La Yuca Rainwater Catchment 2012

ENGR 498: Directed Design
Humboldt State University

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Abstract

In June 2012, a collaborative rainwater catchment project was completed by community members, Universidad Iberro Americana (UNIBE) students, and Humboldt State University (HSU) students in La Yuca, Santo Domingo, Dominican Republic. The technical purpose of the rainwater project was to restore or replace the existing system and ensure that the collected rainwater system can produce cleaning and drinking water, is easy to operate, and is more cost-effective than purchasing potable water. In addition, the social and educational purposes were to provide an opportunity for students to gain an understanding of working across cultures to learn and achieve common goals through service learning, to design a cost effective system that can be replicated in the Dominican Republic, and to increase the local rainwater catchment design capacity in Santo Domingo.

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1 Introduction

Students from Humboldt State University (HSU) traveled to participate in a service-learning program titled *Practivistas Dominicana* in Santo Domingo, Dominican Republic, which included classes in Spanish and Engineering as well as building projects that inspire reuse and better building practices at a lower cost. These projects were completed collaboratively by community members, Universidad Iberro Americana (UNIBE) students, and HSU students. The projects included alternative building, rainwater catchment, and alternative energy.

A rainwater catchment system was built collaboratively by students and community members in 2011 in a small community called La Yuca in Santo Domingo, Dominican Republic. The rainwater catchment was significantly modified in 2012.

1.1 Purpose and Scope

The task for the 2012 rainwater team is to restore or replace the existing system and ensure that the collected rainwater system can produce cleaning and drinking water, is easy to operate, and is more cost-effective than purchasing potable water. Aside from the technical purpose, social and educational purposes helped to guide the project. Additional purposes included: providing an opportunity for students to gain an understanding of working across cultures to learn and achieve common goals through service learning, designing a cost effective system that can be replicated in the Dominican Republic, and increasing the local rainwater catchment design capacity in Santo Domingo.

1.1.1 Objectives

The primary objective of this project is to minimize the cost of potable water for the elementary school in La Yuca. Currently, the school refills 5-gallon jugs of water three to five times per week. Refills cost between 20-50 Dominican Pesos (DOP) ($0.50 to $1.24) per refill, depending on the vendor. Another objective is to compare filtration options for rain water catchment with limited head to inform future rainwater catchment designs.

1.1.2 Business Opportunities

By working with the local community to complete the rainwater catchment design, community members and students learn how rainwater catchments systems are implemented and operated. The implemented design can be replicated, adapted, and improved upon by everyone involved. Once a general understanding of the construction, operation, and acceptance of rainwater catchment systems is achieved, businesses can be created to build these systems elsewhere. A rainwater catchment-building business has the possibility of generating income for the builders and increasing the independence of local communities.

1.2 Background

Background information was included to provide context for the design decisions that were made. Included in the background is a description of the Dominican Republic, La Yuca (a community in Santo Domingo, Dominican Republic), rainwater catchment, and filtration for rainwater catchment.

1.2.1 Dominican Republic

The Dominican Republic is a primarily Spanish-speaking country that covers eastern two-thirds of the Island of Hispaniola in the Carribean. Santo Domingo is the capital city. English is spoken in some of the major cities or tourist areas, but Spanish is the official language of the Dominican Republic (US Department of State, 2013).

1.2.2 La Yuca

La Yuca is a closely-knit, low-income community in Santo Domingo, Dominican Republic. An aerial view of La Yuca and surronding area is shown in Figure 1.1. The construction style is very different from the surrounding city and is one indicator of the sharp economic divide between La Yuca and the surrounding areas of Santo Domingo.

The surrounding area has wide boulevards, high rise buildings, and even a mini cooper dealership. A store's parking area located across the street from La Yuca is shown in Figure 1.2.

La Yuca is very closely-built with very narrow walkways that do not follow the rectangular layout of the surrounding area, but meander through the community. In the open areas, a mixture of young and old play dominoes, eat ice-cream, or make deliveries on motorcycle using the narrow walkways in La Yuca. The center of La Yuca is shown in Figure 1.3 with the community president holding a pet snake in front of one of La Yuca's small stores that sells potable water.

During our construction phase, children in La Yuca were very interested in what the rainwater team was doing and offered their help by delivering heavy cinder-blocks from the road to the school (Figure 1.4).

Figure 1.1: An aerial view of La Yuca and the surrounding city of Santo Domingo, Dominican Republic from Google images.

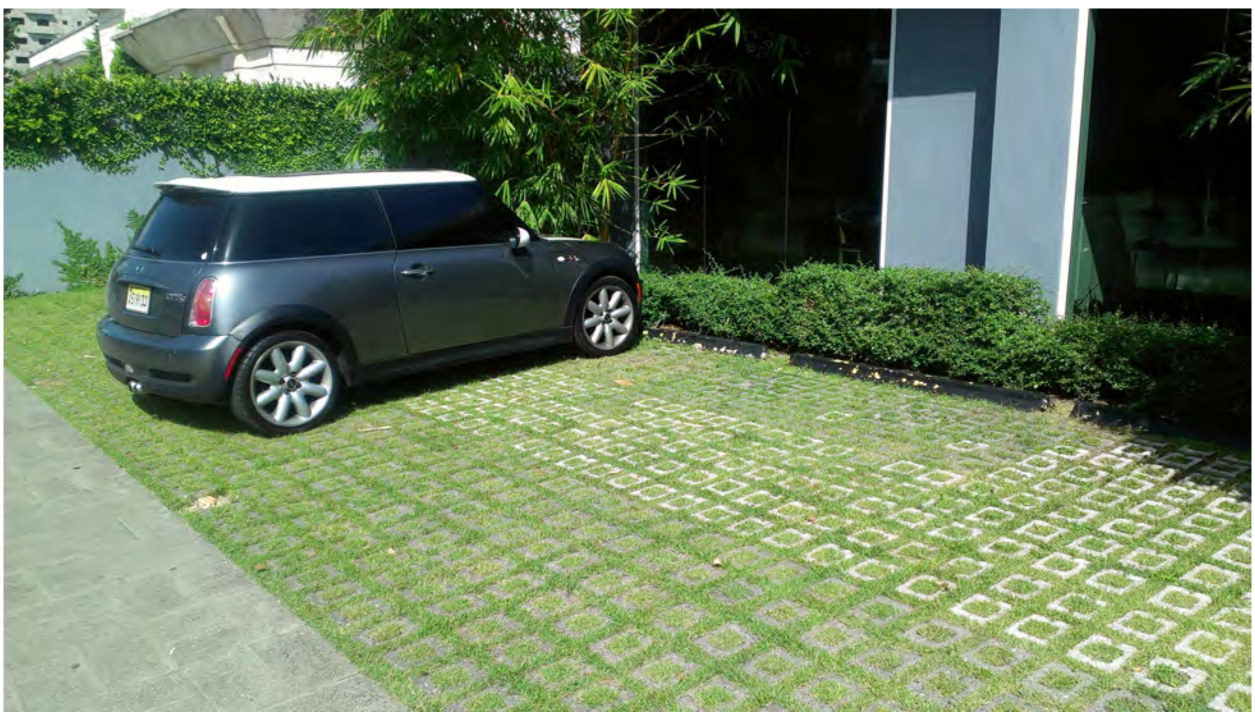

Figure 1.2: A store's parking area located across the street from La Yuca.

Figure 1.3: The center of La Yuca in which the community president is holding a pet snake in front of one of La Yuca's small stores that sells potable water.

1.2.3 Rainwater Catchment

Rainwater catchment is a technique for harvesting naturally treated water that has been utilized for thousands of years for beneficial uses (Boers and Ben-Asher, 1982). The natural treatment occurs through solar-driven evaporation, which de-salts ocean water (desalination) (Viessman and Lewis, 2002). These processes are inherent in the hydrologic cycle. Rainwater catchment offers significant advantages over other sources of water e.g. surface water and groundwater. Water that has reached the ground has had an opportunity to entrain or dissolve constituents from soils, rocks, or other surfaces, which can contribute qualities that are undesirable. The most undesirable qualities would include pathogens, carcinogens, or other contaminants. Rainwater, by contrast, is subjected only to contaminants that it reaches as it descends through the atmosphere and as it flows on the collection surface. As opposed to other water treatment methods, hydrologic, solar-driven evaporation requires no funding, but rainwater supply is susceptible to seasonal and climactic variations in quantity and frequency.

Rainwater catchment is made up several vital components including runoff inducement, runoff collection, as well as storage and conservation of harvested water (Boers and Ben-Asher, 1982). Runoff inducement is a term used to describe the methods used to increase runoff efficiency of a catchment surface, where runoff efficiency is the ratio of runoff produced per unit of precipitation over a given area (LVA, 1984). The term runoff inducement is typically

Figure 1.4: Children in La Yuca were very interested in what the rainwater team was doing and offered their help by delivering heavy cinder-blocks from the road to the school among other tasks.

used for agricultural applications, but is still relevant in this instance; a sloped roof provides the runoff inducement for domestic applications. Runoff collection refers to the aggregation and conveyance of runoff to the storage e.g. a gutter leading to a storage tank. Storage allows for equalization of rainwater flows to maintain water supply between rainy periods.

