2.500 Desalination and Water Purification

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Purification of Water in Phaeton and Paulette, Haiti

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Abstract

Phaeton and Paulette, two small villages in the northeast part of the Haitian coastline, currently suffer from a lack of available freshwater for personal consumption. This paper looks at methods for improving the water supply through desalination techniques and rainwater collection. Mercy and Shairing, a non-profit NGO, hopes to take recommendations and implement the best solution in these two villages. Unfortunately, both villages are subject to abject poverty and cost is the major limiting factor when considering possible improvements to the existing water infratstructure. Humidification-dehumidification (HDH) and reverse osmosis (RO) were the only two desalinations that appeared to be viable options for the area. HDH proved to be too expensive without locally available and inexpensive sources of energy. RO is quite cost competitive with existing supply ($\$0.017/bucket$ vs. existing $\$0.024/bucket$) provided a financing plan can be arranged. Rainwater collection is a viable option for improving the existing water supply, but will not completely solve the problem. By renovating and expanding the existing $100\,m^3$ cistern, up to $462\,m^3$of water can be collected each year. Basic treatment can be added to the cistern to improve the quality of the water. It is our recommendation that if the water quality problem is to be solved as completely as possible that a community-wide RO plant be implemented and the water be sold at cost to pay for the plant's maintenance and security.

Contents

1 Introduction

1.1 Background

Phaeton and Paulette are two small villages (population of 2450 and 1750 respectively) on the northern coast of Haiti and are within one hour's drive from Cap-Haïtien. Unfortunately, the groundwater in both villages is contaminated with seawater, thus resulting in very high salinity levels in the well water. This highly brakish water is not very suitable for drinking and is typically reserved for washing and other nonconsumption uses.

Drinking water is made available to both villages through a pumped system located in the nearby town of Ti Kampeche. Water from the pumped system costs approximately $1\,gourde$ per $5\,gallon$ bucket ($\sim$ \$0.024). While this water is at much lower salinity than the available brakish water, field tests showed that the water had a TDS of about $650\,ppm$ and $450\,ppm$ in Phaeton and Paulette respectively. Often, the water is further contaminated through use of improperly cleaned buckets. These levels of salinity are still higher than the typically recommened maximum TDS of $500\,ppm$ and has resulted in several health consequences including high blood pressure. Tables 1 and 2 summarize the details regarding the available water supplies in the two villages.

Living conditions in both villages is quite poor. Most people live on less than \$1 day and unemployment is as high as 80%. Over 50% of the residents depend on NGOs such as Mercy and Sharing for food and other basic necessities. Both villages desperately need a relibale, safe, and inexpensive source of clean drinking water in order to improve the quality of life. Since most families typically consume $4-5$ buckets of water per day, which requires approximately 10% of a families income. Supplies for possible solutions, including building materials, hardware stores, electronics, as well as various smiths, are often available in the nearby city of Cap-Haïtien. Necessary materials can be transported by truck. Imported goods typically have a $10\% - 20\%$ markup over the standard US prices[1].

The objective of this project is to develop potential designs for systems that would provide clean water in order to improve the current water situation in Phaeton and Paulette. Information regarding the two towns has been provided by Amy Smith as well as representatives from the non-profit group, Mercy and Sharing.

Table 1: Water Sources in Phaeton

Phaeton population: 2450

Source	TDS (*ppm*)	Cost	Notes
Ocean	35000	Free	
1 community well	1200	Free	Broken hand pump
7 hand-dug wells	3500	Free	Samples tested by HUB
Pumped water	650	\$0.024/*bucket*	Low levels of bacterial contamination

Table 2: Water Sources in Paulette
Paulette population: 1750

Source	TDS (*ppm*)	Cost	Notes
Ocean	35000	Free	
3 community wells	3000	Free	Broken hand pump
8 hand-dug wells	2300	Free	Sample tested HUB
Pumped water	450	$\$0.024/bucket$	No bacterial contamination

1.2 Approach

Due to the nature of this project, it was decided that two general design philosophies should be followed. First, a modular design would be favored over a single large system. Since this project is trying to address the neeeds of both Phaeton and Paulette, two villages of different sizes, it makes more sense to design a smaller system well than to design two separate systems. Multiple identical systems can then be used to meet the needs of the populations. Second, due to limiting factors such as cost, social/political unrest, and technological barriers, it is better to try to improve the current conditions rather than to try to completely solve every problem associated with water distribution in the area.

Keeping the above philosophies in mind, two possible solutions are considered in this paper:

Install a modular Desalination Process

From the reports that have been provided, both Phaeton and Paulette do not seem to have a problem with water shortage. Instead, they lack fresh, drinking water. The first solution that comes to mind in this situation is to create some sort of water purification or desalination system. In order to design a desalination system, it is important to first figure out what sort of capacity is required. From the given information, it is known that the total combined population is approximately 4200. Assuming that family size is on average, 4.5 people and that they use 5 buckets per day, then a total of 4667 buckets ($\sim 90\,m^3$) of water are required per day.

Using the modular idea, a system will be designed to accomodate one third of this required amount. One system will fall slighly short of satisfying all of Paulette's needs while two systems will be slightly greater than what Phaeton needs. Since there is an existing supply of drinking water (the pumped system), this size will work. Therefore, a single desalination system that can produce $30\,m^3/day$ will be discussed.

Renovate existing and install new rainwater collection devices

As a tropical country, Haiti receieves a large amount of rain every year. While rainwater can not satisfy the water demand, a well thought out rainwater collection system can greatly increase the amount of available fresh water.

