2.500 Desalination and Water Purification
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Cisterns - A Potential Water Source for Paulette and Phaeton

2.500 Class Project

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Abstract

Paulette and Phaeton are small villages in Haiti that currently rely on a pumped water system to supply their fresh water. Citizens of the villages currently spend 10% of their income on water from the pumped water system. This report details the selection and design of a cistern water system to provide fresh water for Paulette and Phaeton. An analysis of other water sources provided by desalination is also presented. The cistern system is chosen over the desalination alternatives due to its lower cost, ease of construction and maintenance, and ability to be constructed from local materials.

In addition, a full life cycle cost analysis of the cistern system is presented. The resulting life cycle water costs are higher than the water delivered by the current pumped water system. However, the analysis shows that the operating costs for the cistern system are lower than the pumped water system. The suggested course of action is to donate the cistern systems to less fortunate families in Paulette and Phaeton to reduce their water costs. The installation of these systems will stimulate the local economy. Another suggestion from this report is that the pumped water system be properly maintained and an upgrade to this system could also reduce the water costs for the community.

1 Introduction

1.1 Background & Motivation

Paulette and Phaeton are small villages located on the northern coast of Haiti. The majority of citizens in Paulette and Phaeton currently pay for their drinking water from diesel-powered pump system. The average person in these villages earns less than $1.00 per day, and water costs amount to approximately 10% of their income. An inexpensive, clean water system would make a large impact on the lives of citizens of Paulette and Phaeton.

Groundwater could potentially be used to provide drinking water for the people of Paulette and Phaeton. Brackish community wells and hand dug wells exist in both villages. The salinity of these wells varies between 1200 ppm to 3000 ppm based on field test kits. This is well above the recommended limit of 500 ppm specified by the World Health Organization [1]. Desalination will be required to make this water drinkable.

Other natural water sources could also be used to provide drinking water to the citizens of Phaeton and Paulette. Haiti has a rainy season, and rainwater could be captured and stored to provide residents with drinking water. An efficient water transportation system from an area with excess water resources is also another potential source of drinking water.

The remote location of Paulette and Phaeton make the implementation of any clean water system challenging. The location of the two towns can be seen in Figure 1. The two towns are located approximately 32 km east of Cap Haitien. Building materials in Paulette and Phaeton are limited, and any materials for the system construction, maintenance or operation will need to be transported from Cap Haitien. In addition, the towns are not connected to an electrical grid, so energy costs will be a major consideration.

This report presents analysis of different potential desalination systems or natural water systems for Haiti. The basic energetics and the cost of the different alternatives are analyzed. The costs, material availability, and maintenance requirements for different systems were then analyzed. The cistern system was chosen as the most feasible option based on this preliminary analysis and other practical considerations. A detailed design and cost analysis of a cistern system is presented and other operational and implementation issues are discussed.

Figure 1: Geographic location of Phaeton and Paulette [2].

1.2 Design Considerations

Following presentations by Amy Smith of MIT D-Lab and Mercy and Sharing, a non-profit in Haiti, we determined the following considerations were essential for a successful design: cost, complexity/reliability, materials, and operational aspects. It is important to note that all four considerations are critical to a successful system—the proposed solution must meet all of them.

1.2.1 Cost

The current price of water in Paulette and Phaeton is $1.20 USD per cubic meter. The suggested target price is one-half of that, or $0.60 per cubic meter. Compare this to the Ashkelon seawater desalination plant in Israel, considered the most cost efficient in the world, at $0.45 per cubic meter [3]. If desalination of seawater is to be considered, the system would have to have a cost efficiency of the most efficient plant in the world, hardly possible on this small scale. Brackish water, though requiring slightly less energy, has similarly high costs to desalinate.

Both capital and operating costs must be considered. Capital costs may be covered by non-profit donations or recovered through payments. Operating costs must be below the current water price in the villages for the system to be successful.

1.2.2 Complexity and Reliability

The proposed system must be relatively simple and very reliable. These criteria are correlated and are associated with the sustained operability of the system. Concern with complexity is derived from the failure of the repair of hand pumps. It is unknown why these relatively simple systems have not been repaired, but a lack of materials, expertise, and cost are all correlated with increasing complexity. Paulette and Phaeton need sustained solutions if they are to grow and prosper.

1.2.3 Local Materials

The proposed system must be built out of materials which are locally available in the villages or the nearby town of Cap Haitien. However, some non-consumables with long projected lives may be imported. This criterion is to ensure that repairs of the system are possible, ensuring a long-term solution unlike the fate of the existing cistern and hand pumps.

1.2.4 Operational Considerations

The proposed system must be easy to operate and maintain with local personnel and supplies. In addition, the new system must be integrated into the current market and lifestyle of the villages. Specifically, this means that the introduction of a new system must not cause the old pumped water system to prematurely collapse.

2 Alternative Solutions

As stated above, water for Paulette and Phaeton could be provided by desalinating brackish ground water or utilizing natural freshwater sources. This section reviews the different potential solutions and analyzes their feasibility by verifying the outlined design constraints.

2.1 Brackish Water Desalination

Desalination is a mature field, and many large-scale desalination systems have been built and are currently operating. Estimated energy requirements and operating cost of large scale plants are available in literature. Table 1 shows an overview of energy requirements and product costs for large scale desalination systems. The price of water from these large scale systems range between \$0.20 per cubic meter and \$1.80 per cubic meter.

It should be noted that all brackish water systems reported in literature use reverse osmosis and electrodialysis as their desalination method. The energy requirements for reverse osmosis and electrodialysis scale with water salinity, making them more efficient for brackish water. The energy requirements for phase change methods of desalinating water are nearly independent of salinity, making them nearly infeasible for brackish water systems.

Table 1: Typical energy requirements and costs for large scale desalination plants [3, 4].

Feed Water	Desalination Process	Thermal Energy (kJ/kg)	Electrical Energy (kWh/m^3)	Typical Product Costs (\$/m^3)
Seawater	Multi-Stage Flash (MSF)	190-290	4-6	0.70-1.86
	Multi-Effect Distillation (MED)	150-290	2.5-3	0.27-1.49
	Vapor Compression (VC)	-	8-12	0.46-1.21
	Reverse Osmosis (RO) with Energy Recovery	-	3-5	0.45-1.51
Brackish Water	Reverse Osmosis (RO) with Energy Recovery	-	1-4	0.20-0.70
	Electrodialysis	-	1.5-4	0.58

Many small-scale desalination systems have also been developed and have been well documented in the literature. Some typical water costs produced from these small scale systems is shown in Table 2. All of the life cycle product costs for these small systems are well above the target price of \$0.60 per cubic meter that has set. These prices show that is would be extremely difficult to obtain the target price using a desalination technique for a system of our capacity.

Table 2: Typical costs of small scale desalination systems [5].