Rainwater catchment systems often include first flush systems. A first flush system is a component of a rainwater catchment system that preserves water quality at the expense of water quantity. A first flush system works by wasting or diverting the first volume of collected rainwater because of the elevated amounts of solids or contaminants entrained in the collected rainwater. When the first wash of the collection surface by rainfall is diverted or wasted with a first flush system, the collected rainwater for later use contains less solids or other contaminants. Usually, rainwater catchment systems equipped with first flush systems provided safe drinking water (Zhu et al., 2004). First flush systems are comprised of a storage volume, a connection to the rest of the rainwater catchment system, and a way to drain the water to be wasted (e.g. a hole in the bottom of the storage volume). More advanced systems contain an apparatus that reduces mixing of the wasted water with the water to be filtered (e.g. a floating ball valve). As rain hits the collection surface, accumulated particles (contaminants) are dissolved or otherwise entrained in the flow of collected rainwater. The particles entrained in the flow are then transported to the first flush storage volume, which fills with the first collected rainwater. As more rain hits the collection surface less particles are available to be transported by the flow, which means the water will contain less contaminants. After the first flush volume is filled, the subsequent rainwater can be collected for use.

In 2011, Humboldt State University (HSU) students, La Yuca community members, and Universidad Iberro Americana (UNIBE) students (hereafter referred to as "the rainwater team") installed a rainwater catchment system at an elementary school called *Escuela Basica Nurys Zarzuela C.* For various reasons (described later), the rainwater catchment system was unable to provide the elementary school with potable water by 2012. The school was, however, able to use the untreated, collected rainwater to refill their subsurface cistern and was able to purchase potable water from a local vendor. The water in the subsurface cistern is used for cleaning. Before the 2011 rainwater catchment system was built, the cistern needed to be filled one to two times per month. After the 2011 team, the cistern only needed to be filled twice in the eleven months following because of the available rainwater.

1.2.4 Filtration of rainwater

Filters are used to remove particles that can be found in rainwater. Particles in collected rainwater can come from the atmosphere, debris on the collection surface, and components of the rainwater catchment system itself e.g. the dissolution of the collection surface. To get water to flow through a filter, there must be higher pressure on the inlet to the filter than the outlet. The pressure drop caused by friction across filters or other appurtenances is called pressure head loss or simply head loss.

The dominant particle removal mechanism in filters is mechanical screening, where the caught particle's diameter is larger than the pore through which water is flowing. As particles are collected, a cake is created on the filter surface. The cake creates increasingly smaller pore sizes with respect to time (or volume of filtrate). As a result, the filtrate quality increases, while the head loss across the filter increases until water is no longer able to flow through the filter (Davis, 2011). Filtration does not require the addition of chemicals, such as flocculants, to remove particle constituents (EPA, 2012).

The term 'filter run' refers to the time of operation of the filter without intervention. Some types of intervention could be backwashing of the filter (running water backwards to remove caught particles) or replacing the filter or its components.

2 Basis of Design

To achieve the primary objective, it is necessary to know certain parameters about the elementary school. So, estimates of the population and the existing demand for the school's water were taken into account during the design phase of the project.

There are one hundred students that attend *Escuela Basica Nurys Zarzuela C.* Additionally, there are several teachers at the school. In all, there should be no more than 150 persons at the school. Not all people at the school drink the school's water.

Escuela Basica Nurys Zarzuela C. has two distinct demand periods: a higher demand period while school is in session and a lower demand period when school is not in session. The two uses for water at the elementary school are cleaning (not potable) and drinking. For cleaning, the water is stored in a approximately one-thousand liter subsurface cistern. After the first rainwater catchment system was put into place, the cistern has been filled with mostly untreated rainwater. For drinking water, approximately three five-gallon water containers were purchased each week. So, about 15 gallons of drinking water supplied by the school are consumed each week.

3 Regulatory Requirements

The Dominican Republic maintains a set of water quality standards for drinking water (Table 3.1). The standards in Dominican Republic for drinking water include standards that omitted from the World Health Organization's drinking water guidelines including: Chloride, Iron, Manganese, Calcium (Hardness), Sulfates, Total Dissolved Solids (TDS), and pH. The chlorine standard in the Dominican Republic differs from that of the WHO guidelines, which limit chlorine concentration to 5 mg/L (World Health Organization).

Table 3.1: Dominican Republic Water Quality Standards (ISO)

Parameter	Value	Units
Surface tension Agents	0.0	mg / L
Chlorides	250	mg / L
Chlorine	0.0	mg / L
Copper, as Cu	1.0	mg / L
Iron, as Fe	0.3	mg / L
Magnesium, as Mg	150	mg / L
Manganese, as Mn	0.05	mg / L
Calcium, as Ca	75	mg / L
Phenol compounds such as phenol	0	mg / L
Sulfates as SO_4	250	mg / L
Zinc as Zn	5	mg / L
Total Dissolved Solids (TDS)	500	mg / L
pH	$6.5 < \& < 8.5$	mg / L

4 2011 Design

Students and community members constructed a rainwater catchment system in 2011 that connected to a newly constructed classroom with a galvanized metal roof (Figure 4.1). The roof was constructed with a tilt so that the rainwater would flow to one edge of the roof. A three-inch PVC pipe was cut along the length of the pipe and slipped onto the edge of the roof to make a gutter. The length of PVC was cut to be wider at the end of the gutter flow path and narrower at the opposite, capped end. The gutter was secured using thin metal wire to a beam running parallel to the PVC gutter and to the roof itself.

Figure 4.1: A view of the catchment area after some work by the 2012 rainwater team. Arrows indicate the flow direction of the captured runoff. Photo by Lonny Grafman.

The gutter was roughly level and a PVC end cap was placed at one end of the gutter to ensure that collected water would escape at only one end. The uncapped end was connected to a PVC elbow to direct the flow to fall through the primary screen at the corner of the roof (Figure 4.2).

The purpose of the primary screen is to prevent large particulate matter (e.g. leaves) from entering subsequent parts of the rainwater catchment system. The screen is angled above horizontal so that screened material will fall with gravity out of the way of the water flow. The primary screen was created using a five gallon jug commonly used as a drinking water container. The jug was inverted and roughly cut at a sixty degree angle using a hand saw. A square foot of galvanized, steel, hardware cloth was attached to the cut end of the jug using

Figure 4.2: The primary screen separated leaves and other large particulate matter from the water flow. Screenings fell out of the way of the water flow by gravity. Beneath the primary screen was a Tee intersection, which directed water to the first flush system's storage pipes (below, partially pictured) and allowed water to enter the 250 gallon storage tank (right, not pictured).

zip ties.

A PVC Tee intersection directed flow first to the first flush system (Figure 4.3). Once the first flush was filled, the Tee intersection (Figure 4.4) directed the water to the 250 gallon storage tank. The first flush system was constructed entirely out of a loop of 3 inch PVC piping with an end cap at the bottom. The bottom end cap had a hole on the side to allow for automatic draining of the first flush system to make room for the next storm event volume.

As soon as the first flush system is filled with captured rainwater, rainwater is stored in the 250 gallon storage tank. From the side of the 250 gallon storage tank, near the bottom, water was directed through a shut-off valve. Following the shut-off valve water was piped through a hole in a sheet of galvanized roofing to the story below using 1.5 inch diameter PVC (Figure 4.5).

The 1.5 inch pipe from the 250 gallon storage tank led to two different paths that could be controlled by the user. One flow path led to a slow sand filter that was made from an elevated 35 gallon plastic drum that was filled with a small amount of gravel at the bottom and a large amount of sand. The other flow path was used to bypass the slow sand filter drum (Figure 4.6), which ended in spigot.

Figure 4.3: The first flush system was constructed entirely out of 3 inch PVC piping (storage volume) with an end cap at the bottom.

The 35 gallon drum filled with sand and gravel was intended to be used as a slow sand filter. As designed, the water would infiltrate through the sand and gravel media, where constituents would be caught in the topmost layer of the slow sand filter, to be removed later. The gravel media was designed to keep the sand media from escaping with the filtered water.

The filtered water was directed to a locally sourced, cartridge-style, silver-impregnated, activated carbon filter (hereafter the "silver filter") to further filter and disinfect the water (Figure 4.7).

Costs of the 2011 design were compiled (Table 4.1). Maintenance of the 2011 design included replacement of the silver filter every 3500 gallons and checking or cleaning the gutters once a year (Mendoza et al., 2011).

Figure 4.4: The Tee intersection directed the water to the 250 gallon storage tank.

Figure 4.5: Water was piped from storage through a hole in a sheet of galvanized roofing to the floor below using 1.5 inch diameter PVC.

Figure 4.6: 1.5 inch pipe can be directed into the 35 gallon slow sand filter (black) or to a bypass (foreground).

Table 4.1: Costs of the 2011 design were compiled (Mendoza et al., 2011). A conversion rate of 40 Dominican Pesos (DOP) to the US Dollar (USD) was used.

