to make a waterproof bag. The edge seam of this bag can be seen in Figure 11, the full view of the bag in Figure 12, and the inside of the bag in Figure 13. We then filled the bag about a fourth of the way with water and found a few small leaks. These leaks were easily mended and then the bag was completely waterproof.

Figure 12

Figure 13

Results

While we were unable to complete the entire tank in the time allotted, we made several important observations about the materials and methods selected.

Vinyl can be heat-welded to produce water-tight seals, but better materials may exist.

While we did not have the proper nozzle (the aluminum foil was used to improvise) we were able to create water-tight seals with the vinyl. There is a technique to heat welding that requires practice (and a rubber roller--we made do with a rolling pin). Despite lack of expertise, we were able to achieve adequate seals to prove the concept. We tested by creating small "bags" out of the vinyl shades and filling them with water to check for leaks. The seams were folded and sealed twice over. We filled each bag with water and tipped the bags to submerge the seams with water. In the process of heat welding, however, fumes were produced that are likely toxic.

Vinyl becomes rigid and brittle when cold.

The temperature outside was approximately 35°F, slightly above freezing. When we filled the vinyl bags with cold water, the material became stiffer. When outside, it also became more stiff and brittle. Glass transition temperature must be considered in the selection of materials that will be used outside; vinyl may have a glass transition temperature too high for this application.

2. Polyethylene Testing

Materials and Tools

Used:

- 3' x 15' Sheet of Polyethylene
- Heat gun

- aluminum foil (used for nozzle)
- small hose clamp (used to secure aluminum foil
- Stainless steel rolling pin
- Propane torch

Methods

To begin the polyethylene testing, we attempted the same methodology that we found effective on the vinyl. One person moved the heat gun between the two layers of plastic and the other used a stainless steel rolling pin to push the seal together. As before, we tried to tear apart the seam to test how strong it was and mended the holes as needed. A picture of the heat gun sealed bag and seam are shown in Figure 14 and Figure 15.

Figure 14: Heat Gun Sealed Bag

Figure 15: Heat Gun Seal

Though this was creating a waterproof seal, there were many leaks and it required many mends. As shown in Figure 15, water was leaking in many places. Next, we decided to try using a propane torch to test if it made a cleaner, more effective seal. One person moved the flame quickly along the top of both pieces of polyethylene while the other person used the stainless steel roller to press the seal together. The roller and propane torch is shown in Figure 16.

Figure 16: Stainless Steel Roller and Propane Torch

Again we tried to tear the propane torch seal to test its strength and found it was much stronger and more consistent than the heat gun seal. Using the propane torch technique we made another bag to test the waterproof seal. The seal had less leaks than the heat gun seal and looks cleaner as well. Tearing the seal and the second bag can be shown in Figure 17 and Figure 18 respectively.

Figure 17: Ripping Propane Torch Seal

Figure 18: Propane Torch Seal Bag

Appendix F: WPI Tire Tank Prototyping Documents

These documents were presented to Bill Spratt, head of WPI Facilities, to summarize the anticipated activities and help identify a location on campus that would be appropriate for the practice build.

MQP Tire Tank Practice Build

Katie Picchione

MQP Goal: Design water storage tanks that can be easily built from inexpensive and recycled materials in developing and rural areas.

Objective: Test out the tire tank design on campus to determine if it is viable.

Tank Design Summary:

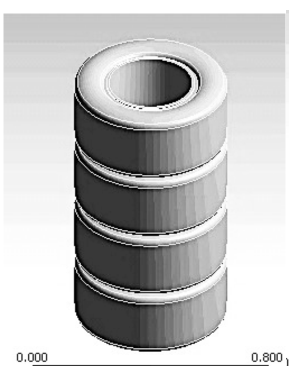
- 4-6 tires stacked in a column
- Plastic interior liner to hold water
- PVC pipes for inlet/outlet

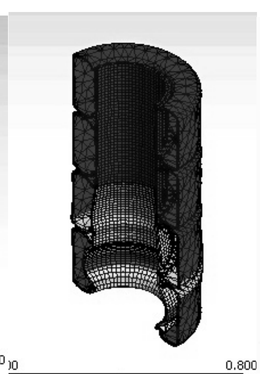
Location Preferences

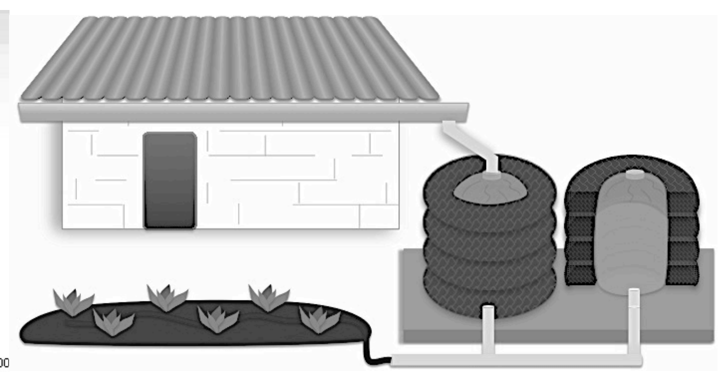
- Access to a water supply (garden hose or similar)
- Could be indoors or outdoors
- Drainage
- ~5 square feet of space
- Daily access would be preferable, if only on weekdays, that is fine

Specific Tasks:

- Check for leaks
- Create a protocol for repairing leaks
- Finalize a materials list
- Determine appropriate maintenance practices







TIRE TANK BUILD SPECS

Estimates for total water volume water and tank weight

	ID	OD
Diameter (in)	18	24
Bottom Area (in2)	254.4690049	452.3893421
Height (in)	36	36
Volume (in3)	9160.884178	16286.01632
Volume (gal)	39.65750726	70.50223514
Weight (lb)	330.7436106	587.988641

The tire tank will hold between 40 and 70 gallons of water, depending on how much of the rim is actually filled. The weight of the water alone will be between 330 and 580lbs. When the weight of the tires and other materials is considered the maximum total weight can be estimated at 600lbs.

The test system will either rest on an existing platform or on flat boards

Planned duration: about 1 week

Materials
6 ties (4 shown)
LDPE plastic liner
bolts
Gasket and hose clamp for inlet
PVC pipe for inlet

TIRE TANK BUILD PLANNING

Prior to the IQP class building a tire tank in-country, I have the opportunity to build a prototype at WPI. By testing the design, I will be able to identify potential issues with the proposed construction techniques and short-term problems that may arise during and immediately after construction. I will also be able to test different inlet/outlet configurations to identify any major design flaws that could impact the ease or difficulty of use and construction.

Leading Questions

1. What are the challenges with building the tank?
2. What are the challenges with using it?
3. What are the challenges and foreseeable problems with the liner?
4. Is the tank stable? Can it be tipped over?
5. Does the single-opening inlet/outlet work effectively?
6. Is the siphon easy to initiate? Will that work in the field?
7. Now that one tank is built, what is the best way to connect multiple tanks?

Timeline

The tire tank is planned to be built on Wednesday, March 23, 2016. The tank will stand for one week with regular inspections to check for leaks or other technical problems. The tank will also be filled and emptied several times to check for ease of use and user-centered design shortcomings.

Location

Working with WPI Facilities, we were able to find a location behind the Ellsworth Apartments that is amenable to spills, has a power supply, can accommodate a water supply, and is currently unused.

Materials

- 6 tires
- Sheet plastic (several layers)
- 90 gal plastic garbage bags (several nested)
- PVC inlet/outlet 2” Pipe
- PVC T 2”
- PVC 90° 2”
- Gasket
- Rubber reducer
- Hose clamps
- Flexible inlet/outlet hose
- Nuts and bolts

Tools

- Drill
- Flat-head screwdriver

Construction Procedure

1. Stack two tires and drill through-holes in the rims of both tires where the bolts will secure the tires together. Drill two holes, one on either side of an imaginary line that bisects the tire along its diameter. Bolt the tires together.
2. Stack the next tire on top and drill two more holes along a diameter that lies in a direction perpendicular to the first two holes. Bolt the tires together.
3. Continue in the same manner until all tires have been stacked in a column.
4. Put the plastic into the interior of the tire column, ensuring that it folds into the rims as much as possible. There should be ample plastic at the top outside of the tank.
5. Synch the opening around the PVC pipe. Wrap the gasket around it and tighten it with the hose clamp.
6. Put the siphon hose through the PVC tube. Use a rubber reducer and smaller hose clamps to seal and hold it in place.
7. Put a stop valve on the end of the hose.

Testing

1. Fill and empty the tank several times. Is the liner affected?
2. Let the water stand for several days. Does the liner leak? Other issues?
3. Attempt to tip the tank over from different directions.
4. Empty the tank and use a different liner, one with an inlet/outlet in the bottom.
5. Fill the bottom tire with dirt and sand. Is stability affected?

Appendix G: Final Curriculum Guide in English

Rainwater Harvesting Curriculum Guide

Katie Picchione

April 28, 2016

INTRODUCTION

The purpose of this program is to teach, in great detail, methods for designing, building, operating, maintaining, and repairing a rainwater harvesting system. Rainwater harvesting (RWH) is the sustainable process of collecting water from precipitation and storing it for later use. Rainwater harvesting systems can improve water security in developing and rural areas by providing access to an increased quantity of better quality water. RWH technology can be used to meet water needs for agriculture, various types of washing, sanitation, etc. Though RWH usually does not render water potable, contaminants can be removed where water for drinking and cooking is unavailable. While straight-forward in principle, each rainwater harvesting system is unique, tailored for the intended water uses and existing conditions of the locale.

The program was originally designed for students at Fundación Paraguaya's San Francisco agricultural high school in Presidente Hayes, Paraguay. It is comprised of four lessons, each crafted to introduce students to a different step in the process of creating and owning a rainwater harvesting system.

- The first lesson introduces students to the concept of rainwater harvesting and generic system components.
- The second lesson engages students in the design process, encouraging them to think about site-specific caveats that impact system design. Lesson two also presents process thinking: what quantities of materials are needed? How will materials be transported? How much will the project cost?
- The third lesson, regarding system construction, is optional. This lesson requires more time and materials than might be afforded. However, direct application of ideas presented in class reinforces principles of RWH system design and realization.
- Finally, the last lesson delves into principles of system operation, maintenance, troubleshooting, and repair. Students are prompted to develop their own plans for long-term system sustainability. If a physical system is available on premises, this lesson can be divided into multiple lessons where students have the opportunity to engage in real troubleshooting and test the plans they devised.

This program was developed based on information and learnings from the Worcester Polytechnic Institute student chapter of Engineers Without Borders, who has been developing rainwater harvesting systems for potable applications in rural Guatemala since 2009. As a four-year member, traveler, and past president of the EWB-USA WPI chapter, and with my background in the disciplines of Mechanical Engineering and Society, Technology, and Policy, I designed the program with keen attention to technical detail, cultural awareness, ethics, and professionalism. While the content reflects my experiences and research on rainwater harvesting, there are undoubtedly innumerable design variations, depending on local materials, intended water uses, and space availability. It is my hope that this curriculum guide serves the instructor well in empowering people of all ages to take action to improve water security for themselves and their community.