Desalination Process	Capacity	Power Source	Cost ($/m^3)
Solar Still	1	Solar	12
MSF	1	Solar	2.84
MED	72	Solar	2.00
Reverse Osmosis	1	Photovoltaics	3.73
Reverse Osmosis	10	Electric	4.00
Electrodialysis	5	Electric	5

2.1.1 Commercial Desalination Techniques

Multi-stage flash, multi-effect distillation, vapor compression, reverse osmosis and electrodialysis were all analyzed to determine their feasibility for installation in Phaeton and Paulette. The feasibility of these systems was analyzed based on the four criteria outlined in Section 1.2: cost, complexity, local materials and operational considerations. A summary of this analysis is shown in Table 3. None of these systems were chosen for further analysis since no system met all of the prescribed criteria. None of these systems are able to be locally made or maintained and operating costs and capital costs are high. Also, any desalination system will require supporting infrastructure (ex. feed water system, water storage system, and brine disposal system) which are not considered in this simple analysis. These aspects add further complexity to all of the desalination techniques.

Table 3: Commercial desalination techniques analysis.

Desalination Technique	Cost	Complexity and Reliability	Local Materials	Operational Considerations
Multi-Stage Flash	-Capital system cost is high. -Energy costs are also high. Cost of diesel alone in 20 stage configuration is $4.20. See Appendix A.	-Complex system. -Once established Systems are highly reliable [6]. -Scale formation can be a problem	-Highly engineered system -Materials would need to be imported.	Maintenance required approx once per year [6]. Would not be able to be locally maintained.
Multi-Effect Distillation	-Capital system cost is high. -Energy costs are also high. Cost of diesel alone in 20 stage configuration is $5.90. See Appendix A.	-Complex system. -Once established Systems are highly reliable [6]. -Scale formation can be a problem	-Highly engineered system -Materials would need to be imported.	- Maintenance required approx once or twice per year [6]. -Cannot be locally maintained.
Vapor Compression	-Capital system cost is not as high as thermal system [6]. -Energy costs are also high. Cost of diesel alone in 1-stage configuration is $2.80. See Appendix B.	- Relatively complex system -Simpler than comparable thermal systems.	-Highly engineered system -Materials would need to be imported.	- Maintenance required approx once or twice per year [6]. - Would not be able to be locally maintained.
Reverse Osmosis	-Capital costs are not as high as other commercial desalination technologies. -Energy costs are much lower than thermal desalination technologies. Approximate energy costs are $0.36/m^3 – See Appendix C. -Maintenance costs are high due to membrane replacement.	-Relatively complex system. -Extensive pretreatment is required. -System is not as reliable as commercial thermal desalination systems [14].	-Highly engineered system -Materials would need to be imported.	- Maintenance required several times per year [6]. - Would not be able to be locally maintained. -Membranes require periodic replacement and would need to be imported.
Electrodialysis	-High Capital Cost. -Energy costs are much lower than thermal desalination technologies. Approximate energy costs are $0.30/m^3 – See Appendix D.	-Relatively complex system. -Basic pretreatment is required. -Established technology, systems are reliable.	-Highly engineered system -Materials would need to be imported.	- Maintenance required several times per year. - Would not be able to be locally maintained.

2.1.2 Solar Still

Of all the desalination systems, the solar still seems the most promising because of its simple design and free energy supply. However, this design still has energy requirements which are simply too high. As shown in the calculations in Appendix E, a high value for the water produced per square meter is 1 L per day. Perfectly pure water from the still could be blended with other water to increase yield. Even with 50% blending, 25 square meters of still are required to supply a family's needs of 50 L drinking water per day. Twenty-five square meters of glass alone is a high cost. Additionally, solar stills must be sealed to operate well, which could be hard to maintain in these villages. Another drawback is that feed water must still be supplied to the system.

2.2 Natural Water Sources

2.2.1 Pump Optimization

Paulette and Phaeton have pumped water systems which pump relatively clean water into the villages, but at a price which is a significant portion (one-tenth) of people's incomes. We can reduce this price by installing a correctly-sized pump, lowering the operating costs associated with purchasing diesel. This solution builds on the success of the existing infrastructure while implementing cost savings.

Recalling the motor store found in Cap Haitien, it is obvious that builders of anything are at the mercy of what is available at any given time. Additionally, it is improbable (though possible) that the builders of the system had the high level of technical expertise required to size a pump correctly. Considering these two factors, the current pump is most likely not operating at an optimal point. Additionally, the 15 kilometers of pipe may have ruptures which are leading to pressure and water loss, decreasing efficiency and increasing diesel use. Repairing any such leaks would lower costs, as a primary step before purchasing a new pump. This would be an easy and cheap first step to a water solution.

Unfortunately, not enough information is available to perform an analysis of the pumped water system for the purpose of this project. We suggest that more information be gathered about this pumped water system in view of finding a more suitably-sized pump. This pump may have to be imported from Port-au-Prince or from abroad, but it would be a one-time expense which would serve the entire village. An efficiency improvement of just ten percent would shave ten percent off the cost (and most likely the price) of water.

2.2.2 Cistern System

In areas where adequate rainfall is available, rainwater can be harvested to provide drinking water. The average daily rainfall for Northern Haiti is shown in Figure 2 [7]. The precipitation in Haiti is not nearly as plentiful as the rainfall in Boston, but it far exceeds the rainfall in Albuquerque New Mexico, an area where brackish water desalination is currently utilized.

Based on this average rainfall, a required collector area for can be calculated. The details of this calculation are presented in Appendix F. Based on this calculation, 28.25 m^2 of catchment area would be required. The cistern system meets the four specified requirements. Pre-existing structures can be used as catchments, resulting in low system capital costs. Redundancy can be built into the system to make it reliable, the cistern can be made from local components, and the cistern system would be simple to build and maintain.

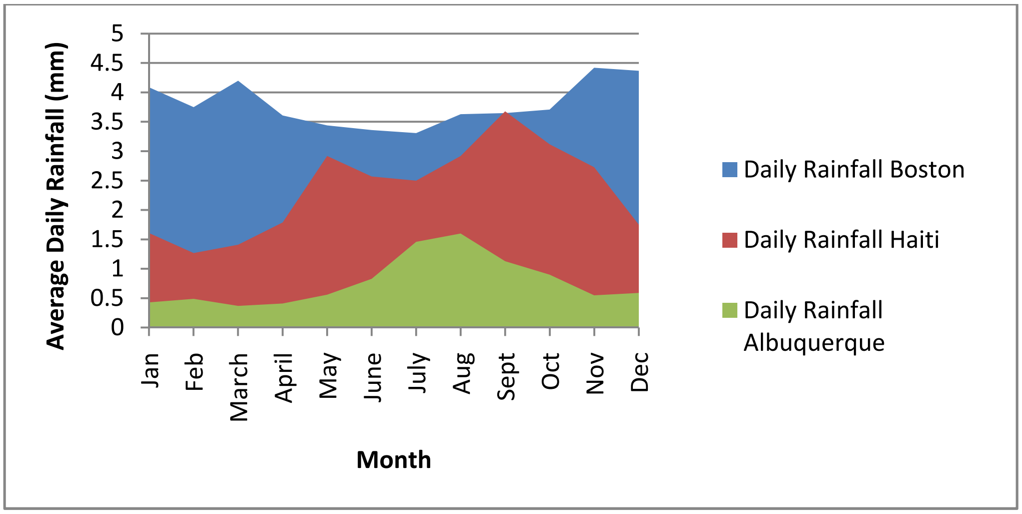

Figure 2: Average rainfall in Haiti.