Material	**Quantity**	**Cost (DOP)**	**Cost (USD)**
PVC 3” (19ft)	1	375	9.38
PVC 1” (19ft)	1	155	3.88
5 Gallon Jug	1	250	6.25
90 Degree- 3” PVC	1	69	1.73
Y Branch- 3” PVC	2	180	4.50
T Branch- 3” PVC	1	90	2.25
90 Degree- 1” PVC	2	70	1.75
45 Degree- 1” PVC	3	105	2.63
55 Gallon Drum	1	850	21.25
Sand (cu. meters)	0.5	400	10.00
Gravel (cu. meters)	0.3	60	1.50
Activated Carbon Filter	1	2500	62.50
Metal Form	1	2000	50.00
Spigot	1	235	5.88
Tinaco	1	3300	82.50
Total		10639	265.98

Figure 4.7: The filtered water was directed to a cartridge-style, silver-impregnated, activated carbon filter to further filter and disinfect the water.

4.1 Use of 2011 Design

The 2011 Design for La Yuca was used for providing cleaning water, but not drinking water. The rainwater was collected, stored, and used to fill the on-site, underground cistern, which was used for cleaning the school facility. Use of the fully filtered water for drinking was essentially non-existent because the primary problem with the 2011 design was the time required to fill even a small container with filtered water. The slow sand filter did not pass water through in a short enough time to be practical. A more practical flow rate for the filter before the silver filter (slow sand filter) would be 5 gallons per minute. School faculty frequently used the filter bypass so that the stored rainwater could be used for the cistern. The 2011 design successfully reduced the amount of times that the subsurface cistern needed to be filled by an outside provider. Before the 2011 design, the subsurface cistern needed to be filled twice each month. After the 2011 design, the cistern only needed to be filled twice in the 11 months following the rainwater catchment construction.

4.2 Identified Problems with the 2011 Design

Identified problems with the 2011 design included:

1. The first flush system was undersized.
2. There was no protection against mosquitoes breeding in the storage tank.
3. The head loss in the slow sand filter was too great, which caused water bottle filling time to be too long.
4. The slow sand filter was losing media to the effluent water or into the subsequent silver filter.
5. There was a lack of faith in the slow sand filter, likely based on the turbidity caused by the filter media loss to the effluent.

Some areas for improvement on the 2011 design included:

1. options for hurricane preparedness
2. flexibility of the design
3. ease of maintenance

5 Development of Preliminary Alternatives

Alternatives were generated to meet the project's various goals and objectives. A method of evaluating and comparing alternatives was decided upon and used to determine the selected alternative.

5.1 Alternative Comparison Method - Pugh

A set of criteria were generated by the 2012 rainwater team (Table 5.1). To determine the preferred alternative, alternative are compared to a selected alternative datum. For each criterion, alternatives are marked with a "+" symbol if they perform better than the datum. Similarly, the alternatives are marked with a "−" symbol or with a "=" if they perform worse than or equal to the datum, respectively. The difference between the amount of +'s and −'s for the alternative is that alternative's score for that iteration. The highest scored alternative becomes the datum for the next iteration. If all the alternative scores are less than zero, the datum is the best alternative according to the Pugh Method.

Table 5.1: A set of criteria were generated by the 2012 team, which included criteria weights and respective constraints.

Criteria	Constraints
Safety	Must be safe for children to play around. Water must be potable.
O&M cost	Must be less than purchasing the same amount of potable water
Reproducibility	Must be replicable in similar situations with minor modifications
Reproduction cost	Must be less than $1000 US
Educational Value	Can be used for lessons by teachers
Durability	Must withstand strong tropical storms
Ease of maintenance	Maintenance must be simple, quick and understandable
Adaptability	Must be flexible to changes desired by the user
Aesthetics	Must be acceptable to the client
R&D cost	Must be less than $1000 US

5.2 Description of Alternatives

Three alternatives designs were analyzed to determine how well they met each criterion.

5.2.1 Slow Sand Filter

The slow sand filter alternative design features a sand filter that removes suspended material with a characteristically low hydraulic loading rate. Typical values for the hydraulic loading rate are between 3 and 8 $m^3/d * m^2$. Removed material is usually caught within the first 75 mm of the filter media (sand). As material is caught in the pores in the sand filter, water passage through the media slows until it can no longer pass through the media. The top layer, or *shmutzdecke*, is removed, cleaned, and replaced. Slow sand filters have been used since the 1800s and continue to be successful despite significant labor requirements and a relatively large footprint (Davis, 2011).

The 2011 design used a slow sand filter created using natural sand. Natural sand has a very wide range of filter media sizes, which causes the average pore size to be much smaller than filter media of uniform (or near-uniform) size. As a result of the small pore sizes, very high filtrate water quality is produced per depth of media. As a consequence of the small pore sizes, the pressure head loss per depth is higher. The head loss increases as smaller and smaller suspended particles are caught, and the flow rate slows until the head loss is too high for water to flow through. No method exists to predict the increase in head loss as the slow sand filter becomes clogged with accumulated solids without full-scale or pilot plant data (Davis, 2011).

5.2.2 Sediment Filter

The sediment filter alternative uses wrapped polypropylene, a commonly-used thermo plastic, as a filter medium to remove particles larger than 5 microns ($5\mu m$) (Figure 5.1). The wrapping increases the amount of surface area that particles can be trapped on. Particles larger than 5 microns will be caught on the exterior or the interior of the sediment filter.

These filters are inexpensive, simple to replace, and are locally available in La Yuca. In addition the filters are very lightweight, attractive-looking, portable, and can be mounted on walls to conserve space. Sediment filters are suitable for flows up to 50 gallons per minute (Rain for Rent, 2012b). Fifty gallons per minute is far in excess of the expected flowrate from the rainwater catchment system in La Yuca. The sediment filter process is diagrammed (Figure 5.2) (Wagenet and Sailus, 1995).

Figure 5.1: A sediment filter cartridge and a wrapped polypropylene filter medium (contained in the cartridge) are held by the community president in a joint presentation to the community about the rainwater catchment system.

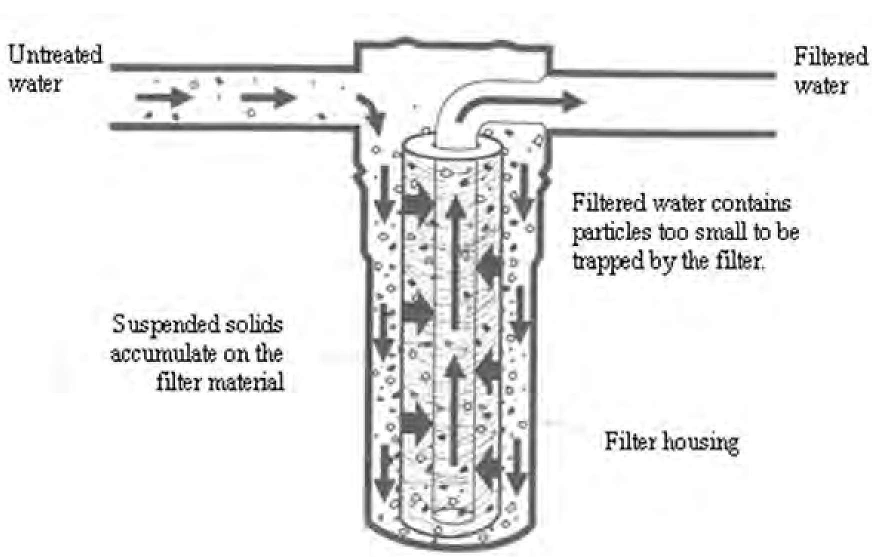

Figure 5.2: The sediment filtration process (Wagenet and Sailus, 1995). From Wagenet, L, K. Mancl, and M. Sailus, 1995. Home Water Treatment, Northeast Regional Agricultural Engineering Service, Cooperative Extension, Ithaca, N.Y.

5.2.3 Bag Filtration

Bag Filtration is a physical process used to remove particulate matter from the influent water, using mechanical screening as the most dominant process (Figure 5.3). Particles are caught solely on the interior surface of the bag filter. The bag filters are sized according to the available pressure head and the pore size necessary to filter adequately. To increase the length of filter runs, bag filters are made larger because of the very limited surface area for trapping particles inside the bag. The bags are simple to dispose of and easy to replace. When in operation, bag filters can be heavy and difficult to transport because of the large volume of water and trapped particulate matter in the housing. Bag filters are suitable for flows up to 100 gallons per minute (Rain for Rent, 2012a).