Curriculum Goals

Students will be able to

1. Explain Rainwater Harvesting as a means to improve water security
2. Assess site-specific functional requirements for a rainwater harvesting system
3. Design a site-specific rainwater harvesting system
4. Make a construction plan
5. Work on or lead a team to build the system
6. Create an individualized plan for system operation and maintenance
7. Troubleshoot problems, develop solutions, and make repairs

Content Standards

L	Code	Category	Standard
1	W1	Water	Articulate the concept of Water Security and explain how quantity, quality, and access affect water security
1	W2	Water	Explain how Rainwater Harvesting is one sustainable solution to water security issues and is pertinent in their lives
2	A1	Assessment	Learn about the intended use of the water to determine quantity and quality needed.
2	A2	Assessment	Use the dimensions of roof height, topography, and roof angles to determine the best placement for rainwater storage tanks.
1	D1	Design	Describe the components of a rainwater harvesting system and their purposes.
2	D2	Design	Calculate the amount of tank space needed based on the daily demand, roof area, and monthly average rainfall.
1	D3	Design	Draw a preliminary schematic for a system.
2	D4	Design	Revise system drawings and finalize a schematic.
2	BP1	Build Planning	Make a list of needed materials and tools based on the revised system schematic.
2	BP2	Build Planning	Calculate the total cost for the build based using a price list [create a budget].
2	BP3	Build Planning	Create a timeline for the build
3	BU1	Building	Base
3	BU2	Building	Gutters
3	BU3	Building	First Flush
3	BU4	Building	Tanks
3	BU5	Building	Piping
4	OM1	O&M	Arrange an individualized use and maintenance plan.
4	OM2	O&M	Estimate the frequency with which roofs, gutters, and tanks should be cleaned based on the surroundings (trees etc.)
4	OM3	O&M	Create an inspection checklist and timeline
4	T1	Troubleshooting	Identify problems and their causes
4	T2	Troubleshooting	Identify potential future problems and their causes
4	T3	Troubleshooting	Design a solution to the problem
4	R1	Repair	Create a plan for making the repair, considering materials, time, and labor required

Lesson 1: Overview of Rainwater Harvesting and Intro to System Design

Goals and Standards

Students will be able to:

G1: Explain Rainwater Harvesting as a means to improve water security
- W1: Articulate the concept of Water Security and explain how quantity, quality, and access affect it
- W2: Explain how RWH is one sustainable solution to water security issues and is pertinent in their lives

G2: Design a sound rainwater harvesting system (Part 1)
- D1: Describe the components of a rainwater harvesting system and their purposes
- D3: Draw a preliminary schematic for a system

Materials and Preparation

- Create a list of project teams, 4-5 students per team, and assign a "system component" and a "Building Schematic" to each team in advance
- Print two copies of a unique **Building Schematic** for each team; only one will be used in this lesson
- Markers, colored pencils, crayons, or other drawing/sketching utensils (optional)
- Print **Component Handouts** of each system component for each student

Instruction

1. Water Security (10:00)

In this program, we will learn about rainwater harvesting and how we can build systems that allow us to capture and use rain as a water source. Ask students: **What are ways we use water in our everyday lives?** Some examples are: cooking, drinking, bathing, cleaning (clothes, dishes), agriculture, etc. Where does that water come from? Do they ever run out of water?

Why might rainwater harvesting be important to water security? It provides water where other sources are unavailable (wells, rivers, lakes, municipal water supply). Rainwater harvesting provides water on-site (access). Systems can be designed to supply enough water to meet daily needs (quantity) and can be adjusted to improve water quality when necessary. When materials are locally available and owners have the knowledge to properly use, maintain, and repair systems, rainwater harvesting is a **sustainable** water source.

Discuss **water security**. A person who has water security is able to meet their water needs. The three dimensions of water security are **quantity, quality, and access**. To have water security, one must have enough water to meet needs (quantity). Water must be adequately uncontaminated for the intended use (quality). Finally, water must be accessible in lieu of socio-political, environmental, technological, and economic boundaries.

Rainwater is available in Paraguay (there is adequate quantity) but is inaccessible without the proper infrastructure. Students will learn to design, build, operate, maintain, and repair inexpensive rainwater harvesting systems. At this point, administer the **pre-program evaluation**

2. Rainwater harvesting system components (10:00)

Ask: **What structures might be necessary to collect rainwater?** Draw a generic house on the board. Draw and describe the following system components. Discuss why each is important and what it's function is:

- Roof: Surface to collect rainwater and concentrate it for storage and use
- Gutters: Transfer rainwater from a collection surface to the enclosed pipe/tanks
- Pipes: Transfer water from gutters to tanks; provide an inlet and outlet to the tanks
- Tanks: Store water for later use; when rain is scarce, water storage ensures continued water security
- First Flush: reduce contamination
- Base: Solid platform to mount tanks

Discuss how water flows through the system from the highest point to the lowest, pulled downward by gravity. The angles of the roof and gutters are crucial to ensuring that water flows in the right direction. Trace the path of water through the system. Explain the importance of ensuring that all connections are sealed to prevent debris and mosquitoes from entering the system.

3. General System Design

To design systems, we can use the Engineering Design Process.

Divide students into teams and pass out the building schematics. Explain that students will be working on teams to design specific systems for each of these buildings. Ask students to draw out the main components of the system on the schematics. Be creative! What might each part look like? Assign different system component to each team to focus on in as much detail as possible. (20:00)

Have each group present their designs to the class with explanations of each component and what factors they considered in their designs. Make suggestions and cover any details omitted. Reference the Component Handouts for complete details. Distribute Component Handouts after each is discussed. (10:00)

Give the teams some time to modify their designs. Pass out the blank Building Schematics. Ask students to think about the quantities of each material needed and the tools needed to complete each part of the system. (10:00)

Lesson 2: Assessing System Requirements Planning to Build

Goals and Standards

G2: Assess site-specific functional requirements and design parameters for a rainwater harvesting system

- A1: Learn about the intended use of the water to determine the quantity and quality needed.
- A2: Use the dimensions of roof height, topography, and roof angles to determine the best placement for rainwater storage tanks.

G3: Design a site-specific rainwater harvesting system (Part 2)

- D2: Calculate the amount of tank space needed based on the daily demand, roof area, and monthly average rainfall.
- D4: Revise system drawings and finalize a schematic.

Materials and Preparation

- Rain Data sheets
- Budget Worksheets (Extension)
- 3rd copy of the Building Schematics

Instruction

1. Review of System Components (10:00)

Draw the generic house on the board. When we are designing a system, we need to think about two things: how it will work and how it will be built.

In the last class, we discussed how the systems work: rain falls on the roof, flows to gutters, flows through pipes into a storage tank, and passes through several filtration mechanisms along the way. Invite students to come to the board and draw specific parts of the system and explain their function. Reiterate that water flows from the highest point to the lowest, pulled downward by gravity. The angles of the roof and gutters direct the flow of water. Sealed connections prevent debris and mosquitoes from entering.

2. Calculating Tank Size to Meet Needs (40:00)

A key part of designing a system that works is making sure that it will supply enough water to meet needs. **What factors determine the amount of water a system is able to provide?**

- Rainwater Input: The amount of water added to the system each day
  - Daily Rainfall: This is the amount of rain that falls each day, typically in [mm]
  - Roof Area: This is the 'capture area' that determines how much rain is actually collected and put into the system; the larger the roof, the more water can be added
  - The Daily Rainwater Input is the product of Daily Rainfall x Roof Area
- Water Demand/Consumption Rate: The amount of water used each day
- Tank size: The tanks must be big enough to supply enough water to meet needs all year. Guide students to compose the following and how each affects the total amount of water: rainfall, water consumption rate, roof area, storage capacity, roof efficiency. Tanks will frequently overflow during rainy seasons but may run out of water during dry seasons if the tank or roof is too small.

Using these parameters, we can discern what the best-sized tank is for our system. The objective is to use the fewest materials possible while ensuring that there will be enough water year round.

Pass out the rain data for one-week. Rainfall is measured as the amount of water that falls at a point. The measurements are the ‘height’ of water that falls in one spot, typically measured in mm or in. Water is added (rain) and removed (used) from the system on a daily basis. By changing the size of the tanks, we can impact our ability to capture and store water. In this exercise, **compare three differently sized tanks: 1000L, 5000L, and 10,000L. By calculating the amount of water in each system each day, determine which is the most appropriate size.**

To calculate the amount of water in the tank each day, students will work in groups to consider:

- Assume that the tanks start empty on the first day
- How much water falls on the roof each day? Think about volume collected, rather than the ‘height’ of rainfall.
- The amount of water in the tank cannot exceed the tank’s capacity. If the tank can only hold 1000L, no more than 1000L will be in the tank at the end of the day, even if 1200L of rain falls.
- Assume that a set amount of water is removed from the tanks at the **end** of each day (indicated as “need” or “demand” on the Building Schematic). By assuming that water is removed at the end of the day, we create a ‘worst-case’ scenario. Engineers make assumptions like this (safety factors) to ensure that systems will always meet needs.
- How much water is in the tank at the end of the day? The next day, this water is already in the tank. The “leftover” water from one day is the “starting” water the following day.
- Remember, if tanks run out of water (have 0L) at the end of the day, then the tanks do not hold enough water to meet needs.

While students are working, visit each group and guide them to correctly calculate the amount of water in the system each day. Rather than writing equations on the board, encourage students to derive their own method for calculating the amount of water in the system each day using weekly rainfall and water consumption information. Provide explanations and guidance to ensure that students arrive at the correct methods and understand how the calculations work.

Using the daily data for one week, we can make a graph showing how the amount of water in the tank varies over time. The graph would have “days” as the independent variable (x-axis) and “volume” as the dependent variable (y-axis).

It would take a long time to calculate the data for each day for an entire year by hand. A computer program like Microsoft Excel can be used to facilitate the process if the technology is available.

Alternatively, weekly approximations can be used. Pass out weekly rain data for the first quarter of the year (about 12 weeks). Rather than calculating the amount of water in the system after each day, we can approximate the amount of water in the tanks at the beginning and end of each week. **Identify which tank will provide the most water for the longest time. Will you run out of water? When? What size tank will ensure that there will be enough water in the tank year round? There are several different methods that can be used. Encourage students to try different methods (using lump sum data, averaging the data, etc.) and evaluate which method is best.** Have groups report findings to the class.

3. Revise Designs (10:00)

Now that students know the optimum size of the tanks, pass out a third blank Building Schematic to each group and give them the rest of class to make revisions on their designs, remembering that the angles of the roof and gutters are essential to ensuring that water will flow.

Lesson 3: Assessing System Requirements Planning to Build

Goals and Standards

G4: Make a construction plan

- BP1: Make a list of needed materials and tools based on the revised system schematic.
- BP2: Calculate the total cost for the build based using a price list [create a budget].
- BP3: Create a timeline for the build

Materials and Preparation

- Budget worksheet
- Materials list

Instruction

1. How the System Will Be Built (30:00)

When considering each component, we need to plan how the structures will be built. While each component has a primary function, each also has auxiliary, or additional, parts and pieces that ensure the system will work properly. These may seem trivial when designing the system to serve a specific function, but are essential to ensuring the structural stability and longevity of the system. To understand the 'nuts and bolts' of the systems, we need to think about how each component is built.

Now that students have improved their designs, students will need to consider for construction:

- Sourcing the needed materials
- Transporting materials
- Purchasing materials (budget)
- Cutting, placing, securing/gluing, etc.

Using these guidelines, give students time to create a plan for building the system. Each group will focus on the same system component as before. What steps are necessary? Pass out the Materials List (with prices) so that students know what materials are available to work with.

Students will once again present their plans to the class. Encourage other students to give feedback and ask questions. Guide students to understand the following:

- Base
  - Lay gravel for the foundation
  - Use wooden boards and stakes to create a squared frame that concrete will be poured into
  - Cut and tie a rebar frame to reinforce the concrete
  - Use large aggregates to fill in spaces so less concrete must be used
  - Mix and pour concrete into the wooden frame
  - Use a 2x4 to level the surface of the concrete
- Gutter Supports and Angles
  - Measure the direction of the roof slant using a line level
  - (remember that water is pulled downward by gravity and ignores the slope of the land, which may go the opposite way or create an optical illusion)

  - Cut .5m lengths of 1x6 boards (or similar)
  - To cut a notch that is shaped like the gutter, trace a gutter cap onto the board and use a hacksaw and screwdriver to chisel out the notch. This is a "gutter clip"
  - Nail the gutter clips to studs of the building or other structural features
  - Use the line level to ensure that there is a slope of 5˚ or more between the gutter clips (this is the angle the gutter will tilt at, ensuring water flow).
  - Place the gutter into the notches
  - Cover the gutter with an arc of wire mesh to dispel debris
  - Cover the downspout of the gutter with mosquito netting to prevent insects from entering the system
  - Alternatively, with adequate support, the downspout pipe can be cut at an angle and mesh can be placed between the two parts of the pipe, creating a surface that will deflect large debris.
- Piping
  - Measure spaces where pipes go before cutting them
  - Use glue cautiously and only where needed. Make sure to leave the connections to the tanks **unglued** to facilitate maintenance and repair
  - 3 90˚ elbows will allow you to direct connecting pipes in any direction, but 2 is usually enough
  - **Reducers** can be used to change pipe sizes
  - 1½ pipe is usually sufficient for ensuring continuous flow (the water won't back up) but using smaller pipes may cause the system to back up
- First Flush
  - Connect a "Y" or "T" pipe fitting to the downspout
  - Use a reducer to increase the pipe size to 3" or 4"
  - The length of the first flush (i.e. the length of the large pipe) should be calculated to remove the first [1mm?] of rain that falls on the roof
  - Inside the pipe, place an empty water bottle that will not pass through the reducer. The cap should be pointed upwards
  - Connect another reducer at the bottom of the large pipe to prevent the water bottle from falling out
  - For a manual first flush (one that requires the user to empty the water after each rainfall) connect a ball valve to the bottom of the pipe
  - For an automatic first flush, put a cap fitting on the end. Use a hot metal pin or needle to melt a small (Diameter~1mm) hole into the bottom of the first flush. This will allow water to slowly trickle out once the rain stops. The hole can be made larger if the first flush does not seem to empty before the next rain.
  - The reducer or cap at the bottom of the tube should NOT be glued so that the inside of the first flush can be cleaned
  - If the reducer/cap regularly falls off when the first flush is full, place a stick or other support below the tube. Tie wire can be used to anchor the first flush to the support
- Filter
  - There are many kinds of filters, many are commonly available in stores

    - Beware of "cartridge" filters that require an internal filtering component to be regularly replaced. "Disk" or "ring" filters, made of plastic, are a more sustainable option for purchased filters
    - Bio-sand or slow-sand filters are another option, but details of their design are outside the scope of this course
    - Filters can be connected to the outlet of a tank/system
    - Filters can harbor bacteria and other contaminants if not properly maintained
- Tanks

Have groups discuss these steps in the context of their specific system and create a timeline, an order of events in which the system components will be built. While teams are working, introduce the idea of a Gantt chart as a tool for planning events in a specific order.