2.3 Cistern and Solar Still Comparison

The cistern system and the solar still were selected as the most feasible systems for implementation in Phaeton and Paulette. A summary of the comparison of these two systems is shown in Table 4. Both systems satisfy the requirements that they can be locally constructed and maintained. Both systems require similar collection areas, but the cistern system has the advantage that its collection area already exists, leading to substantially lower costs. Also, the construction and maintenance of the cistern is much simpler. These facts lead us to choose the cistern system.

Table 4: Solar still and cistern comparison.

Solar Still	**Cistern**
Comparable footprint	Comparable footprint
Materials widely available	Materials widely available
Distributed solution	Distributed solution
No infrastructure in place	Collecting area already exists
Lower manufacturing tolerance	Higher manufacturing tolerances
Daily upkeep	Monthly upkeep
Requires pumped or hauled water	Water supplied by rain

3 Detailed Cistern System Design

3.1 Proposed System

Based on the feasibility analysis, a cistern system was chosen as the preferred method to provide citizens of Phaeton and Paulette with drinking water. The proposed system would be located at residents' homes, using roofs as catchment areas. The initial concern is that the residential roof materials would not be suitable for cisterns. A review of online images revealed that the majority of roofs in Paulette and Phaeton are made of corrugated metal as shown in Figure 3, perfect for implementation in a cistern system.

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Please see http://www.panoramio.com/photo/5695171

Figure 3: Houses in Phaeton [8].

3.2 Water Demand

In the report filed by the D-Lab and Mercy and Sharing, it was reported that the average family of 5 in Paulette and Phaeton used 4-8 buckets of water in a day. This number was higher than expected, and results in a large amount of water required for a single day and makes the design of any system extremely difficult. A review of literature showed lower values for water usage in Haiti. The United Nations reported an average total water usage of 15 L per person per day in Haiti [9]. A portion of this 15 L would not be used for drinking and could be taken from the brackish ground water.

Our system will be designed to provide 10 L of fresh water per day to the citizens of Paulette and Phaeton. This is also in accordance with other studies which have been completed on providing clean water to the people of Haiti [10].

3.3 System Sizing

In order to size the cistern system, a monthly balance of water collected and water consumed was utilized. Two pieces of data were required to determine the amount of water that would collected, average monthly rainfall and the catchment area. Average monthly rainfall data was obtained from the NASA Atmospheric Science and Data Center [7]. It is proposed that roofs of the homes be used for catchment areas. Roof sizes for houses in both Paulette and Phaeton were estimated using satellite imagery in Google Earth [2]. An average house was selected for both Paulette and Phaeton. Details of these calculations are presented in Appendix F.

Based on the average monthly water requirements and the average monthly water collected, a reservoir size can be determined. Here, the reservoir was sized such that in the average year, 0.5 m^3 will always be available and the tank size is larger than 1.5 m^3. This corresponds to a 3 m^3 reservoir for a residential cistern in Paulette and a 1.5 m^3 reservoir for a residential cistern in Phaeton. A larger roof space decreases the size of reservoir required since more water is collected during the drier periods. The amount of water remaining in the cistern at the end of each month for homes in Paulette and Phaeton are shown in Figure 5.

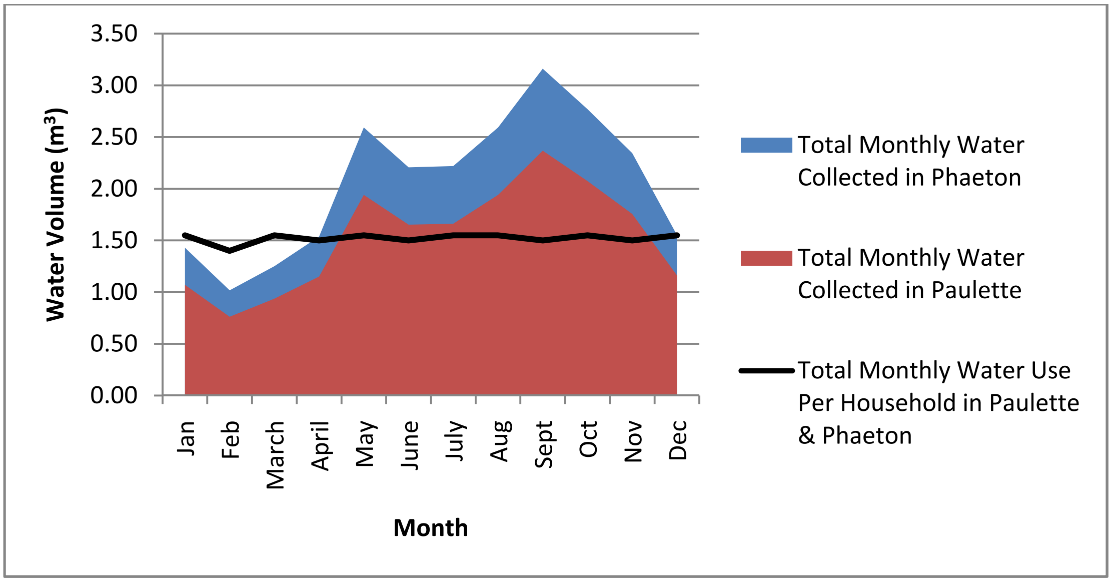

Figure 4: Water collected by homes in Phaeton and Paulette.

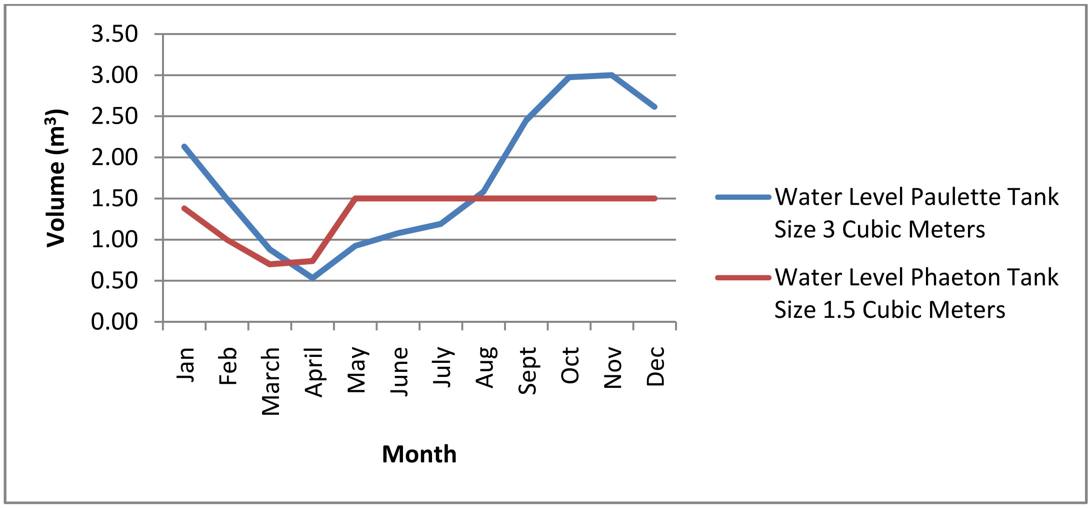

Figure 5: Water in cistern at the end of each month.