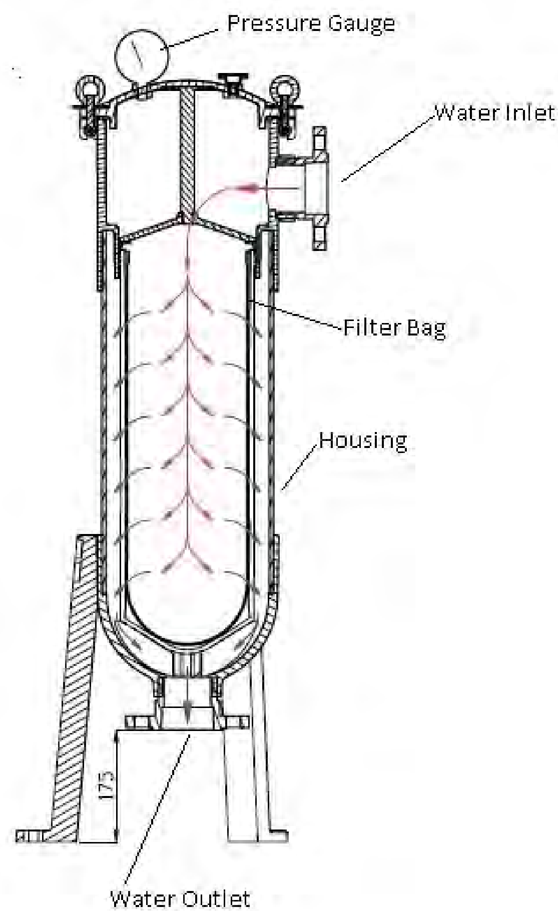

Figure 5.3: Design of bag filter and housing (Guangzhou, 2007).

5.3 Evaluation of Alternatives

The Pugh method was used to evaluate the alternatives and determine the best alternative solution. The slow sand filter was selected to be the datum for the first iteration. The sediment filter had the highest score at the end of the first iteration. Consequently, the sediment filter alternative became the datum for iteration 2. Iteration 2 of 2 of the Pugh method is shown in Table 5.2.

Table 5.2: The Pugh method was used to determine the best alternative solution. Iteration 2 of 2 is shown.

Criteria	Alternatives		
	Sand	**Sediment**	**Bag**
Safety	-	**D**	s
O&M Cost	-	**A**	-
Reproducibility	+	**T**	s
Reproduction Cost	-	**U**	s
Educational Value	+	**M**	s
Durability	-		-
Ease of Maintenance	-		-
Adaptability	+		s
Aesthetics	-		-
R&D Cost	-		s
Total +	3		0
Total -	7		4
Total S	0		6
Overall Score	-4		-4

The primary safety concern of each of the filter alternatives was weight of the filter apparatus. Weight was the primary concern because the rainwater team was constrained to using a small corner that had a metal stand cemented into the ground. If children climbed on or near a heavy, unsteady object it could fall and injure them. Potability of the filtered water was demanded of each alternative design because of the potability constraint. No design was awarded a higher score for increased filtrate quality beyond that which was required for potability by WHO or Domincan Republic standards. For those reasons, a slow sand filter alternative scored the lowest and the sediment filter alternative scored the highest.

Operation and Maintenance (O&M) Cost was determined by estimating the time required by a school employee to maintain the rainwater catchment system in working order. The slow sand filter scored the lowest because the *schmutzdecke* needs to be removed or the filter needs to be backwashed. The sediment filter scored the highest because it would not need maintenance other than buying and replacing the filter medium, which would take one to two hours annually. The replacement cost of the sediment filter cartridge is 100 DOP ($2.50).

Reproducibility was determined by the ability of a person to recreate the technology elsewhere. The slow sand filter scored the highest in this category because sand and large barrels can be procured easily in many places. The sediment filter and the bag filter alternatives scored the same in this category, below the slow sand filter because the components of these alternatives are more difficult to procure than sand and barrels.

Reproduction cost was an estimation of the costs to recreate the technology elsewhere. The sediment filter alternative scored the same as the bag filter alternative, which both scored highest. The cost of the screened sand ideal for the slow sand filter exceeded the costs of the sediment filter and the bag filter.

Educational value was determined by quantifying the principles that could be demonstrated to children by the filtration alternative. The slow sand filter provided the most learning because of its exhibition of microscopic action to purify water. The other alternatives demonstrated mechanical screening solely.

Scores for durability were an estimation of the amount of time before the technology needed to be checked, maintained, or repaired. In addition to the reasons in O&M Cost, the bag filter alternative scored lower than the sediment filter, which scored highest, because the thin bag used to capture particulates could tear and should be inspected occasionally.

Ease of maintenance was scored by the complexity and difficulty of the maintenance task. The sediment filter was the easiest and scored highest because the act of unscrewing the cartridge and replacing the polypropylene medium requires little to no thought or physical exertion. The slow sand filter, by comparison involves climbing on top of the filter, examining the *schmutzdecke*, removing the right amount of media, washing it, and replacing it. Bag filters require inspection, which requires more experience than the sediment filter replacement.

Adaptability was determined by the robustness of the technology. If a change was made to the system by the user, slow sand filters provide the most robustness to preserve water quality because of the multiple modes of water treatment inherent in the technology. As a result, the slow sand filter alternative scored highest.

Sediment filters were viewed as being the most visually attractive alternative and were scored highest.

The research and development (R&D) cost was an estimation of expenditure for the rainwater team to determine if each alternative would work for application at the elementary school. The slow sand filter scored lowest because of the cost of the properly screened sand media and the amount of sand needed was undetermined. Natural sand was purchased for the 2011 design, which performs very differently and costs much less than screened sand. So, the 2011 design could not be used to estimate the amount of screened sand required.

5.4 Result of Screening

Based on the Pugh Method results, a sediment filter was selected as the primary filtering mechanism for La Yuca's rainwater catchement system. The slow sand filter alternative and the bag filter alternative each scored four points less than the selected alternative at the end of the second iteration.

6 Description of Selected Alternative

The selected alternative was a sediment filter used in conjunction with some of the pre-existing components: the rainwater storage tank, the rooftop collection surface, and the PVC gutter. These pre-existing, reusable parts reduced the capital cost of the design, but did not affect the reproduction cost, where those components may not be freely available. The additional major components to complete the rainwater treatment train were a larger first flush system, a cinder-block riser for the rainwater storage tank (to increase the available pressure head for filtration), and a new activated carbon, ceramic, silver-impregrated filter (a new silver filter to replace the previous silver filter, which was inundated by sand from the slow sand filter).

The selected alternative included improvements, and modifications to the existing system in addition to new components. The selected alternative was designed in a somewhat piece-wise fashion, but the overall treatment train plan was clear. The collection surface was in generally good condition, but needed to be cleaned and washed. Some trash had collected on the surface, which was the result of a nearby, tall, apartment-style building whose residents expel some household wastes from their balconies. Also, bird droppings had accumulated on the galvanized roof collection surface. The roof was washed and the trash on the rooftop was removed.

The three inch PVC gutter was weakly attached to the roof using thin, rusted wire. These wires were replaced using thicker, galvanized wire. The gutter was purposefully lifted additionally at one end to reduce the amount of water pooling inside the gutter.

6.1 First Flush

The 2011 first flush (Figure 6.3) was designed so that the volume contained the first ten minutes of rainfall. However, a set amount of time cannot be directly used to size a first flush storage volume and is subject to the source of the rainfall intensity data. The ten minute rule-of-thumb is useful when rainfall intensity data are available in the region.

Few rainfall intensity data are available for the Dominican Republic with even fewer, if any, data for Santo Domingo. A flood event in May 2004 was recorded in Jimani, Dominican Republic with rainfall intensity data. Jimani can be found west of Santo Domingo near the Haiti border.

Using the hyetograph adopted for Jimani, Dominican Republic (Figure 6.1), approximately 20 mm of rainfall occured in a three hour segment of the May 2004 flood event (Brandimarte et al., 2009). In an average ten minute segment of the those three hours, 20 mm /(3 hours $*$ 6 ten-minute segments/hour) = 1.1 mm/ten-minute segment of rainfall. A more typical rainfall event with more typical rainfall intensity would be better suited to the time-based first flush volume analysis. Martinson and Thomas (2005) provided a more conservative rule of thumb: “For each mm of first flush the contaminate load will halve.”

Martinson and Thomas (2005) explained further:

> This means that to reduce very dirty (say 2000 NTU) water to the high WHO standard of 5 NTU (WHO, 1997), the first 8.5 mm of rain will have to be diverted. This is an extreme case and was only encountered at sites close to a dirt road and after a long dry period. The average initial turbidity near a dirt road was closer to 900 NTU (needing 7.5 mm of first flush to reach that standard), away from roads this average dropped dramatically to 150 NTU (needing 5 mm of first flush).