2. Creating a Budget (10:00)

Next, groups will be creating a budget. Each group will use the prices of materials provided. If students have been creative and made up materials that are not on the list, assign approximate prices for them to use. **They will loop up prices and doing the simple mathematics to calculate the total expenses.**

Have each group report what their total cost is and what material they used the most of. Discuss where materials might be purchased and how they might be transported to the site. Remind students to include the costs for materials transportation in the budget.

3. Peer Review (10:00)

Have the teams put their final drawings, materials lists, building plan, and budget in a packet or folder. Pass the packets to different teams for critique. As the teams to review the plans the other teams have prepared. Did they forget any steps? Is the budget reasonable?

Lesson 4: Operation, Maintenance, Troubleshooting, and Repair

Goals and Standards

Students will be able to:

G6: Create an individualized plan for system operation and maintenance
- OM1: Arrange an individualized Operation and Maintenance plan
- OM2: Estimate the frequency with which roofs, gutters, and tanks should be cleaned based on the surroundings (trees, etc.)
- OM3: Create an inspection checklist and timeline

G7: Troubleshoot problems, develop solutions, and make repairs
- T1: Identify problems and their causes
- T2: Identify potential future problems and their causes
- T3: Design a solution to the problem
- R1: Create a plan for making the repair, considering materials, time, and labor

Materials and Preparation

Instruction

1. Brainstorm Contingencies

Now that we have plans for building the systems, we need to think about how we will use, maintain, and repair the systems over time. Brainstorm everything that could go wrong with a system. Think about short term, mid-term, and long-term problems that could arise. Make a chart on the board, inviting students to add ideas. The following table is an example:

	Short-Term	**Long-Term**
Roof	Roof angle Sticks/leaves/debris block or damage roof	Rust Tile/plastic degradation
Gutters	Gutter angle needs to be adjusted Gutter is clogged with debris, overflows Mosquito netting breaks Gutter connections leak	Plastic gutters become brittle and break Metal gutters rust Gutter clips rot/break
First Flush	Falls down Collects sediments	Becomes clogged or harbors rotting debris
Tanks	Plastic tears Leaking connections Sediment or debris in tank	Plastic degradation Bolts become rusty Water is contaminated
Filter	Becomes dirty Harbors bacteria	Missing pieces
Base	Missing cinder blocks	Cracked concrete

Create "short term" and "year-long" maintenance plans for their specific systems. Encourage students to think about what factors may impact the frequency with which maintenance should occur:

- Are there trees hanging over the roof?
- How many tanks need to be cleaned? Consider the time needed
- Will cleaning tanks leave you without water?
- Do you anticipate the roof will harbor other types of debris?
- What kind of filters are being used? How often must they be cleaned?
- Will erosion cause problems?

Once students have made plans, have them work together with students from other teams to compare and edit the maintenance plans. Guide students to come up with maintenance plans that are appropriate for their systems.

2. Troubleshooting and Repair

How will we know when a system needs more than regular maintenance? Suggest scenarios of problems and ask students to troubleshoot. If a system is available, you can intentionally create issues and let students figure out solutions:

- There is water leaking around the tank
  - Leaking tank liner?
  - Leaking faucet or other connection?
- There is a puddle of water under the gutter
  - Did the gutters overflow?
  - Are the gutters leaking?
- The tank is empty even though there has been plenty of rain
  - Clogged pipes?
  - Leaking tank?

Develop a plan for repairing unanticipated issues. Begin with identifying a problem and end with implementing a solution. What factors need to be considered?

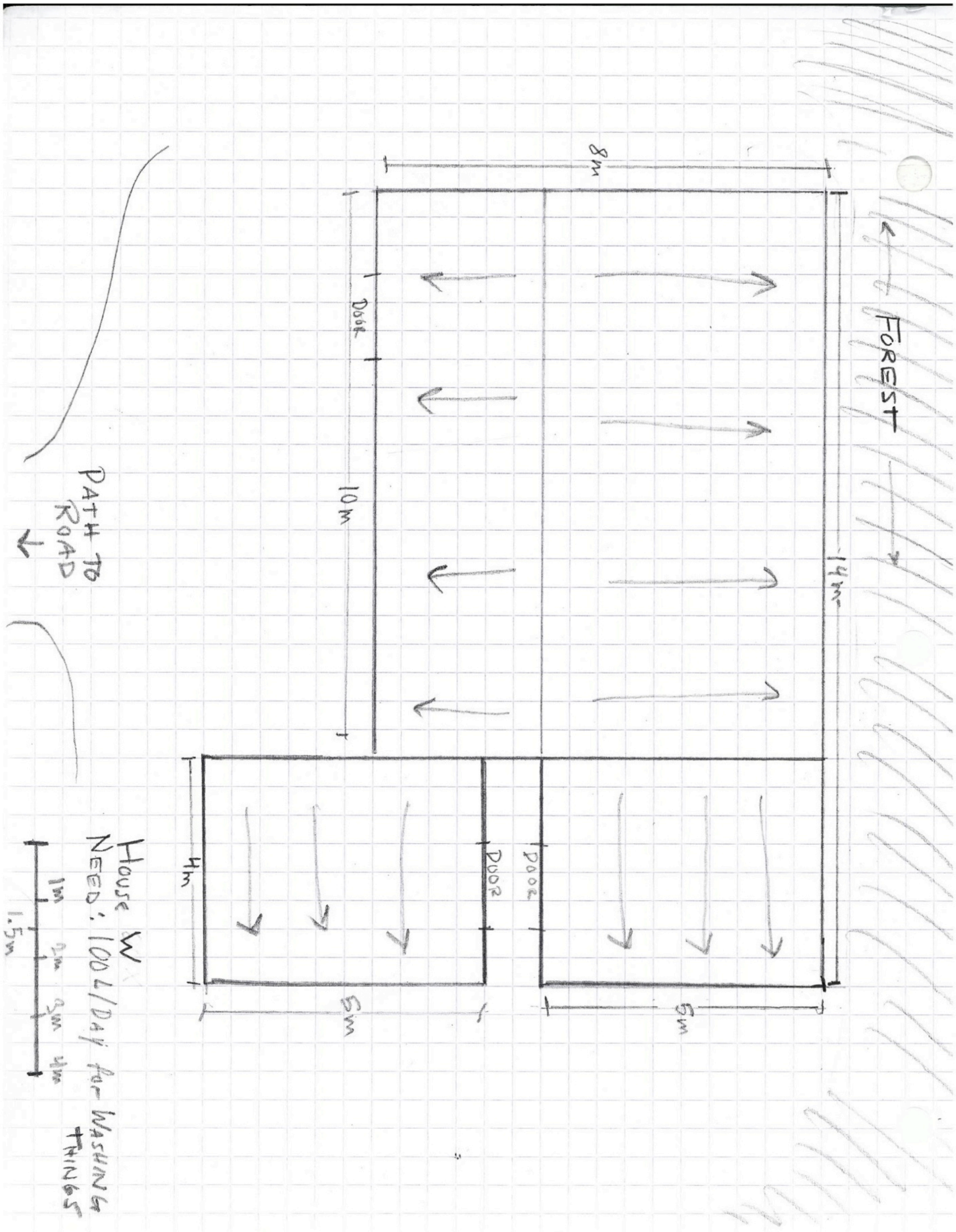
- Identify the problem
- Identify what materials are needed to solve the problem
- Find, purchase, and transport materials
- Do you need additional workers?
- How much time will it take to make the repairs?

Lesson 5: Building The System (Optional)

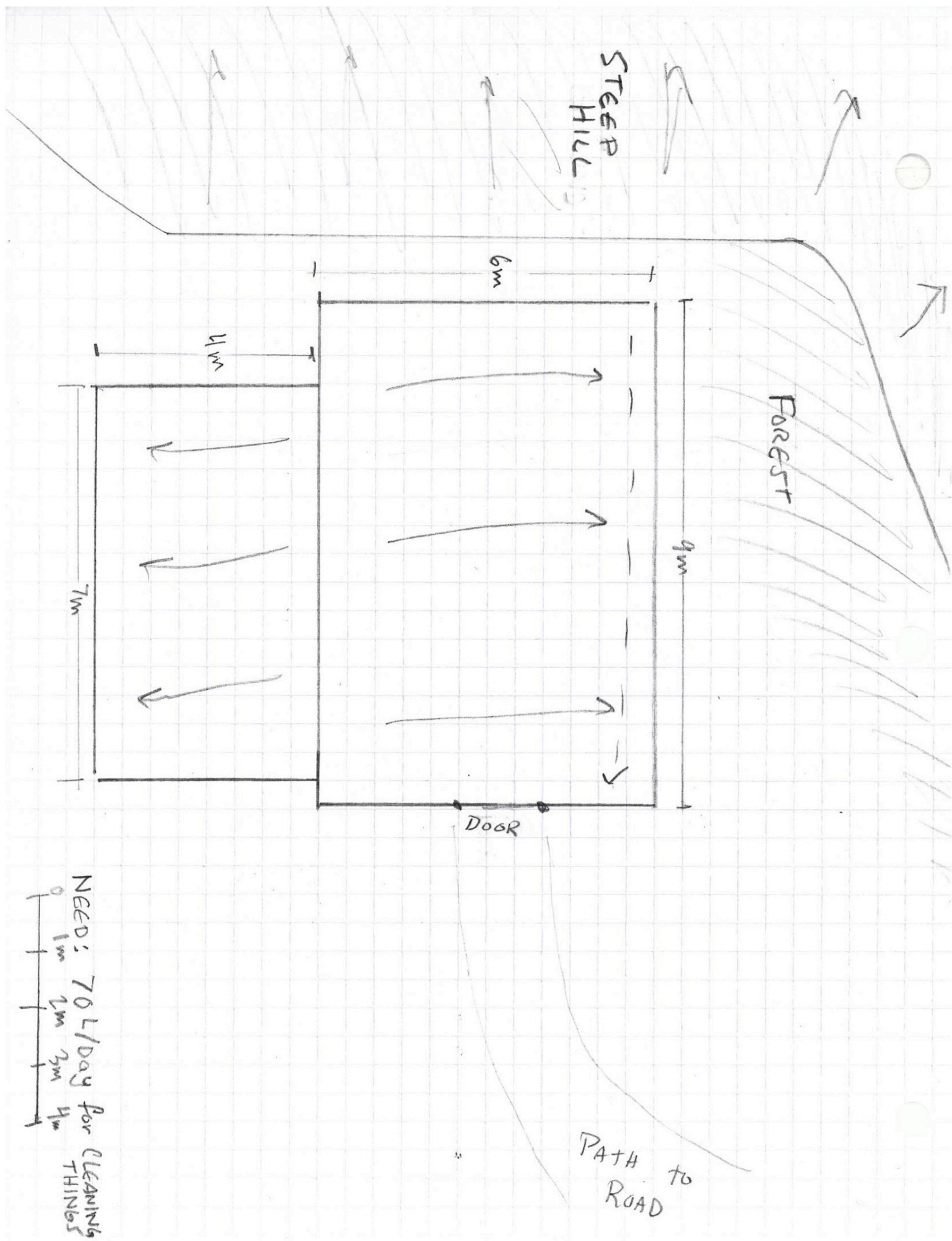
BU1	Building	Base
BU2	Building	Gutters
BU3	Building	First Flush
BU4	Building	Tanks
BU5	Building	Piping