3.4 Materials & Capital Cost

The simplicity of the materials required for the cistern systems make it very appealing. As stated above, the system can be setup at residents' homes to utilize the roofs as catchment surfaces. The major components required for the system are gutters to collect the water, tanks to store the water, and pipes to connect them. The cost estimate for an individual cistern system in Paulette and Phaeton are shown in Table 5. The water tank dominates the system cost. Polypropylene tanks could be utilized to store the water, but a more cost effective option would be to construct concrete water tanks using local craftsman. This not only reduces the system price, but provides employment for the residents of Phaeton and Paulette.

Table 5: Cistern system capital cost estimate.

	Paulette		Phaeton	
Component	**Polypropylene Tanks**	**Concrete Tanks**	**Polypropylene Tanks**	**Concrete Tanks**
Gutters	$45.78 [11]	$45.78 [11]	$52.08 [11]	$52.08 [11]
Gutter Installation Components	$19.62 [11]	$19.62 [11]	$22.24 [11]	$22.24 [11]
Connecting Pipes	$12.00	$12.00	$12.00	$12.00
Sealant	$5.00	$5.00	$5.00	$5.00
Water Tanks	$615.00 [11]	$237.75 [11]	$307.50 [11]	$118.90 [11]
Tank Connecting Fittings, Valves, and Screens	$35.00	$20.00	$35.00	$20.00
Total Capital Cost	$732.40	$355.15	$433.82	$245.22

A conceptual diagram of the cistern system is shown in Figure 7. To allow full visualization of the storage capacity, the polypropylene water tanks were included to allow a full visualization of the water storage volume required. Multiple tanks with connecting valves were utilized to allow an individual tank to be isolated for cleaning and maintenance. Screens would be fixed to the pipe inlets to ensure that leaves, twigs, etc. would not enter the system.

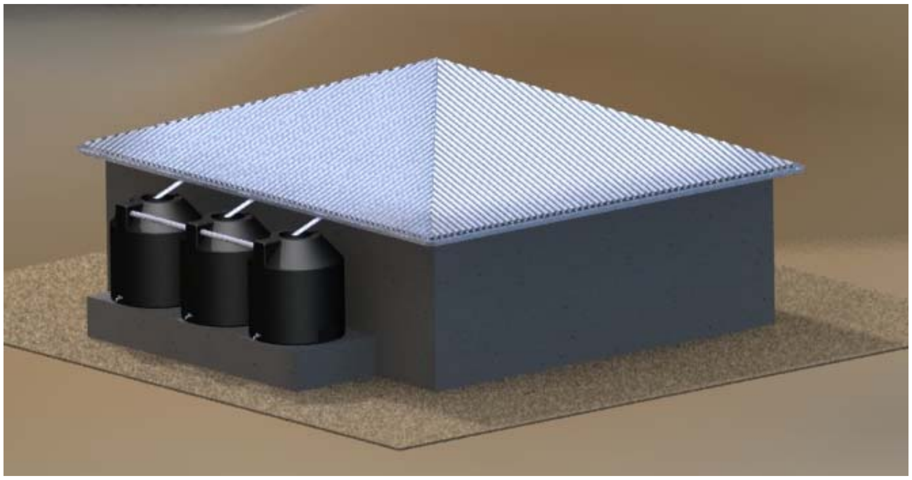

Figure 6: Conceptual cistern water system.

3.5 Operational Aspects

3.5.1 Water Treatment Options

Water from the cistern system will require treatment. Rainwater has the potential to pick up dust, dirt, and animal droppings from the catchment surface [12]. There are many possible treatment options including cartridge filters, reverse osmosis, UV light, ozone and chlorine [11]. The majority of them require materials that would not be readily available in the Cap Haitien area.

Chlorine disinfection is the simplest treatment and the one recommended for this project. In this solution, it is proposed that liquid chlorine, in the form of laundry bleach can be utilized to treat the drinking water. The bleach usually contains 6 percent sodium hypochlorite. Only regular, unscented bleach should be utilized. For disinfection purposes, 2 fluid ounces (¼ cup) should be added per 1,000 gallons of rainwater [11]. This will also prevent the buildup of algae and bacteria inside the water tanks.

Chlorine should also be added after the water has been drawn from the cistern. A small filtration system has been developed by an organization called Gift of Water, are they are currently being distributed in Haiti. The filtration system is very low-tech; consisting of two commercial recycled buckets, cotton fibers, charcoal, and daily addition of bleach drops. The filtration system removes almost all water borne pathogens; preventing Diarrhea, Hepatitis A, and Typhoid [13]. A family that has a cistern is able to consume clean safe drinking water year round. Gift of Water quotes a system price of $25.00 installed in Haiti. A picture of the system can be seen in Figure 8.

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http://www.haitiproject.org/images/purifier.jpg

Figure 7: Low-tech water filtration system [13].

3.5.2 Daily Operation & Maintenance

One of the main advantages of the cistern system is the simplicity of the operation and maintenance of the system. All maintenance would be able to be performed by the owner once the system is installed and some basic training is given. A listing of the basic maintenance required and associated costs are given in Table 4. The main difference between the two different storage systems is due to the reliability of the concrete reservoirs. They are prone to cracking and will require regular tank maintenance.

Table 6: Basic maintenance activities and schedule.

Maintenance Activity	Frequency – Polypropylene Tanks	Cost – Polypropylene Tanks	Frequency – Concrete Tanks	Cost – Concrete Tanks
Clean Gutters	1 per month	Owner Maintenance	1 per month	Owner Maintenance
Clean System Screening	After every major rain	Owner Maintenance	After every major rain	Owner Maintenance
Reseal System	Every 3 years	$5.00 Every 3 Years	Every years	$5.00 Every Years
Clean Water Tanks	As needed – at least once a year.	Owner Maintenance	As needed – at least once a year.	Owner Maintenance
Chlorine Water Treatment	After every major rain – At least once per month.	$0.25 per month	After every major rain – At least once per month.	$0.25 per month
System Component Replacement	Each Year	5% of System Cost	Each Year	5% of System Cost

3.6 Total Water Cost

A water price was developed using the equivalent annual cost method based on the system capital costs, operating costs, and maintenance costs. This price is a price estimate of the cost of water over the entire system life. The details of the cost calculation are presented in Appendix G. A useful system life of 30 years was assumed. A resulting water costs for the different system configurations are given in Table 5. All of these systems result in higher water costs than the pumped water system. This confirms that a promising course of action might be an upgrade of the pumped water system.

Table 7: Life cycle water costs for cistern systems.