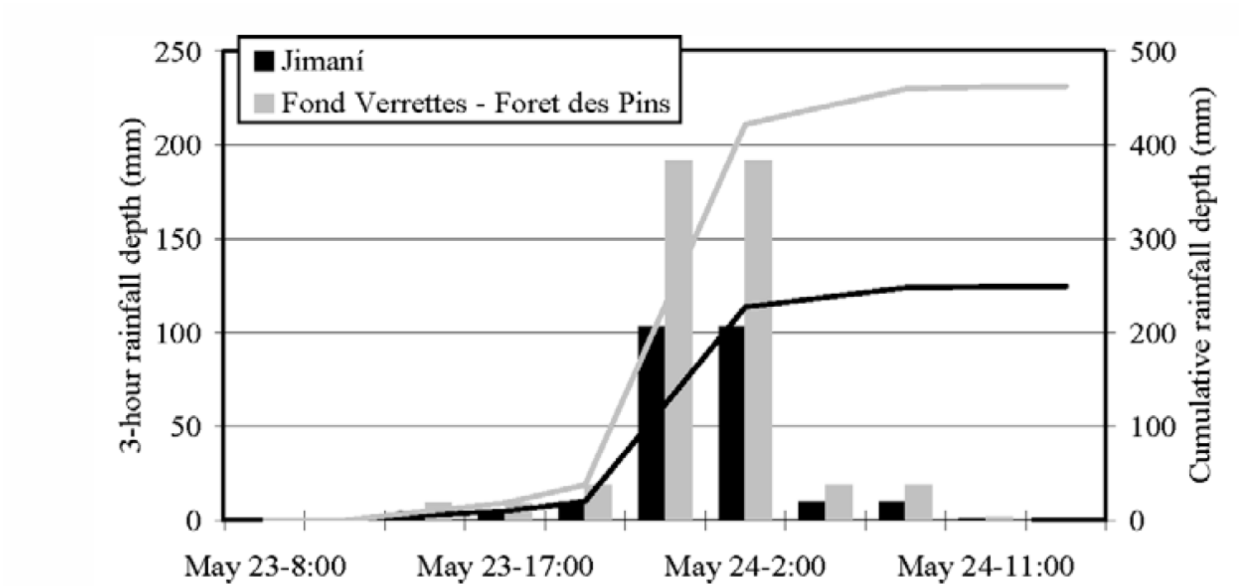

Figure 6.1: Hyetograph from “May 2004 flood event: hyetographs adopted for the event-based simulation for Jiman (Dominican Republic)” (Brandimarte et al., 2009)

To create the first flush in La Yuca, a volume equal to an eighth of an inch (3.175 mm) of rainfall across the collection surface was used. A height of 3.175 mm of rainfall on the surface of the roof catchment area (175.4 ft^2) yielded 13.67 gallons of storage. To achieve this volume inexpensively, two five-gallon jugs for drinking water were used. The estimated as-built volume was estimated from pictures (Figure 6.2). The estimation of as-built first flush volume is 17.8 gallons from the two five-gallon jugs as well as about 3 feet of 2 inch PVC pipe and about 4 feet of 3 inch PVC pipe, with a total estimated piping volume of 7.8 gallons.

The as-built storage volume corresponds with a height of 4.14 mm (0.163 inches) of rainfall on the catchment surface. Using Martinson and Thomas’s rule, a table of contaminant reduction

Figure 6.2: The as-built first flush volume was estimated from this photo.

was created (Table 6.1. Linear interpolation was used to find the estimated contaminant reduction based on the estimated as-built first flush volume. The estimated contaminant reduction is 94.2%. Turbidity was not measured to verify this estimation.

Table 6.1: A table of contaminant reduction based on the amount of rain captured in the first flush system. The data are based on the rule of thumb "For each mm of first flush the contaminate load will halve."(Martinson and Thomas, 2005).

Rainfall Captured in First Flush System (mm)	Contaminant Reduction
1	50.00%
2	75.00%
3	87.50%
4	93.75%
5	96.88%
6	98.44%
7	99.22%
8	99.61%
9	99.80%
10	99.90%

These jugs were attached to PVC pipes that connected to the primary screen. The connections were removable so that the first flush system could be easily cleaned and maintained. The jugs were painted so that they would not be confused with potable water jugs and so that algae growth would be slowed by the shading. A small pinhole was made in the side of each jug near the bottom so that the first flush would slowly drain between storms and be ready for the next rainfall. Due to the height of the first flush system and its likely instability in the event of strong winds, galvanized wire was used to attach the first flush system to the adjacent wall's supporting beams in several locations along the height of the first flush system.

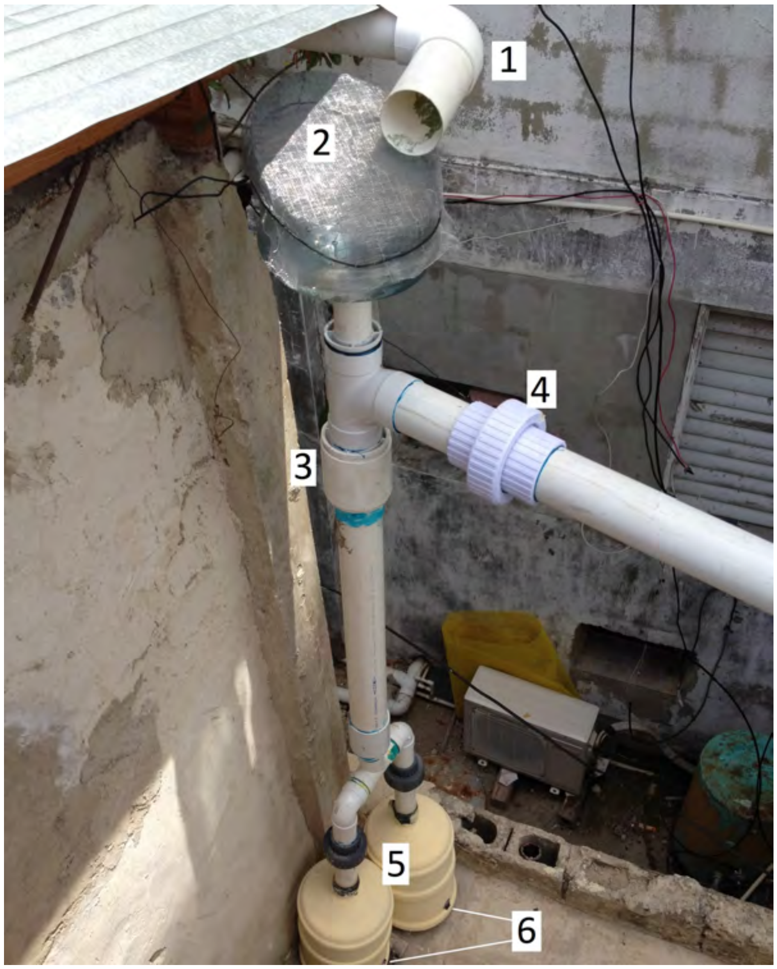

Figure 6.3: The completed first flush system was constructed out of two detachable five-gallon jugs and PVC. 1: Three inch PVC gutter directs water to the primary screen. 2: Primary screen separates large particulate matter from the flow stream. 3: A floating ball valve prevents mixing of the first flush water with water to be filtered. 4: A detachable joint allows for the first flush system to be separated, maintained, and/or cleaned. 5: Two painted five gallon jugs increase the amount of storage volume in the first flush system. 6: Small holes (pin-holes) near the bottom of the five-gallon jugs allow the first flush to drain slowly to prepare for the next rainfall.

6.2 Storage Tank

The three inch PVC pipe connection of the first flush system to the storage tank was raised so that the storage tank could be raised accordingly. Raising the storage tank allowed for additional available pressure head for the filtration system that follows the storage tank in the flow path. Removable joints were added at each end of the PVC pipe connection so that the entire first flush assembly could be easily removed for maintenance or cleaning (on the right side of Figure 6.3).

The storage tank was built with an opening for an overflow pipe. The bare overflow opening in the tank would allow for mosquitos to colonize the stored rainwater. To circumvent this, a short PVC pipe was attached to the overflow opening. The exposed end was cut at an angle and covered with plastic netting, secured by galvanized wire (Figure 6.4).

Figure 6.4: A short PVC pipe was attached to the overflow opening of the storage tank. The exposed end of the PVC pipe was cut at an angle and covered with plastic netting, secured by galvanized wire.

As previously stated, the storage tank was raised to increase the amount of pressure head for the filtration system. Doing this caused a possibly hazardous condition for children that attempted to climb it, as they frequently demonstrated, because the partially filled tank could tip and fall onto them. Community provided telephone wires and thick, galvanized wires were used to secure the storage tank to the cinderblocks on which the tank sat (Figure 6.5).

Figure 6.5: Community provided telephone wires and thick, galvanized wires were used to secure the storage tank to the cinderblocks on which the tank sat.

6.3 Sediment Filter

The sediment filter housing was attached to the concrete wall on the story below the storage tank (Figure 6.6). The sediment filter is approximately 3 feet below the bottom of the storage tank. The blue, plastic cartridge housed a 5 micron sediment filter. A shutoff valve preceded the sediment filter, which allowed the rainwater to bypass the sediment filter and directly fill the subsurface cistern, if so desired.