Appendix H: Building Schematics

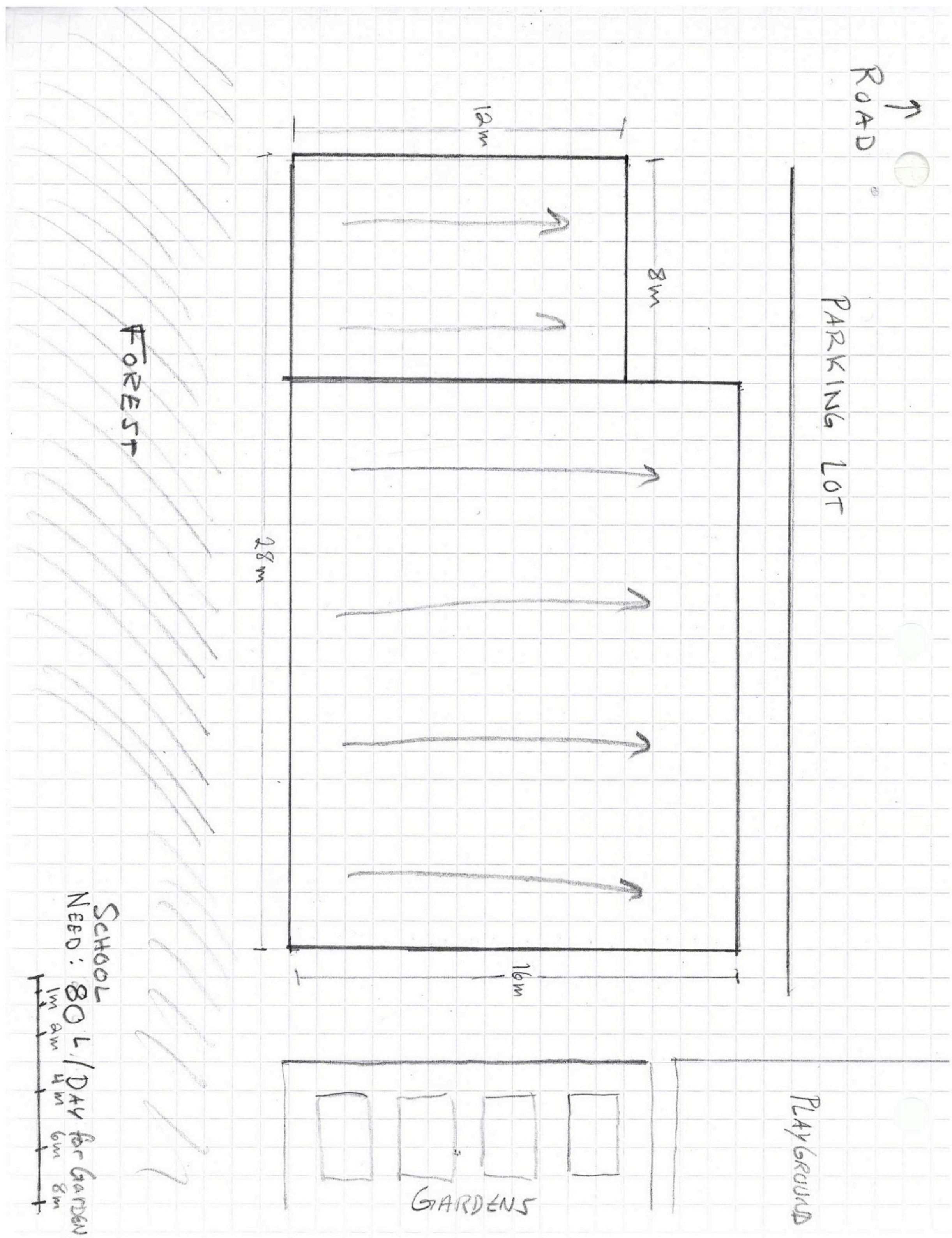
Building 1



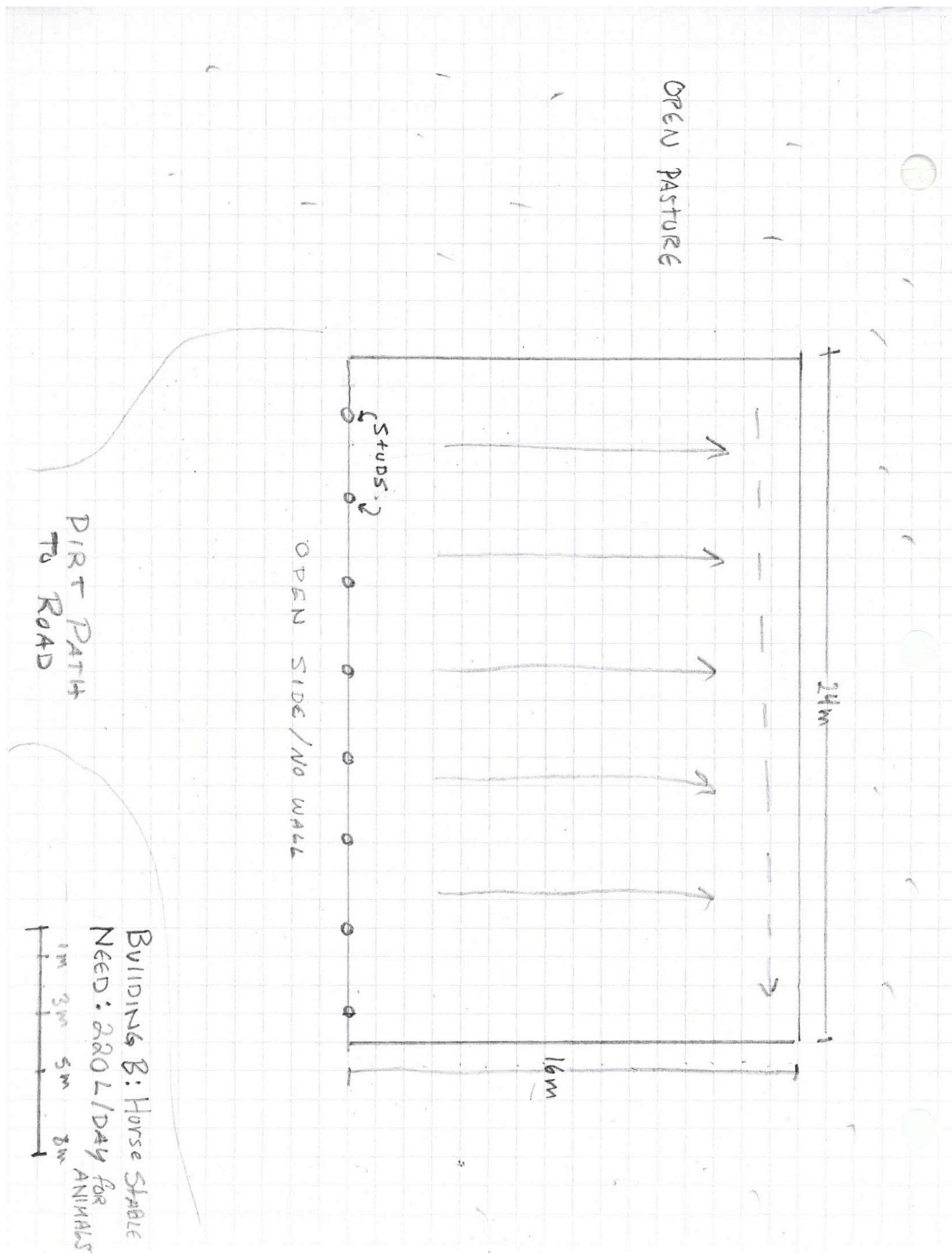
Building 2


STEEP HILL
6m
4m
7m
9m
FOREST
DOOR
NEED: 70 L/Day for CLEANING THINGS
0
1m
2m
3m
4m
PATH to ROAD

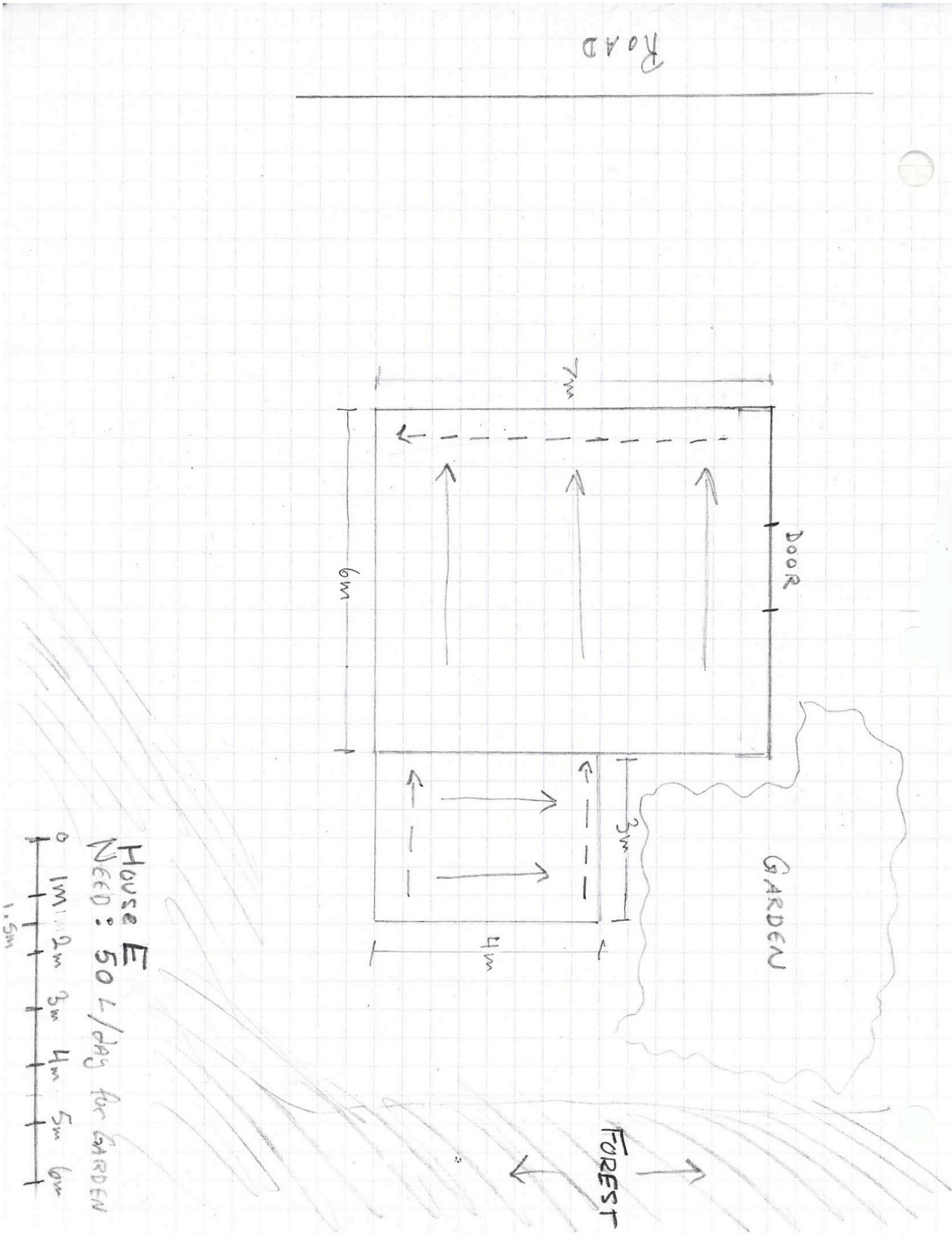
Building 3


ROAD
12m
8m
PARKING LOT
FOREST
28m
16m
SCHOOL
NEED: 80 L/DAY for GARDEN
1m 2m 4m 6m 8m
GARDENS
PLAYGROUND

Building 4


OPEN PASTURE
STUDS
OPEN SIDE / NO WALL
DIRT PATH TO ROAD
24m
16m
BUILDING B: Horse Stable
NEED: 220 L/DAY for ANIMALS
1m 3m 5m 8m

Building 5


ROAD
7m
6m
DOOR
3m
4m
GARDEN
FOREST
House E
NEED: 50 L/day for GARDEN
0 1m 2m 3m 4m 5m 6m
1.5m

Appendix I: Rain Data Exercise Worksheet

The purpose of this exercise is to understand how the size of a water storage tank determines the amount of water available. To save money, we want to use the smallest tank possible.