	Paulette		Phaeton	
	Polypropylene Tanks	**Concrete Tanks**	**Polypropylene Tanks**	**Concrete Tanks**
Capital and Operating Costs	\$3.61/m^3	\$1.99/m^3	\$2.22/m^3	\$1.47/m^3
Operating Costs Only	\$2.23/m^3	\$1.39/m^3	\$1.06/m^3	\$0.82/m^3

4 Practical Considerations

4.1 Deployment

Considering the cost of the system, we believe that the cistern systems should be donated to the first few households. Need and efficiency (based on roof space) would be good considerations in choosing these families. While capital costs would be covered through donations, operating costs would be covered by each household (who should be apprised of these costs when given the system).

Local workers, properly supervised, would install the systems. The training they receive should enable them to adopt a small trade in building additional systems for families who can afford it. Upkeep of the systems could also be delegated to them, although we believe that the maintenance is simple enough to be carried out by family members.

Other incarnations of the cistern system are possible. Large-scale, more cost-efficient rainwater collection systems on community buildings are a significant consideration. Water could be simply donated or sold at a cheaper price with profits to support the community.

4.2 Disadvantages

The main disadvantage of the distributed cistern system is that the resulting water cost is more than the pumped water system. This indicates that the best investment might be made in an improvement of this system. Another disadvantage of the cistern system is that it would be susceptible to hurricane damage. Hurricanes regularly damage building roofs and other infrastructure and could put the cistern systems out of commission.

It is also possible that families in Phaeton and Paulette already collecting rainwater and have cistern systems. Another possibility is that poorer families might have homes with thatched roofs or other materials that would not capable of integrating with a cistern system. It this is the case for the majority of homes, larger community buildings should be considered as potential cistern sites.

Another disadvantage of the cistern system is that the amount of rainfall is not fixed. There is potential that there could be many dry days in succession, and the cistern could run out of water. Here, the system is oversized to limit this occurrence, but time constraints didn’t allow for a full statistical analysis. It is recommended that another water source be available in case of this event.

Another disadvantage is the potential market effects a new water system could have on Paulette and Phaeton. The current fresh water sources of Paulette and Phaeton must be preserved. New project must not subject the current water supply to the two threats of market forces and disrepair (disrepair being extremely common in the area). One dangerous scenario to be avoided involves the establishment of an alternate fresh water supply which is cheaper but less reliable. Initially, the cheaper water supply will draw customers from the pumped water supply, leaving it with less income and attention and likely to suffer from a lack of maintenance. When (presumably) the new water supply fails in some way, the population will be unable to return to (now broken) pumped water supply.

There are two options that will prevent this breakdown scenario. The first option is to design an extremely reliable and well-maintained new system. The pumped water would eventually fall into disrepair but the new system would be able to be repaired. The second option is to design a distributed, household level system which can be targeted at the neediest populations. Building these systems for the poorer elements of society will mean that they have access to the cheaper water but the bulk of the population still purchases water at the pumped station. Eventually, all households can possess one, and then the pumped water system may fall out of use (leading to a negative network effect problem).

4.3 Advantages

The proposed cistern system has many advantages over other water solutions. Firstly, unlike the many desalination approaches, the cistern is a simple system. The system maintenance is technically easy, and maintenance can be performed by the system owner. This simplicity also means the cisterns can be locally constructed. This would create employment in Paulette and Phaeton and help to provide a sustainable future.

As was stated above, this distributed design allows for the poorest families to be targeted. The system could be donated to families in need and then they could be responsible for the system upkeep. Analysis shows this would reduce their water costs.

In addition to keeping a functioning pumped water system and targeting poorer populations, the cistern systems have another benefit in its redundancy. When one part of the system breaks, the whole community has not lost its water supply. As the nine broken hand pumps show, community property often falls into disrepair. Additionally, maintenance on each system should be more regular as the family has a direct incentive to keep their unit in operation. Households must have the expertise and supplies to perform this maintenance.

5 Conclusion

This report analyzed different water solutions for Paulette and Phaeton. Two different water sources were considered, brackish groundwater and natural water. Many different techniques were considered brackish water desalination. The high energy requirements and complexity of these systems make their implementation infeasible.

Natural water sources provide more economically and technically feasible options. The current system provides water at a relatively low cost, and an upgrade of this system could result in the most economical water solution for the citizens of Phaeton and Paulette. Lack of information prevented a full analysis of the pumped water system.

This report detailed the design of a cistern system to provide water in Haiti. The systems would be distributed, and each family would have a cistern which would collect water from the roof of their homes. This solution is low cost, can be made from local materials, and could be easily maintained by the system owner.

A full system life cycle cost analysis for the proposed cistern system was completed. When all costs are considered, the cistern system resulted in higher prices than pumped water system. If only operating costs are considered, water prices are lower than the current pumped water system. This suggests that systems could be donated to less fortunate families in Haiti to help ease their financial burden.

6 References

1 World Health Organization. "Guidelines for Drinking Water Quality, 3rd Edition," 2006, Available HTTP: http://www.who.int/water_sanitation_health/dwq/gdwq0506.pdf

2 Google, "Google Maps", May 9, 2009, Available HTTP: http://maps.google.com/?ie=UTF8&ll=19.518375,-75.498047&spn=25.574959,46.582031&z=5,

3 Yunos, T. "The Economics of Desalination," Journal of Contemporary Water Research & Education, Vol. 132, pp. 39-45, Dec. 2005.

4 Tzen, E., and R. Morris. "Renewable energy sources for desalination," Solar Energy, Vol. 75, pp. 375-379, 2003.

5 Banat, F, and N. Jwaied, "Economic Evaluation of Desalination by small-scale autonomous solar-powered membrane distillation units," Desalination, Vol. 220, pp. 566-574, 2008.

6 German Aerospace Center (DLR) Institute of Technical Thermodynamics, "Aqua-CSP, Concentrating Solar Power for Seawater Desalination – Final Report," Stuttgart, Germany, 2007.

7 National Aeronautics and Space Administration, Atmospheric Science and Data Center, "NASA Surface meteorology and Solar Energy: Global Data Sets," 2009. Available HTTP: http://eosweb.larc.nasa.gov/sse/

8 Hertfelder, J. "Phaeton Houses", [Online Image], Available HTTP: http://static.panoramio.com/photos/original/5695171.jpg

9 United Nations Development Program, "Human Development Report 2006", 2006, Available HTTP: http://hdr.undp.org/hdr2006/pdfs/report/HDR06-complete.pdf

10 Bower, K. M. "Final Report: Increased Drinking Water Supply Through Improved Cistern Construction in Barasa Haiti", U.S. Environmental Protection Agency, National Center for Environmental Research, 2005. Available HTTP: http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.abstractDetail/abstract/7748/report/F

11 Krishna, H. J. "The Texas Manual on Rainwater Harvesting, Third Edition" Texas Water Development Board, Austin, Texas, 2005.

12 Senders, A. W. "Cisterns – Planning and Design." U.S. Department of Agriculture and West Virginia University, Cooperative Extension Service, Oct. 17, 1971.