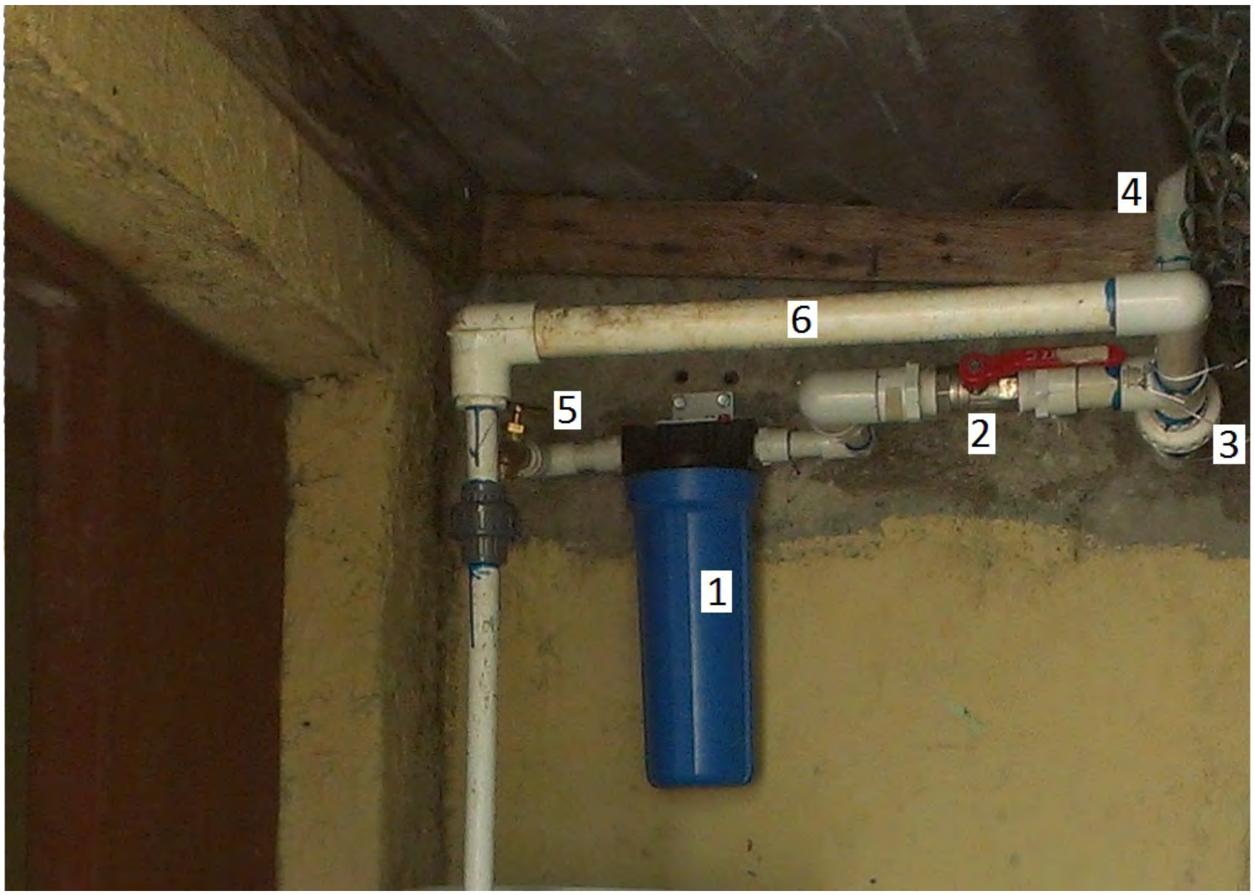

Figure 6.6: 1: The sediment filter housing was attached to the concrete wall on the floor below the storage tank (Figure 6.5). The blue, plastic cartridge housed a 5 micron sediment filter. 2: A shut off valve allows maintenance to be done on the sediment filter. 3: A Tee Branch allows the rainwater to flow from the floor above to the sediment filter and/or to the filter bypass. 5: A spigot controls the flow of filtered rainwater to the silver filter (not pictured). 6: A filter bypass allows water to flow directly from the storage tank to a different spigot (below, out of the frame).

7 Service Learning Analysis

7.1 Community Engagement

Figure 7.1: The rainwater team worked with the community president to dismantle the slow sand filter.

Figure 7.2: The rainwater team worked with the community president to dismantle the slow sand filter.

Figure 7.3: The rainwater team explores various design possibilities in the local hardware store. Having a community member present helped the team communicate what they wanted to purchase.

Figure 7.4: The community audience during the presentation.

Figure 7.5: The community president presents the final design.

Figure 7.6: The community president works to improve the gutter by securing it to the roof with thicker wire.

7.2 Institutional Partnership

Figure 7.7: UNIBE and HSU students work together to plan modifications to the 2011 design.

Figure 7.8: HSU Students work alongside the community president in planning and construction.

Figure 7.9: UNIBE and HSU students work together to improve the design of the storage system.

8 Detailed Analysis of Selected Alternative

The detailed analysis of the selected alternative, the rainwater catchment system that includes the sediment filter, includes an analysis of the costs and the hydraulics.

8.1 Costs

The costs analyzed in the detailed analysis include construction costs, operation and maintenance (O&M) costs. These costs are used to calculate a payback period. These costs were converted from Dominican Pesos (DOP) at an exchange rate of 40 DOP to the US Dollar (USD).

8.1.1 Construction Costs

An itemized listing of the construction and reproduction costs of the rainwater catchment system was prepared (Table 8.1).

Table 8.1: Itemized listing of construction and reproduction costs for the rainwater catchment system in US dollars (USD).

Material	**Qty**	**Total (USD)**
PVC 3" (29ft)	1	40.00
PVC 1" (5ft)	1	1.75
PVC 1/2" (5ft)	1	1.25
5 Gallon Jug	3	18.75
90 Degree- 3" PVC	1	3.75
90 Degree- 1/2" PVC	3	0.38
T Branch- 3" PVC	1	3.13
T Branch- 1" PVC	1	0.38
90 Degree- 1" PVC	5	1.50
45 Degree- 1" PVC	2	0.55
Junct.- 1/2" PVC	1	0.55
Junct.- 1" PVC	1	2.55
Junct.- 2' PVC	2	11.35
Junct.- 3' PVC	2	14.50
Connectors PVC	6	3.00
Epoxy/Silicon	2	7.50
Cinder-blocks	20	22.00
Shutoff Valves	2	17.50
Act. Carb. Bucket Filter	1	40.00
Ball valve	1	15.00
Spigot	2	11.75
Tank	1	95.00
SUM		312.13

8.1.2 O&M Costs

According to the filter store salesman nearest to La Yuca, both the sediment and the silver filters will need to be replaced annually. While annual replacements may be a safe replacement schedule, it is not the most economical. The replacement schedule will most likely be guided by the appearance of the sediment filter media or the inability of the water to flow through the filter. Regardless, an annual replacement of both the sediment and the silver filters will be used for the baseline economic analysis. The sediment filter replacement costs $2.50 (100 DOP), while the silver filter costs $25.00 (1000 DOP). Drinking water use was three five-gallon jugs per week before the rainwater catchment system was installed. 15 gallons per week will therefore be used to compare the costs of the rainwater catchment versus the no-project alternative.

The undiscounted costs of the rainwater catchment system versus high and low costs for potable water jugs were calculated and plotted (Figure 8.1). Assuming stationarity and that 15 gallons of drinking water are consumed per week, a range of payback periods were generated because of the range of costs for five-gallon jugs. Five-gallons jugs of drinking water cost between $0.50 and $1.25 and varied from vendor to vendor. At a capital cost of $312.13 for the rainwater catchment and an annual cost of $27.50 for the pair of filter replacements, a step-like cost curve was generated (Figure 8.1). The rainwater cost curve was compared to the high and low annual costs of buying potable water, which were plotted as curves. The intersection of these curves on a time-undiscounted cost plot corresponded with a simple payback period. The payback period for the $1.25 five-gallon jug was approximately 1.7 years, while the payback period for $0.50 five-gallon jug was approximately 5.2 years.

The interest rate dictates the rainwater catchment alternative's viability as a cost-saving alternative. The current interest rate in the Dominican Republic is 5%, but has been recorded as high as 50% (Figure 8.2)(Trading Economics: Central Bank of the Dominican Republic, 2013). Based on recent interest rate and its recent variability, an interest rate of 6% was used as the baseline for analysis. At an interest rate of 6% and a system design lifetime of 20 years, the 20-year net present value (NPV) can be calculated, using Equation 1. The 20 year NPV at a 6% interest rate is $1609 for five-gallon jugs at $1.25 each and $267 for five-gallon jugs at $0.50 each.

$$NPV(i = 6\%, n = 20) = P + A * \frac{(1+i)^n - 1}{i(1+i)^n} \tag{1}$$

A sensitivity analysis of the NPV with respect to the cost of five-gallon jugs and the interest rate was performed (Figure 8.3). At interest rates above 15% the rainwater catchment alternative is no longer a good financial investment when five-gallon water jugs cost less than or equal to $0.50. Similarly, at interest rates above 53%, the rainwater catchment alternative is no longer a good financial investment when five-gallon water jugs cost less than or equal to

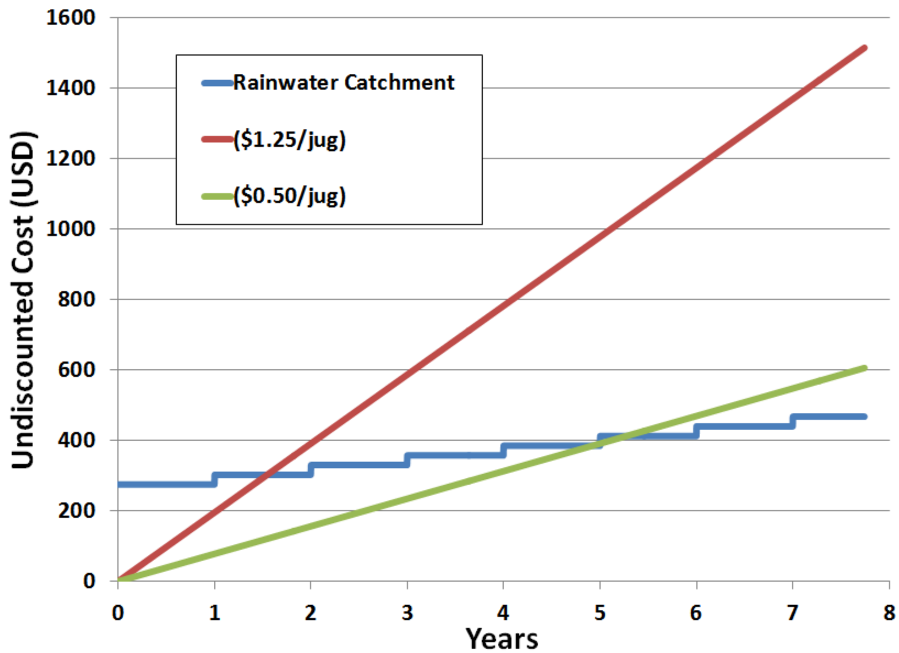

Figure 8.1: The undiscounted costs of the rainwater catchment system versus high and low costs for potable water jugs.