What is the smallest tank that will provide enough water for your building? To find out, calculate the amount of water in the tank at the end of each day for a week. Try three different tanks, sized 1 m^3, 5 m^3, and 10 m^3. If the tank is empty at any time, you need a larger tank or a larger roof. Assume that the tank is empty on the first day.

Day #	Daily Rainfall (m)	Rain collected (m^3)	Water used (m^3)	Water in the Tank at The End Of The Day		
				Tank 1 (1 m^3)	Tank 2 (5 m^3)	Tank 3 (10 m^3)
1	.0144					
2	.0018					
3	0					
4	0					
5	.0114					
6	.0013					
7	0					

With more time, you can calculate the amount of water in the tank every day for the whole year or for a series of years. Meanwhile, we can use weekly rain data to estimate the amount of water in the tank each week. Observe how the amount of water in the tank changes over several weeks.

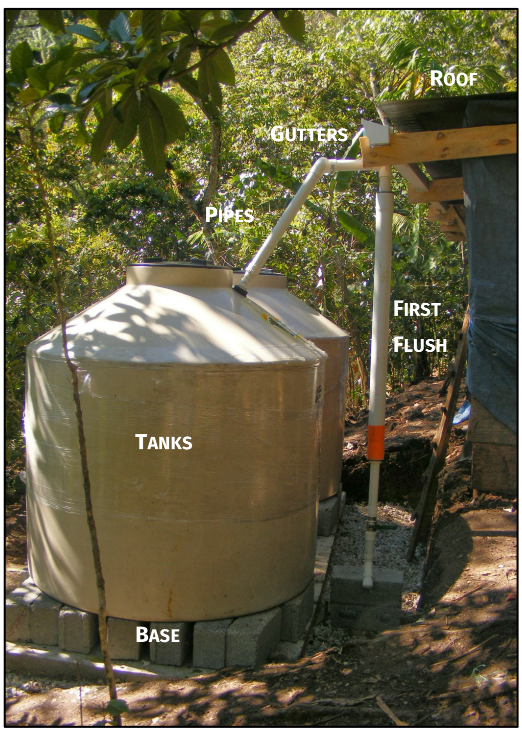
Week #	Weekly Rainfall (m)	Rain collected (m^3)	Water used (m^3)	Water in the Tank at The End Of The Week		
				Tank 1 (1 m^3)	Tank 2 (5 m^3)	Tank 3 (10 m^3)
1	.04078					
2	.0232					
3	.02634					
4	.01722					
5	.03178					
6	.0259					
7	.08746					
8	.0927					
9	.0201					
10	.01342					

Appendix J: Rainwater Harvesting Guide Book

RAINWATER HARVESTING OVERVIEW

Rainwater harvesting (RWH) is the practice of capturing rain and storing it for later use. Water can be captured from a variety of surface, most commonly from the roof of a building. This manual details methods for designing, building, maintaining, and repairing rooftop rainwater harvesting systems. While the approach presented here was developed by the Worcester Polytechnic Institute student chapter of Engineers Without Borders-USA for applications in rural Guatemala, rainwater harvesting is an adaptable technology that has infinite variations.

As seen in the photograph below, typical rainwater harvesting system has a roof (or other surface for capturing rain), gutters, pipes, water storage tanks, and a base. Filtration mechanisms, like a First Flush or slow sand filter, can improve the quality of the water.



ROOF

Surface to collect rainwater and concentrate it for storage and use

GUTTERS

Transfer rainwater from a roof or collection surface to an enclosed pipe/tank system.

PIPES

Transfer water from gutters to tanks; provide an inlet and outlet to the storage tanks.

TANKS

Store water for later use; when rain is scarce, water storage ensures continued water security.

FILTRATION

(First Flush, sediment filter, etc.) Reduces organic and inorganic contamination.

BASE

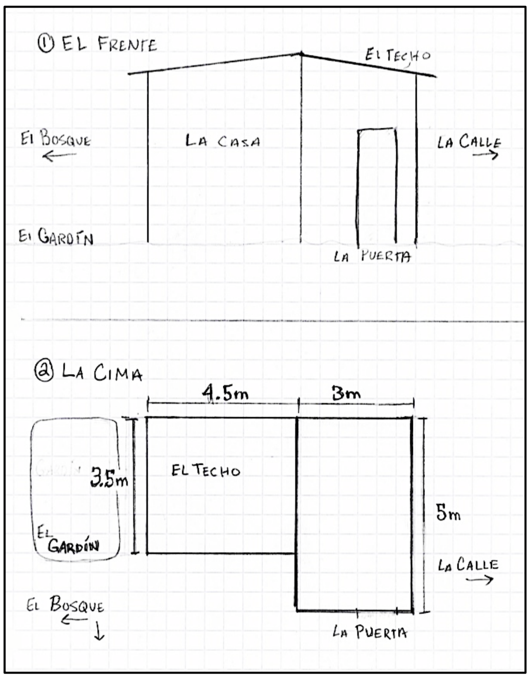
Solid and unmoving platform on which to mount storage tanks to improve longevity of the system

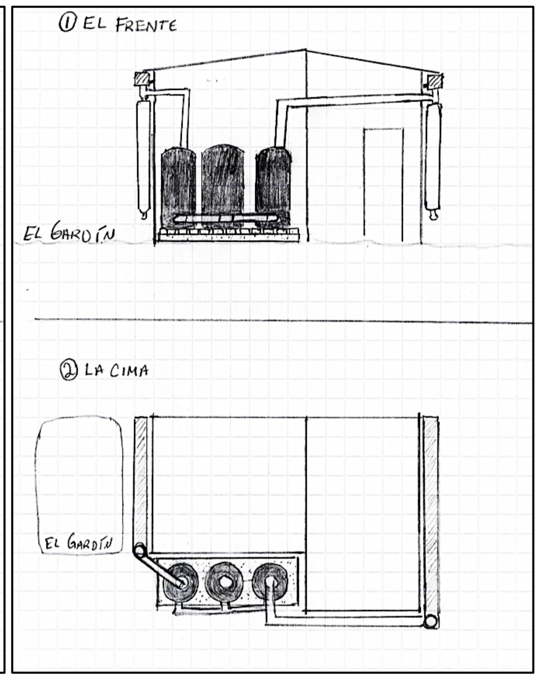
RWH can reduce water poverty and provide individuals and communities with *water security*, defined broadly as having adequate quantity, quality, and access to water to meet needs. Rainwater is most commonly used for horticulture, cleaning, and other non-potable applications, but can provide water for drinking and cooking when other sources are unavailable. As an adaptation strategy for communities in difficult and changing environments, RWH can be ethno-engineered to serve many parts of the world.

DESIGNING THE SYSTEM

This section explains methods for designing each system component and the system as a whole. First, the function of each component is explained, followed by photographs of sample systems, detailed sketches, and short-hand sketches that can be used in the design process. Also included are explanations of factors to be considered during the design process.

Each component is explained through photographs, perspective drawings, and field drawings. The field drawings present shorthand ways of drawing a system, useful for on-site system design and accurate implementation. Conventions have been modified from those developed by EWB-USA WPI to be more versatile.





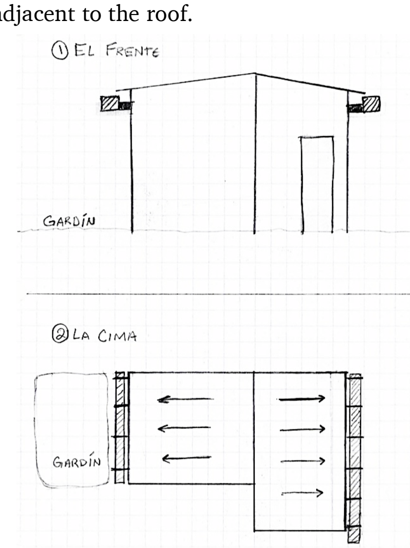
GUTTER DESIGN

Gutters capture water that falls on a roof, roof structure, or other raised rain capture area and channel it to the pipes and tank.

Field Sketch

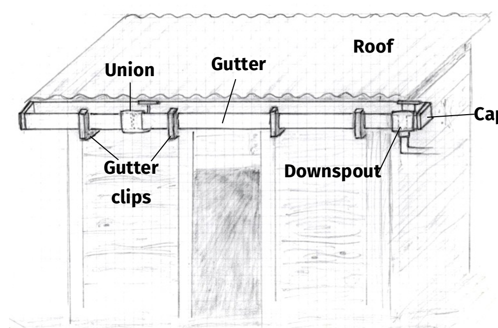
For the top-view sketch, draw the roof of the building. Include dimensions. Use arrows to indicate the direction in which water will flow.

On the side-view sketch, be sure to note which side of the building is being drawn. For both 'lengthwise' and 'end' perspectives, use a hatch-marked rectangle. Indicate gutter clips with thick vertical lines. Gutters should always be adjacent to the roof.



Basic Design

Plastic or metal gutters catch water that falls off a roof. The gutters are supported by wooden or metal "clips" that hold the gutters at an angle, sloping gently downward toward the pipes and tank. Gutter "unions" are fittings that join two shorter pieces of gutter, and a "downspout" fitting, placed at the lowest part of the gutter, connects the gutter to a pipe. Gutter "caps," placed at the ends of the gutters, prevent water from spilling out of the gutter. Mesh placed over the gutter and/or over the downspout prevent debris and insects from infiltrating the system.



Factors To Consider in the Design

- Which direction is the roof slanting? Gutters must be positioned to catch water that runs off the roof.
- The angle of the roof must be enough to ensure water will flow into the gutter.
- Gutters must be angled to direct the flow of water.
- Gutter clips must be anchored to stable supports; the studs of a building or roof rafters may work.
- More than one gutter may be needed if there are several roof segments.

TANK DESIGN

Tanks store the water collected by the rainwater harvesting system.

Basic Design

There are a wide variety of tanks. Large plastic water tanks, 200L drums, concrete and ferrocement tanks, underground reservoirs, and others can all be used. The "tire tank" design presented here can be built of inexpensive materials and locally made and repaired.

Old tires are stacked on top of each other as the structural component of the tank. A plastic liner on the inside of the tire tank holds water. The plastic should be thicker than _____. Tanks can be made of any size tire and connected in series when more tank volume is needed.

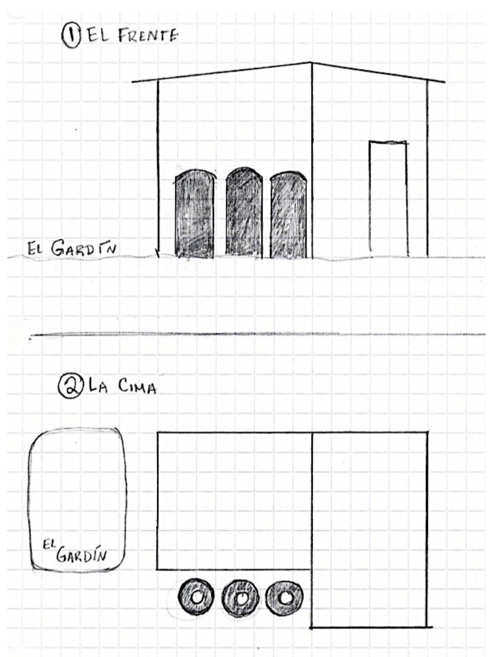
Factors To Consider in the Design

- Calculate the needed tank volume using rain data and consumption rate.
- Tire tanks may not be the best or least costly water storage option in all areas.
- Find inexpensive used tires.

Field Sketch

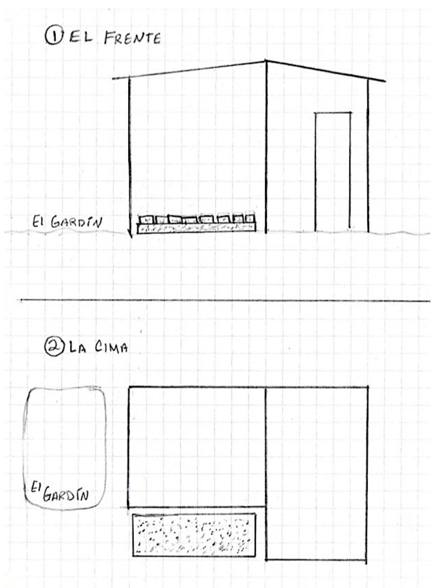
For the top-view sketch, draw circles where the tanks will be placed. Draw them to scale if possible to ensure there will be enough space near the building.