13 Gift of Water, "The Purifier", 2009, Available HTTP: http://www.giftofwater.org/site/cpage.asp?cpage_id=140018465&sec_id=140005522

Appendix A. Thermal Desalination Calculations

Least Heat of Separation

The minimum energy required by any thermal desalination system is limited by the theoretical least heat of separation. This can be derived using the first and second laws of thermodynamics to show:

$$q_{least} = \frac{\dot{Q}_{least}}{\dot{m}_d} = \frac{\dot{W}_{least}}{(1 - {}^{T_0}/_{T_H})}$$

Where $\dot{W}_{least}$ is the least work of separation (3 kJ/kg), T_H is limited by scaling (< 125 °C), and T_0 is the feed temperature (20 °C). Using these values, we find that $q_{least} \approx 11.4\ kJ/kg$.

We can use this value to determine the amount of fuel required to operate this thermal process. If we consider diesel fuel, we can determine the amount of fuel required. This is given by

$$m_{fuel} = \frac{E_{req}}{\eta \Delta H^0{}_{comb}}$$

Since 1 L of water weighs 1 kg, the amount of energy required per L is 11.4 kJ. Using a heating value of diesel is 44.8 MJ/kg and 100% efficiency (lower bound) results in:

$$m_{fuel} = 255 \frac{mg\ diesel}{L\ water}$$

Using a diesel price of $3.00 per gallon, the resulting energy cost for the water produced is $0.24 per cubic meter.

Single-Stage Flash

A multi-stage flash system would be difficult to implement in Paulette and Phaeton. First, a single-stage system is considered. This system is not very energy efficient, but for completeness an estimation of the energy requirements was completed. A diagram of the system used in this analysis is shown in Figure 9 below.

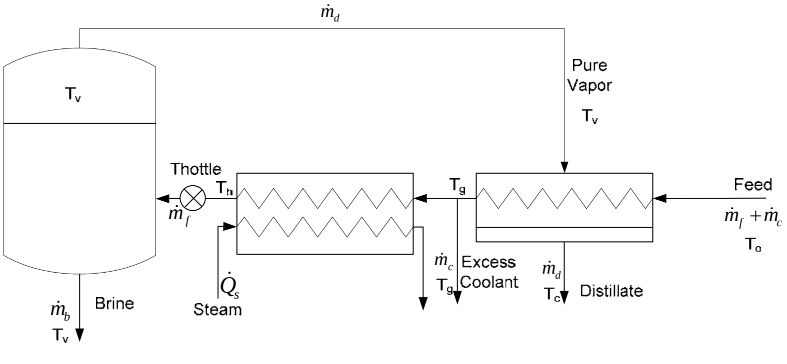

Figure 8: Single stage flash system

In class, the following equation was derived to determine the amount of heat required per unit:

$$q = \frac{\dot{Q}_s}{\dot{m}_d} = \frac{\dot{m}_f}{\dot{m}_d} C_p (T_h - T_g) \approx h_{fg} \left[1 + \frac{\delta_{bpe} + \Delta T_{terminal}}{\Delta T_{flash}} \right]$$

From class, we also know that $\Delta T_{flash} \approx 3 - 5\ K$, $\Delta T_{terminal} \approx 3 - 4\ K$, and $\delta_{bpe} \approx 1K$. Using these values, we can estimate the heat required.

$$q \approx 2326\frac{kJ}{kg}\times\left[1+\frac{1K+4K}{4K}\right] = 5234\frac{kJ}{kg}$$

This corresponds to a specific energy consumption of $1454\ kWh/m^3$. The GOR for this system is approximately 0.5, and the diesel fuel requirements for this type of system with 100% conversion efficiency is given by:

$$m_{fuel} = \frac{5234\frac{kJ}{kg}\times 1kg}{44.8\ MJ/kg} = 116.8\frac{g\ diesel}{L\ water}$$

Using this number, and a diesel price of \$3.00 per gallon, we find that the cost of energy for this type of system is \$108.20 per m^3.

Multi-Stage Flash Calculation

A multi-stage system is more efficient. This would be very difficult to implement in Haiti, but the energy costs are calculated for comparison. In class, a 28 stage system was reported to have a Gain Output Ratio of 12 and thermal energy requirement of 200 kJ/kg of water produced. This system would require 4.5 g of diesel to produce 1 L of water considering a 100% efficient conversion. At \$3.00 per gallon, the cost of energy for this type of system is \$4.20 per m^3. The energy costs alone still exceed the target price, and a system of this type would be extremely complex.

Single Effect Distillation Calculation

The implementation of a single effect system would be difficult. However, for completeness the energetics of a single effect distillation system were considered. Only thermal energy requirements are analyzed. A diagram of the system used in this analysis is shown in figure below.

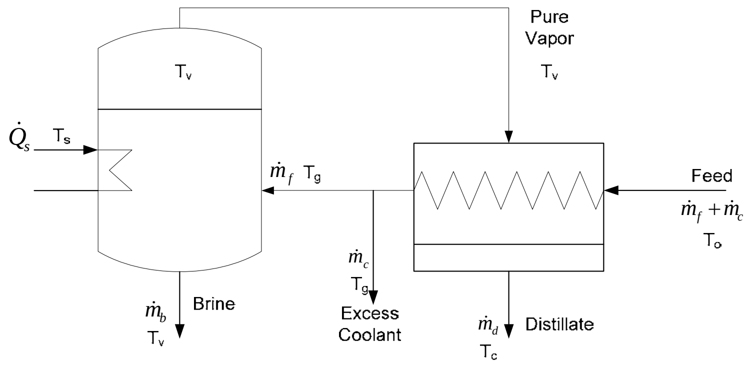

Figure 9: Single effect distillation system

In class, the following equation was derived to determine the heat required per unit mass of distillate.

$$q = \frac{\dot{Q}_s}{\dot{m}_d} \approx h_{fg}|_{T_c} + \frac{\dot{m}_f}{\dot{m}_d}C_p(T_v - T_g)$$

From class, we know $\frac{\dot{m}_f}{\dot{m}_d}>2$ to prevent scaling, and that

$$(T_v - T_g) = \delta_{bpe} + \Delta T_{terminal} \approx 1 + 5$$

Using these values, we can approximate that

$$q \approx 2350\frac{kJ}{kg}$$

This corresponds to a specific energy consumption of $652\ kWh/m^3$. The GOR for this system is approximately 1, and the diesel fuel requirement for this type of system with 100% conversion efficiency is given by:

$$m_{fuel} = \frac{2350\frac{kJ}{kg} \times 1kg}{44.8\ MJ/kg} = 52.5\frac{g\ diesel}{L\ water}$$

Using this number, and a diesel price of \$3.00 per gallon, we find that the cost of energy for this type of system is \$49.16 per m^3.

Multi-Effect Distillation Calculation

Multi-stage systems are more efficient. From class, an upper bound, $R \leq N$, was placed on the GOR for multi-effect distillation system. N is the number of stages. For a system with 8 stages, this limit on the GOR allows us to estimate a lower bound on energy required:

$$q = \frac{L_r}{R} \leq \frac{h_{fg}}{N} = \frac{2257kJ/kg}{8} = 282.1\ kJ/kg$$

This system would require 6.3 g of diesel to produce 1 L of water considering a 100% efficient conversion. At \$3.00 per gallon, the cost of energy for this type of system is \$5.90 per m^3. The energy costs alone still exceed the target price, and a system of this type would be extremely complex.