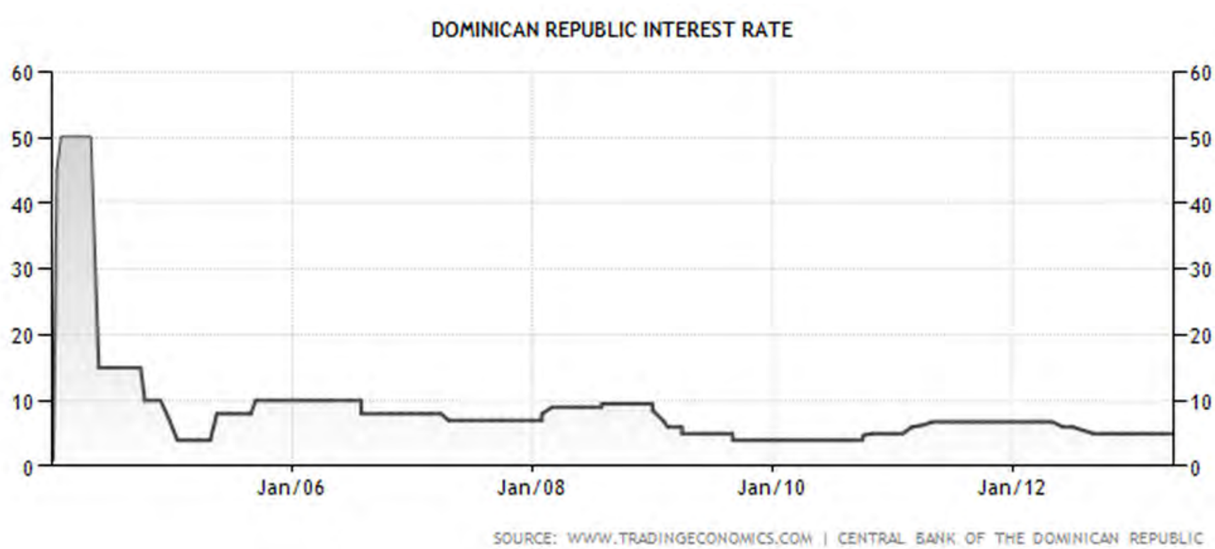

Figure 8.2: The interest rate in the Dominican Republic is currently 5%, but has been recorded as high as 50%. The interest rates have been recorded since January 1st, 2004 (Trading Economics: Central Bank of the Dominican Republic, 2013).

$1.25.

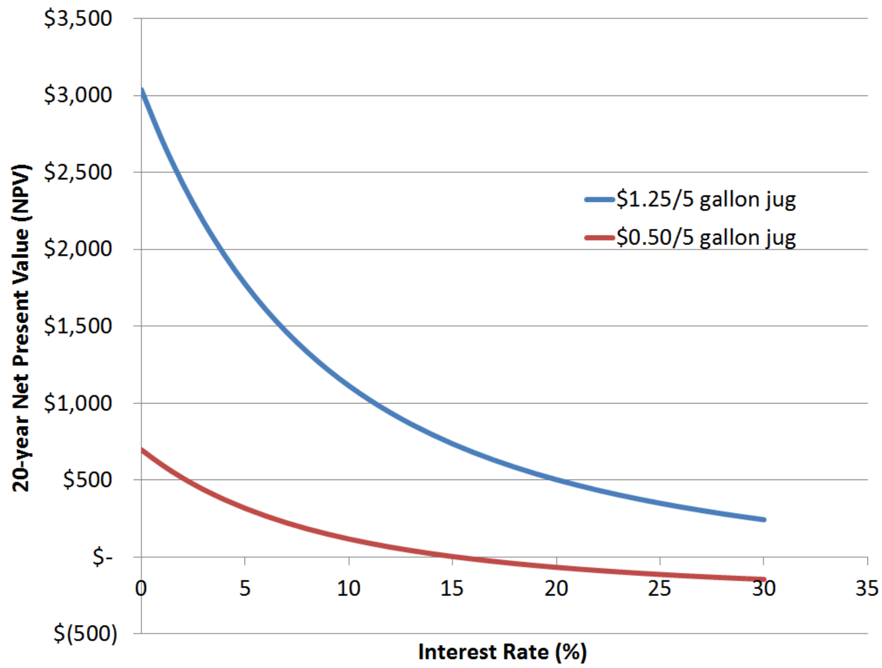

Figure 8.3: A sensitivity analysis was performed on the 20 year NPV with respect to the interest rate for five-gallon jugs at two different costs: $1.25 each and $0.50.

In addition, a sensitivity analysis of the NPV with respect to more frequent filter cartridge replacements and the interest rate (Figure 8.4). Completing more than five filter replacements per year was not considered to be economical at any interest rate, but four filter replacements per year could be economical so long as the interest rate was below 13%. This information can potentially be used to determine economic feasibility based on water quality, filter clogging, and filter replacements as those data become available.

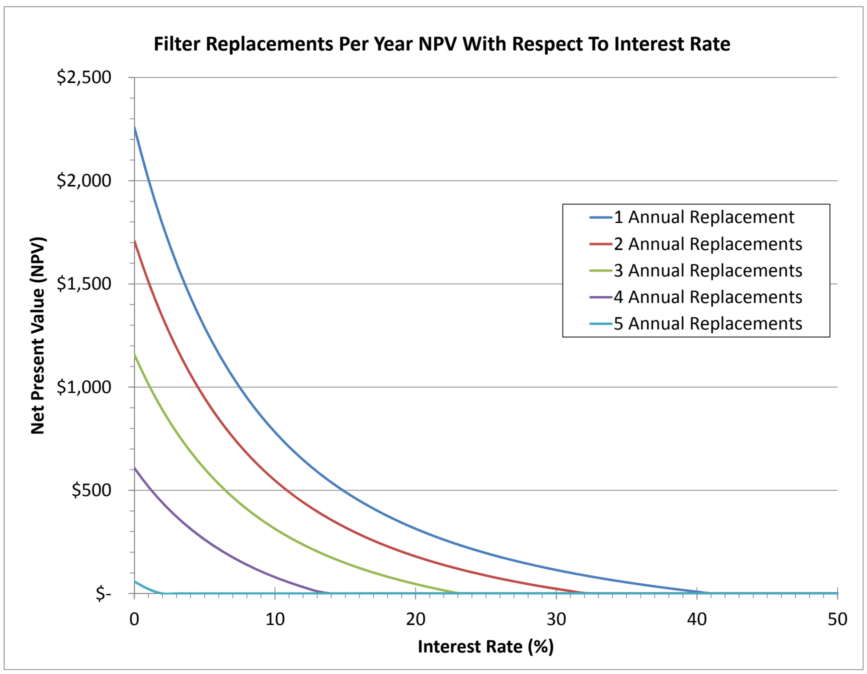

Figure 8.4: A sensitivity analysis was performed on the 20 year NPV with respect to the interest rate for five-gallon jugs at two different costs: $1.25 each and $0.50.