For the side-view, draw a shaded rectangle where each tank will be placed.



BASE DESIGN

The base provides a stable foundation for the water storage tanks.



Basic Design

The base is a concrete slab 3” – 4” with internal rebar reinforcement. Cinder blocks placed on top of the slab to increase the height of the storage tanks. When the tanks are higher, it is easier to access a faucet on the bottom of the tank and there is less residual water when the tank is emptied. Additionally, there is more head pressure; if tanks are connected to a drip irrigation system, a pump may not be needed.

Factors To Consider in the Design

- Find a space that is large enough to accommodate the base.
- Is the base near the gutters or will long lengths of pipe be needed?
- Note the slope of the land the base sits on. Will erosion cause the base to slide?

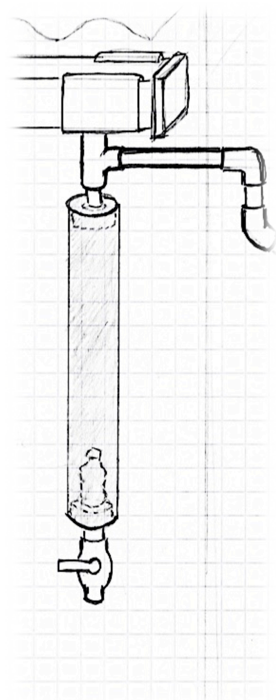
Field Sketch

For the top-view sketch, draw a rectangle around the tanks to indicate the perimeter of the base. Be sure to note the dimensions.

For the side-view, draw a thin rectangle under the tanks. Optionally, draw segmented rectangles to indicate bricks/cinder blocks.

FIRST FLUSH DESIGN

The First Flush reduces contamination in the system by diverting the first few millimeters of rain that fall on the roof. The "first rain" can carry pollutants from the atmosphere and roof.



Basic Design

The First Flush is a 3" or 4" PVC tube connected vertically to the downspout. On each end of the tube, there is a reducer to connect the large tube of the first flush to the rest of the system.

Water must fill the first flush *before* the tank. There is an empty water bottle inside the First Flush; as the tube fills with rain, the bottle floats up. When the tube is full, the bottle acts as a stopper to isolate the dirty water.

The First Flush must be drained after every rain. A "manual" First Flush has a ball valve at the bottom that must be opened to drain the water. With a manual First Flush, the water can be utilized for non-consumption purposes.

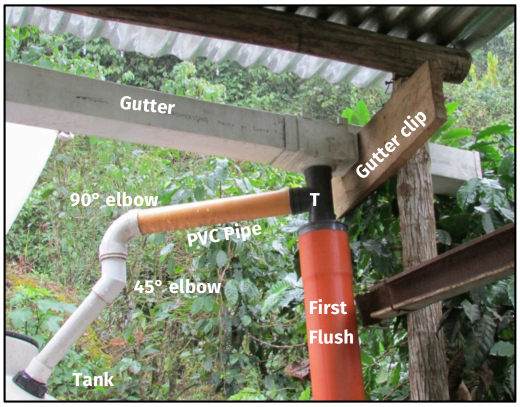
An "automatic" First Flush slowly and autonomously drains water. The First Flush has a PVC cap on the bottom in place of a ball valve; the cap has a pinhole drilled in it that allows water to drip out

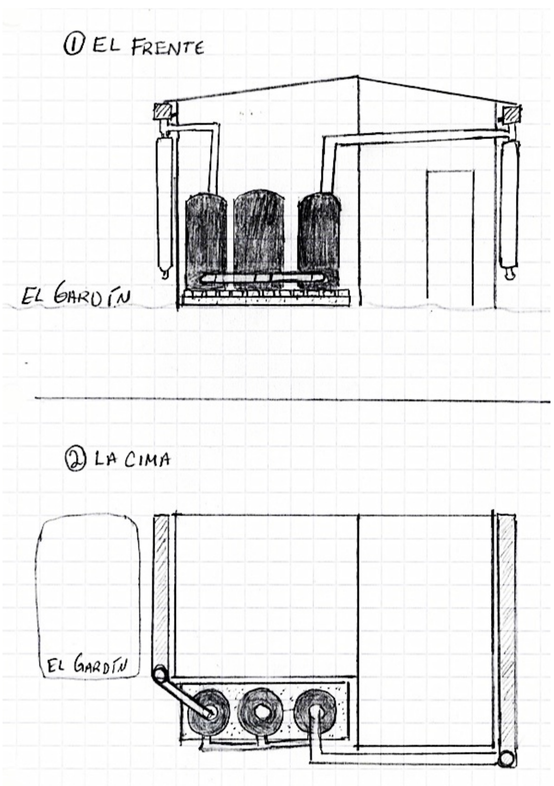
Factors To Consider in the Design

- One end of the First Flush must not be glued. If both ends are glued, it cannot be easily cleaned.
- Longer First Flushes remove more water. Systems with large roofs require longer First Flushes.
- Automatic First Flushes require less regular attention but must be cleaned more frequently if leaves or large sediments block the pinhole.

PIPING DESIGN

Pipes carry water from the gutters to the storage tanks. Pipes are enclosed and sealed to protect the water from contaminants and insects.





Basic Design

The arrangement of pipes is unique to each rainwater harvesting system. Pipes connect to the downspout of the gutter and the inlet of the tank. Immediately below the gutter, pipes may connect a filtration mechanism like the First Flush or an angled screen to remove water contaminants.

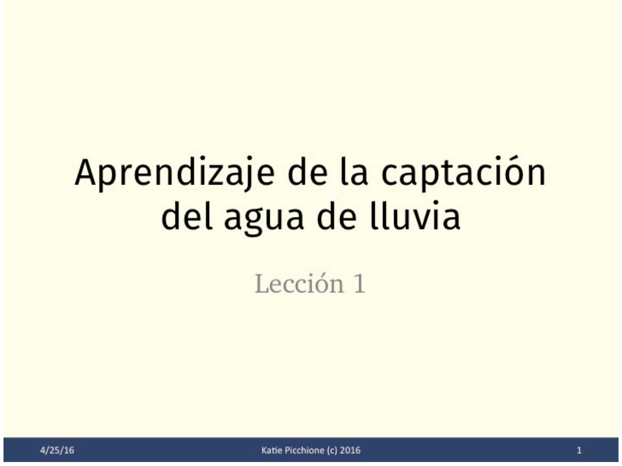
PVC plastic pipes are available in most parts of the world and are relatively inexpensive. 90° elbows, 45° elbows, and T connectors are the most common connection fittings. “Reducers” may be used to change from one pipe size to another. Pipes should fit snugly to prevent insects from entering the system. They may be glued at most joints, but one joint at the inlet of the tank must be left unglued to facilitate maintenance.

Factors To Consider in the Design

- Sometimes pipes that traverse long distances may be buried.
- With three 90° elbows, a pipe can be turned in any direction, but one or two are usually sufficient.

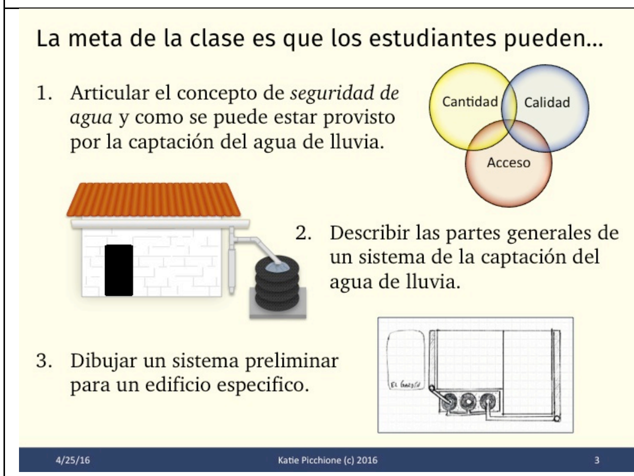
Appendix K: PowerPoint Presentations for Lessons 1-4

Lesson 1



1

2

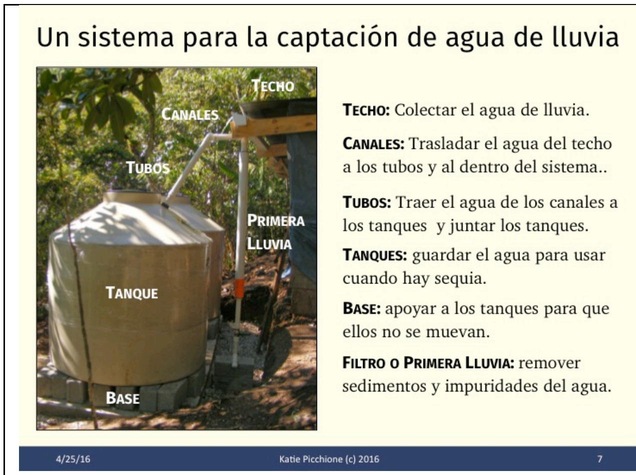


3

4

5

6


Un sistema para la captación de agua de lluvia
Techo
Canales
Tubos
Primera Lluvia
Tanque
Base
Techo: Colectar el agua de lluvia.
Canales: Trasladar el agua del techo a los tubos y al dentro del sistema..
Tubos: Traer el agua de los canales a los tanques y juntar los tanques.
Tanques: guardar el agua para usar cuando hay sequia.
Base: apoyar a los tanques para que ellos no se muevan.
Filtro o Primera Lluvia: remover sedimentos y impuridades del agua.
4/25/16
Katie Picchione (c) 2016
7

7


La gravedad causa que el agua fluye del punto más alta al punto más bajo.
4/25/16
Katie Picchione (c) 2016
8

8


Es muy importante que cada conexión está sellada para alejar insectos y la suciedad.
4/25/16
Katie Picchione (c) 2016
9

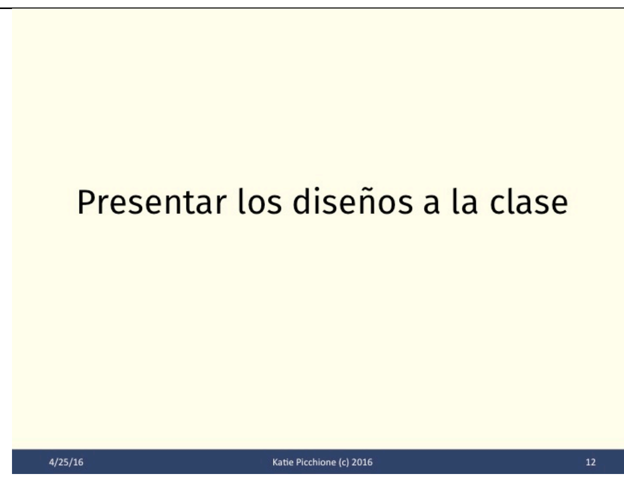
9


Proceso de designar
1. Explorar muchas ideas
2. Diseñar una solución
3. Crear un prototipo
4. Probarlo y evaluarlo
5. Mejorarlo
4/25/16
Katie Picchione (c) 2016
10

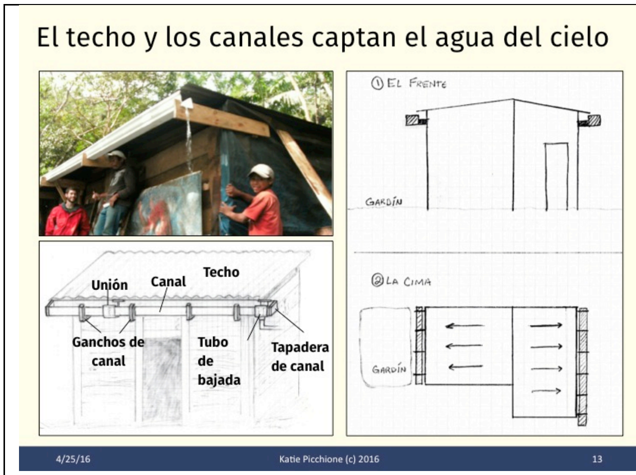
10


Trabajar en grupos para designar un sistema e incluir los componentes visto aquí
Techo
Canales
Tubos
Primera Lluvia
Tanque
Base
① EL FRENTE
② LA CIMA
4/25/16
Katie Picchione (c) 2016
11