Appendix B. Vapor Compression Calculation

The majority of the work for a vapor compression system is done by the compressor. The work for an isentropic compressor can be expressed as:

$$W_c = \frac{\gamma}{\gamma - 1} R_s T_1 \left[\left(\frac{P_2}{P_1}\right)^{\frac{\gamma-1}{\gamma}} - 1 \right]$$

Since our system will need to be simple, we will only consider one stage in the vapor compression system. Using the basic numbers provided in class with the tank set at atmospheric pressure, a pressure ratio of 1.2, we get the following compressor work:

$$W_c = \frac{1.32}{1.32 - 1}\frac{8314.5}{18.01}101.5\left[(1.2)^{\frac{1.32-1}{1.32}} - 1\right] = 34.5\frac{kJ}{kg\ water} = 9.6\ kWh/m^3$$

If you consider a compressor efficiency of 65%, the actual work becomes:

$$W_{actual} = \frac{W_c}{\eta} = 53.1\frac{kJ}{kg\ water} = 14.8\ kWh/m^3$$

The amount of fuel required for the system can be estimated using the following equation, assuming 40% conversion efficiency:

$$m_{fuel} = \frac{E_{req}}{\eta \Delta H^0{}_{comb}} = \frac{53.1\frac{kJ}{kg} \times \frac{1kg}{L\ water}}{0.4 * 44.8\ MJ/kg} = 2.96\frac{g\ diesel}{L\ water}$$

Considering a diesel price of \$3.00 per gallon, this corresponds to an energy cost of \$2.80 per cubic meter of water.

Appendix C. Reverse Osmosis Calculation

In this simple calculation, a single pass reverse osmosis system with no energy recovery is analyzed. This configuration was chosen so the system was as simple as possible. A diagram of this configuration is shown in Figure 11.

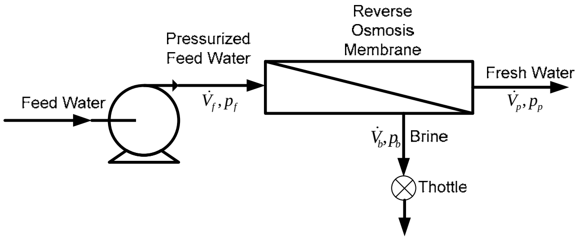

Figure 10: Reverse osmosis system.

The recovery ratio is the fraction of fresh water that is produced from the feed water and is given by:

$$R_p = \frac{\dot{V}_p}{\dot{V}_f}$$

$$\frac{C_{s,b}}{C_{s,f}} = (1 - R_p)^{-SR}$$

For a brackish water system without energy recovery, a high recovery ratio would be desired. From the recovery ratio, the concentration of the brine and permeate can be found using:

$$\frac{C_{s,b}}{C_{s,f}} = (1 - R_p)^{-SR}$$

$$\bar{C}_{s,p} = \left(\frac{C_{s,f}}{R_p}\right)\left[1 - (1 - R_p)^{-SR}\right]$$

where the salt rejection is given by the membrane manufacturer.

The only energy required for reverse osmosis is the energy required to operate the pumps. The pumping power and energy are given by:

$$P_{pump} = \frac{p_f \dot{V}_f}{\eta_{pump}\eta_{motor}} = \frac{p_f \dot{V}_p}{\eta_{pump}\eta_{motor} R_p}$$

$$E_{pump} = P_{pump} \times 24\ hours$$

For a given operating pressure and water salinity it is also possible to determine the amount of membrane area required. In order to determine the membrane area, the osmotic pressure must be found. The following empirical relation was given in class to estimate the osmotic pressure:

$$\pi = 0.00076 \times C(ppm)$$

With the average differential pressure across the membrane, and the average differential osmotic pressure across the membrane, the membrane flux is given by:

$$J_v = A(\Delta\bar{p} - \Delta\bar{\pi})$$

where A is the membrane permeability. The required membrane area is then given by:

$$A_{membrane} = \frac{\dot{V}_p}{J_v}$$

The values used in the calculation and resulting energy requirements are shown in Table 6. Parameters were chosen based on typical values given in class.

Table 8: Reverse osmosis calculation details.

Given Parameters	**Value**
Recovery Ratio (R_p)	75%
Feed Pressure (p_f)	27 bar
Feed Concentration ($c_{s,f}$)	3000 PPM
Membrane Permeability (A)	6 L/(m^2 X hour X bar)
Motor Efficiency (η_{motor})	75%
Pump Efficiency (η_{pump})	70%
Membrane Pressure Drop	0.5 bar
Permeate Flow ($\dot{V}_p$)	17500 L (10 L per day for 1750 people)
Salt Rejection (SR)	0.98
Calculated Values	
Brine Concentration($c_{s,b}$)	11672 PPM
Permeate Concentration($c_{s,p}$)	110 PPM
Membrane Area (A_m)	6.0 m^2
Pump Power (P_{pump})	1.3 kW
Energy used in 1 Day	31 kWh
Specific Energy	1.8 kWh/m^3, 6.4 kJ/kg
Mass of Diesel per L of Water (η=40%)	356 mg diesel / L water
Cost of Water Produced Using Diesel($3.00 per Gallon)	$ 0.36 / m^3

Appendix D. Electrodialysis Calculations

In class, the following equation was derived to relate the change in concentration and the change in concentration and flow rate to current required:

$$I = \frac{\Delta c_d \dot{V}_d F |z| v}{\xi}$$

Assume we are designing a 1-stage system for use in Paulette to produce 17.5 m^3 per day. Assume our electrodialysis system has 150 cell pairs. If we are desalinating 3000 ppm to a concentration of 500 ppm, we have the following change in concentration:

$$\Delta c_d = c_f - c_d = 2500\, ppm = 42.77\, mol/m^3$$

If we have a current efficiency of 90%, the resulting current is given by:

$$I = \frac{42.77 \frac{mol}{m^3} \times \frac{17.5}{150} \frac{m^3}{day} \times \frac{1\, day}{86400\, sec} \times 96485 \frac{C}{mol}}{0.9} = 5.572\, A$$

To give a power estimate, use the fact that the normal operating voltage of these systems is approximately 200 VDC. This gives:

$$P = VI = 200 \times 5.572 = 1.114\, kW$$

If this system is operating for 24 hours, the energy required would be:

$$E = P \times 24\, hours = 26.75\, kWh$$

If we assume that the energy comes from a diesel system as was done in previous sections, the cost of the energy to produce 1 m^3 of water is \$0.31 per cubic meter. It should be noted that this calculation does not account for the energy required to pump the water through the system.