8.2 Hydraulic Analysis

To determine the head required for a rainwater catchment system that may or may not include filtration, a hydraulic analysis was performed. To begin, Equation 2 was used (White, 2006). Due to the atmospheric pressure at both the inlet and outlet, P_1 and P_2 can be assumed to be zero.

$$\frac{P_1}{\rho g} + \frac{V_1^2}{2g} + z_1 = \left(\frac{P_2}{\rho g} + \frac{V_2^2}{2g} + z_2\right) + h_f + \Sigma h_m \tag{2}$$

where:

g = acceleration due to gravity
h_f = head loss due to friction
h_m = head loss due to minor losses
P = pressure
ρ = fluid density
V = velocity
z = elevation

The flow rate exiting the sediment filter should be fast enough so that users of the rainwater catchment system will not have to wait a long time to fill a five-gallon jug. One minute was determined to be a practical amount of time to wait to fill a five-gallon jug. Consequesntly a design flowrate of 5.0 gallons per minute was used. Using a design flowrate of 5.0 gallons per minute (0.0111 cfs), the resulting velocity through a 1 inch, circular pipe (where the internal diameter is actually 1.049 inches) is roughly 0.0128 ft/s ($V = Q/A$ where A is the cross-sectional area and Q is the volumetric flow rate). The Reynolds number can be calculated using Equation 3, where $\nu = 0.926 \times 10^{-5}$ (ft^2/s) at 80°F. Therefore, $Re_d = 121.25$,

$$Re_d = \frac{Vd}{\nu} \tag{3}$$

where:

d = diameter
ν = kinematic viscosity of water

which is below the transition to turbulence at around $Re_d = 1000$ (White, 2006). Equation 4 can be used for laminar fully developed pipe flow and is "valid whenever the pipe Reynolds number... is less than about 2300" (White, 2006).

Substituting Equation 4 into Julius Weisbach's correlation for head loss in pipe flow problems, Equation 5, yields the laminar pipe flow head loss.

$$f_{lam} = 64/Re_d \tag{4}$$

where:

$$f_{lam} = \text{laminar flow Darcy friction factor}$$

$$h_f = f\frac{L}{d}\frac{V^2}{2g} \tag{5}$$

where:

$$\begin{aligned} d &= \text{diameter} \\ f &= \text{Darcy friction factor} \\ L &= \text{length} \end{aligned}$$

The pipe length of 1 inch PVC was not accurately measured, but is assumed to be roughly 8 ft. The pipe head loss is then equal to:

$$h_f = 64/Re_d\frac{L}{d}\frac{V^2}{2g} = 64/121.25\frac{8\text{ft}}{1.049\text{in}/12\text{in}/\text{ft}}\frac{0.0128^2(\text{ft/s})^2}{2(32.2)\text{ft/s}^2} = 8.59 \times 10^{-07}\text{ft}$$

For all intents and purposes, the estimated major losses at the design flowrate in the 8 ft of 1 inch PVC pipe are negligible.

The minor head loss should be expected to be more substantial, even neglecting the head loss across the filter. The total frictional head loss (minor and major losses) can be found using Equation 6. The minor loss coefficients were calculated (Table 8.2).

$$\Delta h_{tot} = h_f + \Sigma h_m = \frac{V^2}{2g}\left(\frac{fL}{d} + \Sigma K\right) \tag{6}$$

where:

$$\begin{aligned} h_{tot} &= \text{total head} \\ K &= \text{loss coefficient} \end{aligned}$$

Table 8.2: Quantities of appurtenances and their respective minor loss coefficients (Toolbox, 2013).

Type of Component or Fitting	Minor Loss Coefficient - K -	Quantity
Tee, Flanged, Dividing Branched Flow	1	1
Union, Threaded	0.08	1
Elbow, Flanged Regular 90 °	0.3	3
Elbow, Flanged Long Radius 45 °	0.2	2
Gate Valve, Fully Open	0.15	1
Ball Valve, Fully Open	0.05	1

The sum of the products of the quantities and the corresponding minor loss coefficients yields the ΣK term in Equation 6. The ΣK term was determined to be 2.58 from Table 8.2.Therefore the total head loss is:

$$\Delta h_{tot} = h_f + \Sigma h_m = \frac{0.057^2(\text{ft/s})^2}{2(32.2)\text{ft/s}^2}\left(64/218\frac{5\text{ft}}{0.5\text{in}/12\text{in/ft}} + (2.58)\right) = 1.40 \times 10^{-04}\text{ft}$$

This means that the minor losses are an order of magnitude larger than the major losses. However, the minor losses are still six orders of magnitude smaller than the available pressure head and are therefore negligibly small.

CAL Water (2012) recommends that the cartridge filter be replaced when the pressure drop across the filter is 10 psi. However, even with the increased height of the storage tank using cinder-blocks, 10 psi are not available to the system. was created based on pictures and measurements of the 2012 rainwater catchment systems (Figure 8.5). At minimum, with the increased height of the storage tank, there is 3 ft of head above the filter, which is only 1.30 psi, assuming .434 psi/ft water column. At maximum with a full storage tank, the available head is 7 ft or 3.03 psi. Because of this limitation, the flow rate through the filter will not reach the filter's design flowrate of 40 gpm.

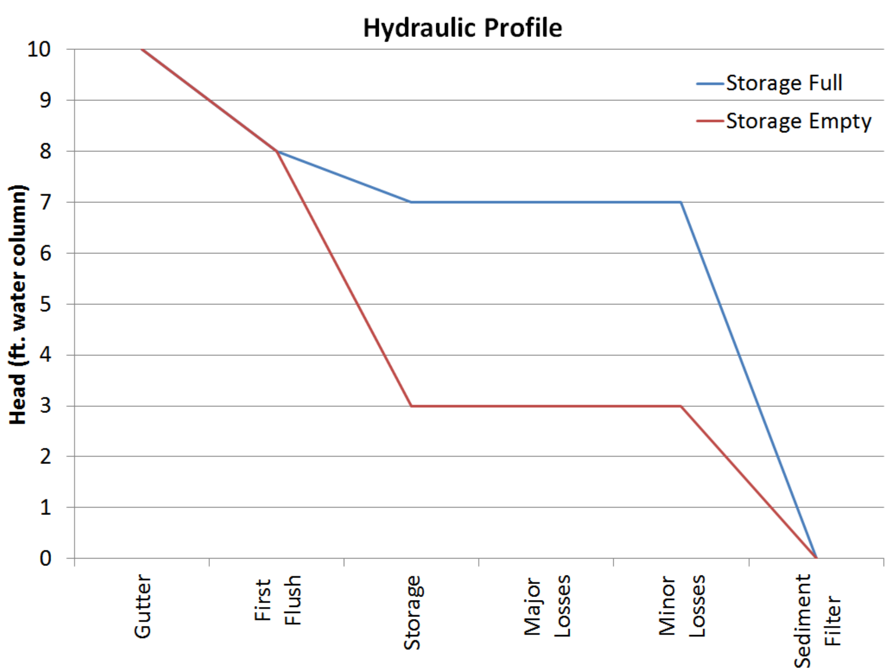

Figure 8.5: A hydraulic analysis was performed and a hydraulic profile was created based on pictures and measurements of the 2011 rainwater catchment system

The filter accumulates matter on the pores and the head loss increases over time. If the head loss is greater than the available head, water will not flow through the filter. A lack of flow through the filter necessitates that the filter be replaced. This may be before the design lifetime for the sediment filter of one year. The actual lifetime of the filter will be dictated by the rainwater quality, where high solids larger than the sediment filter pores will shorten the filter lifetime.

9 Conclusions

Several conclusions were drawn from the 2012 rainwater team that participated in the 2012 Practivistas Program in Santo Domingo, Dominican Republic.

- A set of criteria and constraints were generated with input from the school's principal. Alternatives were generated which focused on the primary filter. The Pugh method was used to determine the selected alternative.
- The selected alternative was to replace the slow sand filter used in the 2011 design with a 5 micron polypropylene sediment filter. The sediment filter was superior that the other alternatives based on the Pugh method analysis and the criteria. The selected alternative was determined to be safer, cheaper, more durable, easier to maintain, and more aesthetically pleasing than the other alternatives.
- The 2011 rainwater catchment design successfully reduced the need to purchase water to fill the elementary school's cistern from a bi-monthly purchase to only two purchases in the 11 months following the 2011 rainwater team's implementation. The same system was unable to provide potable water to the elementary school by 2012.
- The 2012 rainwater catchment design included improvements to the gutter, a larger first flush storage volume, detachable PVC unions for maintenance or modifications, reduced access to mosquitoes, and increased available pressure head for filtration by raising the 250-gallon storage tank on cinder-blocks.
- The 2012 rainwater team constructed a rainwater catchment system that fulfilled the purposes of the project by ensuring that the collected rainwater system can produce cleaning and drinking water, is easy to operate, and is more cost-effective than purchasing potable water. Additionally, the design can be replicated in the Dominican Republic and the design increases the local rainwater catchment design capacity in Santo Domingo, Dominican Republic. The amount of time required to fill a five-gallon jug with filtered water was reduced from the 2011 design's time to fill a five-gallon jug.
- The simple payback period for the rainwater catchment system for drinking water built in La Yuca is between 1.7 and 5.2 years, depending on the cost of locally-purchased drinking water.
- A net present value analysis was completed based on 6% interest, 15 gallons per week, and one filter replacement per year. A sensitivity analysis of the net present value was performed by changing the interest rate because of the variability of the interest rate in the Dominican Republic. In addition, a sensitivity analysis was performed by changing the number of filter replacements per year to be economical across a range of interest rates.

- A hydraulic analysis was performed and a hydraulic profile was created based on pictures and measurements of the 2012 rainwater catchment systems (Figure 8.5). The head losses due to friction were found to be negligible relative to the expected head losses across the sediment filter. The sediment filter head loss is the most important to quantify for the hydraulic analysis.

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