11


Presentar los diseños a la clase
4/25/16
Katie Picchione (c) 2016
12

12



13

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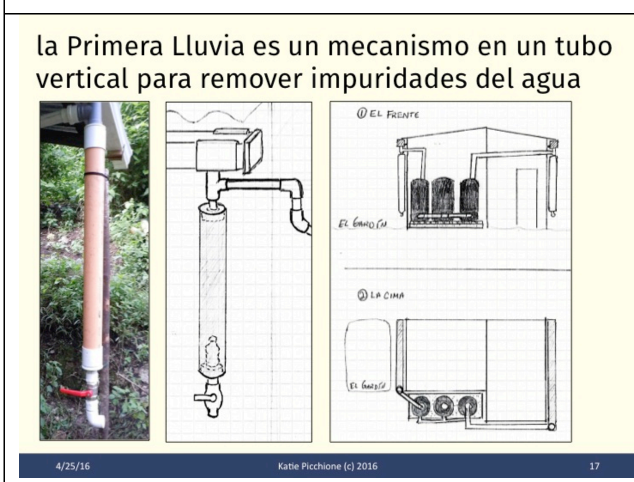
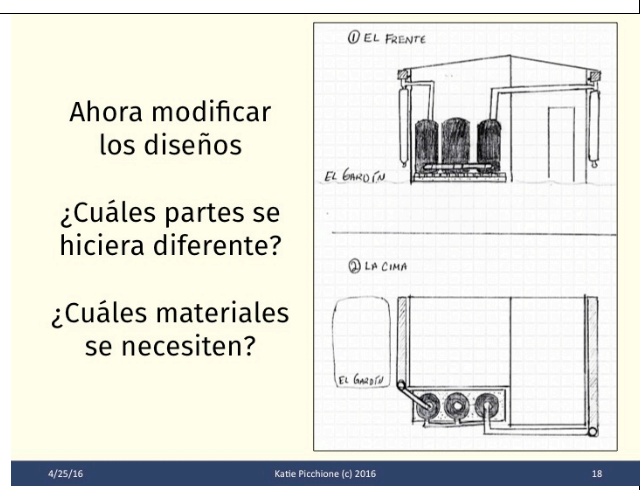
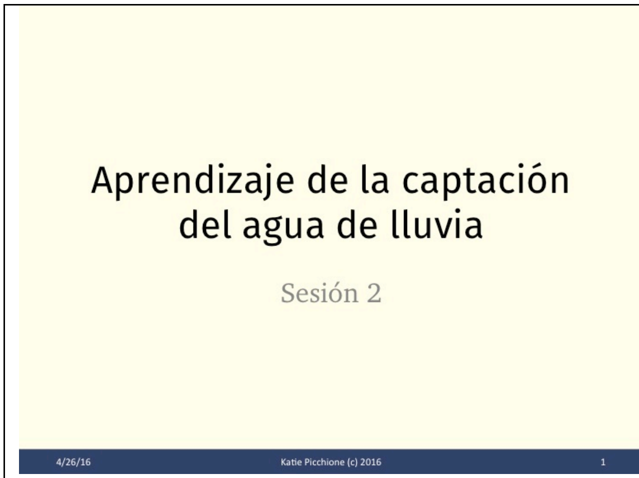


17

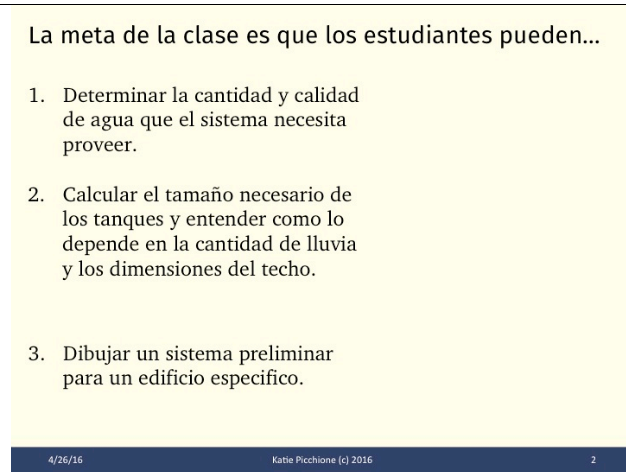


18

Lesson 2



1



2

3

4

5

6

En una dinámica, miramos que la capacidad del tanque afecta la seguridad de agua:

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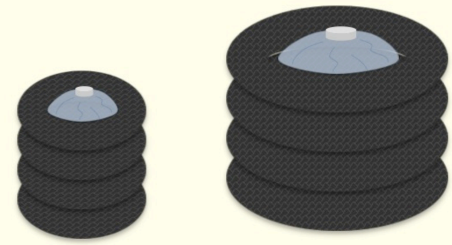
7

Calculamos la cantidad de agua que sería disponible con dos tanques diferentes



1,000 L (1 m³) 5,000 L (5 m³)

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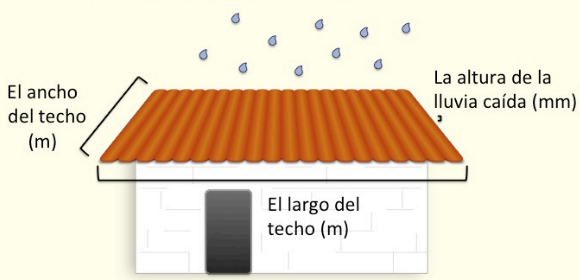
8

Primeramente, tenemos que saber la cantidad de agua que caiga cada día y el tamaño del techo para calcular la cantidad de agua que está captada por el sistema



Cantidad captada (volumen) = ancho x largo x altura

9

En este manera, calculamos la cantidad captada por cada día en una semana

Largo del techo = 20 m
Ancho del techo = 5 m
Área del techo = 20m x 5m = 100m²

Día	Precipitación (m)	Lluvia captada (m³)
lunes	0.0144	0. 0144m x 100m² = **1.4m³**
martes	0.050	0. 050m x 100m² = **5m³**
miercoles	0	0m x 100m² = **0m³**
jueves	0	0m x 100m² = **0m³**
viernes	0.0114	0. 0114m x 100m² = **1.14m³**
sabado	0.001	0. 001m x 100m² = **0.1m³**
domingo	0	0m x 100m² = **0m³**

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Ahora sabemos la cantidad de agua añadida cada día y podemos calcular la cantidad en el tanque

La demanda de agua indica la cantidad sacado del tanque cada dia. En este ejemplo, usamos 500L (.5m³) cada dia.

Día	Añadida (m³)	Agua sacado (m³)	Cantidad de agua en el taque de 1000L (1 m³)
lunes	1.4	0.5	1.4 – 0.5 = **0.9 m³**
martes	5	0.5	5 – 0.5 + 0.9 = 5**1.4m³**
miercoles	0	0.5	El tanque se rebalsa
jueves	0	0.5	
viernes	1.14	0.5	
sabado	0.1	0.5	
domingo	0	0.5	

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Ahora sabemos la cantidad de agua añadida cada día y podemos calcular la cantidad en el tanque

La demanda de agua indica la cantidad sacado del tanque cada dia. En este ejemplo, usamos 500L (.5m³) cada dia

Día	Añadida (m³)	Agua sacado (m³)	Cantidad de agua en el taque de 1000L (1 m³)
lunes	1.4	0.5	1.4 – 0.5 = **0.9 m³**
martes	5	0.5	5 – 0.5 + 0.9 = **1 m³**
miercoles	0	0.5	1 – 0.5 + 0 = 0.5
jueves	0	0.5	0.5 – 0.5 + 0 = 0
viernes	1.14	0.5	El tanque está vacío.
sabado	0.1	0.5	No hay suficiente
domingo	0	0.5	capacidad

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Segunda, consideramos el tanque de 5,000L ($5m^3$) para ver si hay suficiente capacidad

La demanda de agua indica la cantidad sacado del tanque cada dia. En este ejemplo, usamos 500L ($.5m^3$) cada dia

Día	Añadida (m^3)	Agua sacado (m^3)	Cantidad de agua en el taque de 5000L (5 m^3)
lunes	1.4	0.5	1.4 – 0.5 = **0.9 m^3**
martes	5	0.5	5 – 0.5 + 0.9 = 5 m^3
miercoles	0	0.5	0 – 0.5 + 5 = 4.5 m^3
jueves	0	0.5	0 – 0.5 + 4.5 = 4 m^3
viernes	1.14	0.5	1.14 – 0.5 + 4 = 4.64
sabado	0.1	0.5	0.1 – 0.5 + 4.64 =4.24
domingo	0	0.5	0 -0.5 + 4.24 = 3.74

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Ahora ustedes pueden hacer una tabla asi con los datos de precipitación y las notas de su edificio

1. Cuanta agua esta añadida cada dia?
2. Cuanta agua esta sacado cada dia?
3. Cual es mejor, un tanque de 1,000L ($1m^3$) o de 5,000L ($5m^3$)

Día	Añadida (m^3)	Agua sacado (m^3)	Cantidad de agua en el taque de 5000L (5 m^3)
lunes			
martes			
miercoles			
jueves			
viernes			
sabado			
domingo			

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Revisar los diseños de nuevo si hay tiempo

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Lesson 3

Aprendizaje de la captación del agua de lluvia

Sesión 3

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1

La meta de la clase es que los estudiantes pueden…

1. Hacer un billete de materiales y herramientas necesarias basada en es esquemático.
2. Calcular el costo total para la construcción.
3. Hacer una línea de tiempo para el proyecto.

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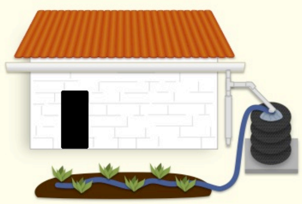
2

Tenemos que planear la manera de construir cada componente del sistema.



- De donde se llevarán los materiales?
- Por cual manera se traslada los materiales?
- Cuanto cuesta los materiales? (ha hecho un presupuesto?)
- Como cortar, ubicar, y fijar los componentes del sistema?

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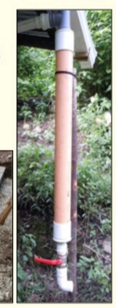
3

En grupo, pensar de este tema y hacer un proceso para construir una parte. Hacer un listado de materiales.

- De donde se llevarán los materiales?
- Por cual manera se traslada los materiales?
- Cuanto cuesta los materiales? (hay un presupuesto?)
- Como cortar, ubicar, y fijar los componentes?

Después, presentar a la clase



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4

Hacer un listado de todos los materiales que necesiten para el sistema y la construcción

Materialç	Cantidad
Madera 2” x 4”	
Canal (3m)	
Tapaderas de canal (pareja)	
Piedrín (m^3)	
Tubo PVC 2” (3m)	
Tubo PVC 1.5” (3m)	
Codo 90° 2”	

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Hacer la base

- Poner piedrín como el fondo.
- Usar madera para hacer el tambor y nivelarlo.
- Cortar y amarrar acero para reforzar el concreto.
- Poner rocas en los espacios para que se use menos concreto.
- Mezclar y echar el concreto.
- Usar mader para nivelar el base y cubrirlo con plástico.

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Canales y las grapas de canal

- Medir la dirección del ángulo del techo con un nivel de línea.
- Cortar una tabla de madera o corte de acero para ser una grapa de canal.
- Fijar las grapas a la casa con clavos.
- Asegurar que hay un grado a través de las grapas para dirigir el agua.
- Levantar el canal a las grapas.
- Cubrir el canal con un arco de malla de acero para alejar los detritos y insectos.
- Cubrir la bajada de canal con malla de mosca para alejar los mosquitos.

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Tubería

- Medir los espacios donde se van los tubos antes de cortarlos.
- Usar el pegamento con cuidado y solamente donde es muy necesario. No pega las conexiones a los tanques.
- Usar 3 codos de 90˚ para dirigir el agua en cualquier dirección. Tipicamente 2 es suficiente.
- Usar reductores para cambiar el tamaño del tubo.
- Usar tubos de 1.5” o 2”

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Primera Lluvia

- Conectar una conexion “Y” o “T” a la bajada de canal
- Usar un reductor para ampliar el tubo al tamaño 3” o 4”
- El largo de la primera lluvia se puede calcular o estimar para remover 10L por 1000m2.
- Al dentro del tubo, poner una botella de agua vacia que no pasará por el reductor.
- Poner otro reductor al bajo de la primera lluvia para quedar la botella.
- No pega el reductor al bajo del tubo para que se puede laval al dentro del tubo.
- Ubicar una rama para apoyar la primera lluvia. Fijarla con alambre de amarr si es necesario.