Appendix E. Solar Still Calculation

Haiti gets roughly 5 sun-hours of insolation a day.

$$5\ sun-hours * 41.6\ \frac{\frac{W}{m^2}}{sun-hour} = 210\ \frac{W}{m^2}$$

A thermal desalination process requires the heat of vaporization plus the heat needed to bring the feed water to 100 degrees C:

$$water\ produced = \frac{insolation}{h_{fg} + c_p\Delta T}$$

Considering only the heat of vaporization for a moment:

$$Production\ Capacity = \frac{210\ W}{m^2}\ \frac{J/_s}{W}\ \frac{kg\ H_2O}{2260 \times 10^3 J}\ \frac{L\ H_2O}{kg\ H_2O}\ \frac{24 \times 3600\ s}{day} = \frac{8\ L}{m^2\ day}$$

Solar stills would produce a maximum of 8 L per meter squared of area. Considering that solar stills have an efficiency of about 25%, this is reduced to 2 L per day. To supply the needs of a typical person at 10L/day, 5 square meters of area (at least) are required. For the whole village, entire football fields of stills would be needed.

Appendix F. Cistern Calculations

In order to size the cistern system, a monthly balance of water collected and water consumed was utilized. Two pieces of data were required to determine the amount of water that would collected, average monthly rainfall and the catchment area. Average yearly rainfall data was acquired from the NASA Atmospheric Science and Data Center [2]. This data is derived from 22 years of satellite imagery. Based on the average rainfall data, and collection efficiency of 75%, a catchment area of 28.25 m^2 would be required to provide enough water. Roof sizes for houses in both Paulette and Phaeton were estimated using satellite imagery in Google Earth [10]. An average house was selected for both Paulette and Phaeton. The measured dimensions are shown in Figure 12. In both cases the roof areas were larger than the minimum requirement.

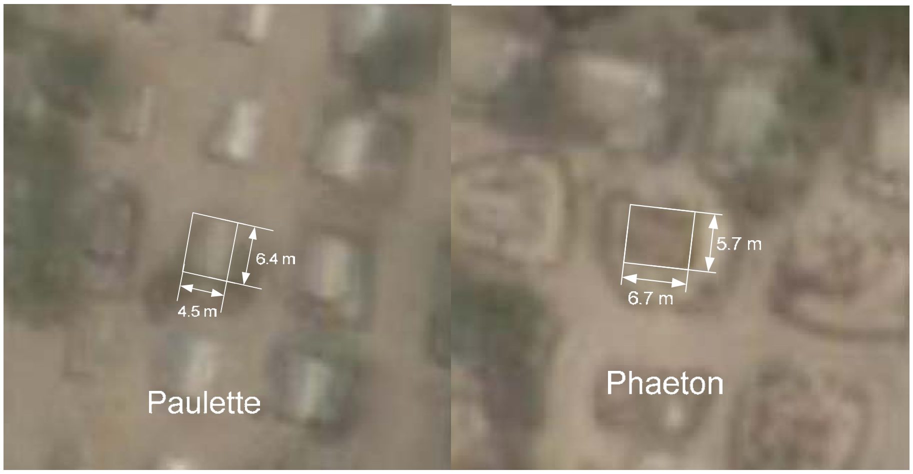

Figure 11: Roof areas in Paulette and Phaeton [2].

The cistern reservoir sizes were determined using a monthly balance. The amount of water collected each month was found using:

$$Amount\ Collected\ Per\ Month = V_{in} = R\ \times A \times \eta_{collect}$$

Where R is the average monthly rainfall, A is the roof area, and $\eta_{collect}$ is the collection efficiency. Here, a conservative collection efficiency of 75% is used [8]. The amount of water used per month was found using the following relation:

$$Amount\ Used\ Per\ Month = V_{out} = Daily\ Usage\ \ \times \#\ of\ days\ in\ month$$

Using these simple relations, the amount of water in the tank at the end of each month can be found using:

$$V_{water,i} = \max\left(V_{water,i-1} + V_{in} - V_{out}, V_{tank}\right)$$

where $V_{water,i-1}$ is the amount of water in the tank at the end of the previous month, and V_{tank} is the tank volume. The tank volume was then determined using an iterative approach. A tank size is initially selected, and then the volume of water in the tank at the beginning of the year is modified until it matches the volume available at the end of the year. The tank size was then decreased by 0.5 m^3 and the process was repeated. The smallest tank that would result in at least 0.5 m^3 in the tank at the end of final month of the dry season was chosen for the system. The minimum allowable tank size was set to 1.5 m^3 (1 months supply of water). The resulting monthly water volumes are shown in Table 10.

Table 9: Monthly water volumes.

Month	Average Daily Rainfall (mm)	Total Monthly Water Collected in Paulette	Total Monthly Water Collected in Phaeton	Total Monthly Water Use Per Household	Water Level Paulette Tank Size 3 m^3	Water Level Phaeton Tank Size 1.5 m^3
Jan	1.61	1.07	1.43	1.55	2.13	1.38
Feb	1.27	0.76	1.02	1.40	1.49	1.00
March	1.41	0.94	1.25	1.55	0.88	0.70
April	1.79	1.15	1.54	1.50	0.53	0.74
May	2.92	1.94	2.59	1.55	0.92	1.50
June	2.57	1.65	2.21	1.50	1.08	1.50
July	2.5	1.66	2.22	1.55	1.19	1.50
Aug	2.92	1.94	2.59	1.55	1.58	1.50
Sept	3.68	2.37	3.16	1.50	2.45	1.50
Oct	3.12	2.07	2.77	1.55	2.97	1.50
Nov	2.73	1.76	2.35	1.50	3.00	1.50
Dec	1.75	1.16	1.55	1.55	2.61	1.50

Appendix G. Cistern Cost Details

The cost of the water produced by the cistern system was calculated using the annualized equivalent cost method. The annual fixed costs of the cistern system can be found using:

$$A_{fixed} = aDC$$

where DC is the full system direct capital cost and a is the amortization factor given by:

$$a = \frac{i(1+i)^n}{(1+i)^n - 1}$$

where n is the system lifetime in years, and i is the interest rate. The total annualized cost is then given by:

$$A_{Total} = A_{fixed} + \ A_{O\&M}$$

Where $A_{O\&M}$ is the annualized operating and maintenance costs which are detailed in section 3.5.2. The cost of water can then be found using:

$$c_{unit} = \frac{A_{Total}}{m}$$

where m is the yearly capacity of the system. The values used in this analysis are shown in Table 11.

Table 10: Cistern life cycle cost analysis.

	Paulette		**Phaeton**	
	Polypropylene Tanks	**Concrete Tanks**	**Polypropylene Tanks**	**Concrete Tanks**
Interest Rate	5%	5%	5%	5%
Capital Cost	\$732.40	\$355.15	\$433.82	\$245.22
Annual Fixed Cost	\$47.64	\$23.10	\$28.22	\$15.95
Annual Operating Cost	\$41.29	\$25.75	\$26.36	\$20.26
Yearly Production	18.48 m^3	18.48 m^3	24.68 m^3	24.68 m^3
Life Cycle Product Cost including Capital Cost and Operating Costs	\$4.81/m^3	\$2.64/m^3	2.21/m^3	\$1.47/m^3
Life Cycle Product Cost including only Operating Costs	\$2.23/m^3	\$1.39/m^3	\$1.06/m^3	\$0.82/m^3