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Hacer un presupuesto

Materialç	Cantidad	Costo por unidad	Costo total
Madera 2” x 4”			
Canal (3m)			
Tapaderas de canal (pareja)			
Piedrín (m^3)			
Tubo PVC 2” (3m)			
Tubo PVC 1.5” (3m)			
Codo 90° 2”			

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Ahora intercambiar los planes con otro grupo y revisar el trabajo de sus pares

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Lesson 4

Aprendizaje de la captación del agua de lluvia

Sesión 4

4/27/16 Katie Picchione (c) 2016 1

1

La meta de la clase es que los estudiantes pueden…

1. Crear un plan especifico para hacer inspecciones y mantenimiento al sistema.

2. Identificar problemas, planear soluciones, y hacer reparaciones.

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2

Pensar de problemas que podrían pasar en el corto plazo y largo plazo por cada parte del sistema

	Corto Plazo	Largo Plazo
Techo	• Angulo del techo no es suficiente • Ramas y hojas se caen en el techo y dañarlo	• Esta oxidada • Hay degradación de las materiales del techo
Canales	• El angulo no esta bien • La bajada de canal esta bloqueada con hojas u otro detritos • La malla se rompe	• Canales de plástico se convirtieren frágil • Canales de metal se oxidan • Las grapas se rompan
Primera lluvia o filtro	• Se cae el tubo • Hay demasiado sedimentos	• Esta bloqueada con detritos • La válvula se rompe
Tanques	• Se rompe el plastico • Hay conexiones que gotean • Hay sedimento al fondo	• El plástico se degrada • Los pernos se oxidan • Hay mucho contaminación
Base	• Se falta bloques	• Esta rejada el concreto

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3

Appendix L: Kalenian Award Proposal

BRINGING WATER TO THE WORLD

A movement to use recycled materials for Rainwater Harvesting (RWH), improve domestic and agricultural water security, promote sustainable social entrepreneurship, and mitigate poverty by capitalizing on the combined power of individuals and communities who act in harmony with the environment

• November 1, 2015 •

I. Overview: Rainwater Harvesting + Learning -> Social Enterprise

Opportunity exists to build a social enterprise that mitigates chronic domestic and agricultural water poverty through affordable ***rainwater harvesting*** (RWH). New water storage technologies, under development at Worcester Polytechnic Institute, can reduce the cost of RWH systems, making water security affordable for families and farmers in rural and developing areas. Through a partnership with Fundación Paraguaya, an agricultural RWH system will be implemented at a rural agricultural high school in Paraguay in April 2016. In accompaniment, students will be offered hands-on training focused on using RWH to reduce drought-related vulnerabilities on small-scale farms. From this program, a social enterprise can launch to promulgate technically sound, culturally appropriate, affordable RWH. Locally trained RWH technicians will be employed to teach system design, construction, maintenance, and repair strategies to future owners. The enterprise will create opportunities for local economic growth, promote community-driven development, and improve quality of life.

II. The Problem: Water Poverty, Worldwide and in Paraguay

Water security can be contextually defined as the state of having reliable access to adequate quantity and quality water for drinking, cooking, bathing, domestic cleaning, and agriculture.[1] In Paraguay, an agrarian South American country, 97.8% of farms rely solely on rainwater to cultivate crops.[2] 225,587 of these (86%) are family-farms, built on 20 hectares or less, that rely on the land for both subsistence and cash crops.[3] In a 2015 World Bank report, Paraguayan farmers identified drought as the most serious production threat; harvests dry up, causing severe loss of livelihood.[3] With droughts predicted to become more severe as global climate change progresses,[4] adaptation strategies are needed to ensure agricultural and domestic water security.

Though technologies exist to remediate water challenges, nuanced environmental, geologic, economic, social, and political factors preclude a single universal solution. However, customizable technologies can be adjusted for use in a variety of scenarios.

III. The Technology: Sustainable Rainwater Harvesting and Training Program

Rainwater harvesting (RWH) is one simple and elegant technology that can be locally tailored to meet water needs in a technically sound, culturally appropriate way. RWH systems (depicted in Appendix A) capture rainwater from roofs and store it for later use, typically in plastic or concrete tanks. Gutters and pipes channel water from roof to tank while filters and 'first flush' mechanisms remove contaminants. The fundamental concepts of RWH are accessible and straightforward. To best meet the needs of a family or farm, systems should be individualized, designed based on intended use, daily rainfall, water consumption rate, available materials, spatial constraints, and budget. With site-specific considerations, RWH systems can be optimized for diverse domestic and agricultural settings. In developing countries, stored rainwater is pragmatic. In Paraguay, RWH promises a secondary water source to sustain crops during droughts. However, RWH is expensive; tanks alone typically account for more than 50% of the total system cost.[5] Families unable to buy adequately-sized water tanks are unable to attain water security.

With a focus on agricultural water needs in Paraguay, our team at WPI is engineering affordable water storage tanks crafted from locally available, recyclable materials. Tarps, tires, and natural substances are candidate tank materials that can reduce system cost. Tanks must be: of sufficient size, to meet water consumption requirements; inert, to prevent chemical contamination of the water or environment; viably built, repaired, and maintained; and culturally appropriate, to be adopted as a widespread solution.

In addition to new tangible technology, we are developing a training program to facilitate the spread of RWH. The training has both theoretical and practical components. A pictorial manual, with descriptions translated into native languages, will be a reference and guide to understanding the general form of a RWH system and methods for customization. Through team-based, hands-on workshops, each participant will design a RWH system that meets their needs, learn proper RWH maintenance and repair strategies, assist in building a system at a neighboring farm, and ultimately construct their own. Through this process, participants are empowered to create and sustain a system that provides water security.

Fundación Paraguaya, a nongovernmental organization in Paraguay, runs several agricultural schools that teach high school students practical skills for farming and business administration.[6] The RWH project will work with Fundación Paraguaya's St. Francis Agricultural School, located near Paraguay's capital, Asunción, where many of the 150 students come from small-scale farming families.[6] Fundación Paraguaya has close ties with WPI as an IQP sponsor and has welcomed a pilot implementation of the new RWH tanks and the accompanying trainings. Using lessons learned from the pilot, we will work to kick-start a sustainable social enterprise that will spread water security through rainwater harvesting.

IV. Activities to be Undertaken and 18-Month Outcomes

This project is framed as both an interdisciplinary Major Qualifying Project and as scaffolding to leverage a social enterprise. The project is advised by Dr. Diran Apelian, director of the WPI Materials Processing Institute, and by Dr. Robert Traver, director of the WPI Paraguay Project Center. It has resolute logistical support from Sñ. Martin Burt, founder of Fundación Paraguaya. Members of the project team have experience designing, building, and evaluating domestic RWH systems in Guatemala with Engineers Without Borders-USA WPI (EWB-USA

WPI), and are well versed in creating and conducting manufacturing trainings at the WPI Haas Technical Education Center.

The academic goal of this project is four-fold: to engineer affordable RWH storage tanks, to create educational infrastructure to disseminate the technology, to pilot the technology and training program, and to monitor and evaluate the pilot. Kalenian Award will enable this project to expand into a social enterprise that promulgates RWH technology.

Objective 1: Develop inexpensive rainwater storage tanks made of recycled local materials.

We will systematically develop inexpensive storage tanks by focusing on user needs through an iterative design process. Steps to be completed by January 2016 include: (1) assess stakeholder needs to articulate functional and technical system requirements; (2) analyze and compare candidate materials, including tarps, tires, and natural materials; (3) create and test a prototype; (4) iteratively improve designs.

Objective 2: Create a team-based, hands-on training program.

To complete Objective 2, we will create a series of hands-on workshops to teach system design methods, construction techniques, operations and maintenance guidelines, and repair strategies. Trainings will be pedagogically based in learning sciences, Paraguayan cultural norms, experiences from the WPI Haas Technical Education Center, recommendations from EWB-USA WPI, and agricultural education programs in Paraguay and other Latin American nations. Trainings will culminate in a practice build and realization of a self-designed system. The above-mentioned pictorial manual will be designed strategically to accompany the practical trainings as a guide that can inform decisions and a reference that trainees can later review. By March 2016, we will develop protocol for group size, program timeline, communication, and certification upon program completion. Materials supply chain, program expenses, and funding opportunities, including volunteer tourism and microfinance, will be explored.

Objective 3: Construct a pilot system at the St. Francis School.

In March and April 2016, the new RWH storage tanks and RWH training program will be piloted and evaluated at the St. Francis School. Due to academic time constraints, the training program will be adjusted to take place over approximately a two-week period. We aim to work closely with five or six students initially, a group size recommended by EWB-USA WPI. Upon completion, students will be certified as RWH technicians who can design, build, maintain, and repair systems at other local farms.

Objective 4: Evaluate the techniques and trainings and establish a monitoring plan.

Finally, the technology and training will be evaluated for technological integrity and cultural congruency. Pre- and post-training interviews, focus groups, and surveys will shed light on the experiences of the students who participated in the training and others in the St. Francis School community. An ongoing monitoring program will be arranged with paid, on-site personnel, who will collect weekly data about system function and the user experience. Based on monitoring methodologies developed by EWB-USA WPI, data collection will highlight performance of the tanks made of recycled materials. Feedback will advise changes in system design, maintenance recommendations, and training methodologies. Pilot monitoring will continue through the Kalenain Award period.

Next Steps: Identify key players, write a business plan, and launch the RWH business

Certified students and lessons learned from the pilot are bedrock elements to build a sustainable social enterprise. During the term of the Kalenian Award, we will write a comprehensive business plan with guidance from the WPI Foisie School of Business and Sr. Martin Burt. Further. We will develop relationships with suppliers, materials transporters, and the microcredit branch of Fundación Paraguaya, all essential to bringing the plan to fruition. Ongoing innovations in RWH technology and organizational infrastructure can improve widespread access to this elegant solution to water poverty.

V. Long-term Outcomes, Value, and Impacts

In the nexus of global challenges, water and quality of life are closely linked. 663 million people lack access to improved water sources and 863 million live in extreme poverty.[7] Affordable, custom rainwater harvesting technology promises a solution that targets both challenges. The social, economic, and environmental benefits of RWH are multiplied when coupled with entrepreneurial activities.

Once a sustainable social enterprise is formed around inexpensive, customizable RWH, long-term impacts will continuously unfold. RWH is one technology that will help the global community achieve universal water security. The enterprise will spur local economic growth in developing nations and help mitigate poverty holistically. The educational component will create a framework for new innovations through the sharing and development of ideas. Finally, this project and social enterprise will foster global cooperation, understanding, and cultural interchanges through international partnerships. It will benefit society by creating opportunities for local economic growth, community-driven development, knowledge sharing, and improved quality of life.

Appendix A: Figures

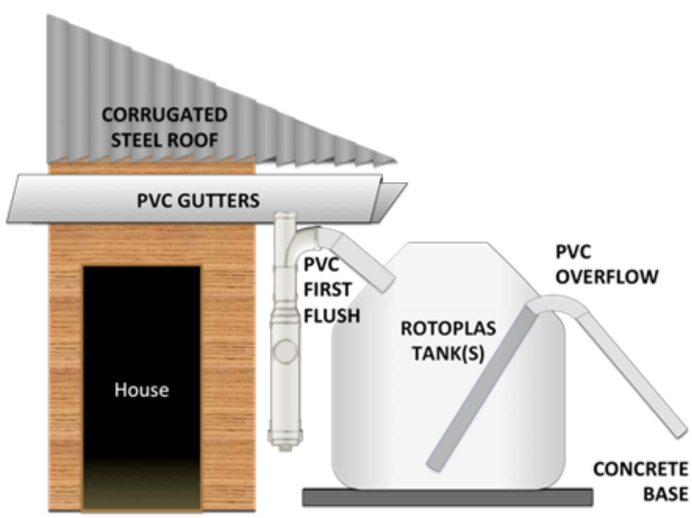

Figure 1: Concept diagram of a domestic rainwater harvesting system developed by EWB-USA WPI. EWB-USA WPI spent 6 years designing and implementing domestic RWH systems with families in rural Guatemala. Plastic Rotoplas tanks are valued at $300 each, accounting for upwards of 50% of the total cost. For families that live on approximately $2 per person per day, unsubsidized systems are currently unaffordable.

Figure 2: Photo of a corresponding system, built to provide drinking and cooking water to a family in Guatemala. Following three years of research and development, the system featured here was one of 34 constructed by EWB-USA WPI from 2013 – 2015.

Diagram and photo credit to Engineers Without Borders-USA WPI, published by Dr. Laureen Elgert, 2015.

Appendix B: Resources

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