2 Desalination Processes

2.1 Humidification Dehumidification

Humidification dehumidification (HDH) desalination is a thermal process that essentially consists of three simple components - a humidifier, a dehumidifier, and a heater. In HDH, water vapor is evaporated from the saline water source in the humidifier and is condensed in the dehumidifier. A heater is used on one of the streams in order to improve the overall efficiency of the system. This process is similar to that of a basic solar still. However, by separating the humidification and dehumidification processes, HDH is able to recover the heat of vaporization which is normally lost when the vapor condenses in a still.

After much consideration, it was decided that the best approach for using HDH is to build a modular system that can satisfy some of the demand. The units being considered are designed to produce $20\,m^3/day$ of water (from seawater) which will then be mixed with $10\,m^3/day$ of well water from Phaeton. Since Phaeton's water has a TDS of approximately $1200\,ppm$ and the condensaste from HDH is essentially pure, this diluted water would have an approximate TDS of $400\,ppm$, which is a great improvement over the existing water supply. The water in Paulette is to saline to benefit from dilution, and therefore, mixing should not occur. Cost figures below are based on mixing with Phaeton's well water.

2.1.1 HDH Cycle Selection

There are several different variations of HDH cycles that are being developed. One of the more promising cycles is the closed air, open water (CAOW) cycle, in which the air stream is heated prior to entering the dehumidifier. Figure 2 in Appendix A shows a simple block diagram of the cycles components as well as the numbering system used to describe each of the states. All of the values at each state are also displayed.

In order to determine the optimal operating conditions, the mass flow rate ratio (sea water to dry air) and the top operating temperature were varied over a wide range of values. All calculations were performed at atmospheric pressure since it is much easier and cheaper to build atmospheric pressure components rather than pressure vessels. It was found that the optimal operating conditions for the cycle are when the mass flow rate ratio is 1.25 and the top temperature is $80\,°C$. Under these conditions, the gain output ratio ($GOR = \dot{m}_{product}h_{fg}/\dot{Q}_{in}$) is 3.45.

2.1.2 Power Sources

Selection of an appropriate power source for the HDH cycle is the most critical aspect of the system design since the cost of power is the major expense for this system.

Solar Collector Solar power would be the ideal source of power for HDH since it is essentially an endless, free energy source once the solar collectors have been purchased.

Table 3: HeatStar HS6000DF

Parameter	Value
Cost	\$3157.38
Heating Capacity	$610,00\,Btu/hr$ ($179\,kW$)
Fuel Consumption	$4.46 gal/hr$

In areas that have strong solar insolation, solar collectors are a great option. However, even though Haiti is close to the Equator, Haiti is often overcast/cloudy, and the average solar insolation is quite weak [2]. Unfortunately, this means that using solar heaters would either be very inefficient, or require a very large surface area which would drive up costs. Additionally, building solar collectors would require a lot of materials (such as plate glass) that might not be easy to come by in Phaeton and Paulette.

Heat Pump Since solar heat is not a viable option in the climate being considered, use of a heat pump was discussed. The idea is that a motor could be used to power a compressor that would drive a heat pump. By using a heat pump, energy is taken from both the fuel being burned as well as the environment. Unfortunately, the gains from a heat pump (coefficient of performance, $COP = Q_{hot}/(Q_{hot} - Q_{cold}) \approx 3$) is offset from the losses due to Carnot efficiency ($\eta_c \approx 0.3$). Through proper design, a engine/heat pump arrangement could be designed that provides a greater heat transfer than just burning the fuel directly. However, the heat pump adds several more components to the system which results in more complications and higher cost. Therefore, the idea of using a heat pump was abandoned.

Burn Wood/Charcoal Another option for generating heat for the cycle is to burn fuel and use the heat of combustion directly. One of the most obvious sources of fuel is to use wood, which has an energy density of $18 - 22\,GJ/tonne$[3]. Unfortunately, Haiti already has a substantial deforestation problem and using large quantities of wood to power the desalination process will only exacerbate the problem. Charcoal, which has an energy density of $30\,GJ/tonne$, would also make a good fuel, but for similar reasons, is not a viable option in this environment.

Diesel Combustor The most likely power source for Haiti is to use a diesel fuel combustor in order to directly heat the air. Use of the combustor will provide the greatest amount of heating per unit of input fuel. The HeatStar HS6000DF[4] is a $610,000\,Btu/hr$ ($179\,kW$) unit that consumes ($4.46 gal/hr$) and costs \$3157.38. Data is tabulated in Table 3. One of the major advantages of using a heater (rather than solar power) is that the unit can be operated both day and night, thus reducing the amount of power needed since the water production can take place over a longer time period.

Table 4: McMaster Heavy Duty Heat Exchanger #3586K43

Parameter	Value
Cost	\$1286.86
Cooling Capacity	$720,000\,Btu/hr$ ($211\,kW$)
Flow Rate	$24\,gal/min$ ($1.5\,kg/s$)
Dimensions	7.25” × 53.25” ($0.18\,m \times 1.35\,m$)

2.1.3 Component Design

Dehumidifier The dehumidifier is a fairly simple component since it is a basic heat exchanger. The most viable type of heat exchanger for this system would be a shell and tube exchanger since they offer high heat transfer area with minimal pressure drop. While other heat exchanger designs can also be used, the advantage of having a lower pressure drop means less pumping power is required for the system. Shell and tube heat exchangers can be purchased from standard suppliers such as McMaster. One such heat exchanger that matches the heat capacity of the heater as well as the required flow rates is the Heavy Duty Heat Exchanger #3586K43[5]. Data for the exchanger is tabulated in Table 4.

Humidifier A humidifier can potentially be built fairly easily using cheaply available materials. One suggested humidifier design is to build a tower using horizontal PVC piping as a packing. There is no existing design for an easily fabricated humidifier and further development would be needed for this component. An important aspect that is critical to proper operation of the system is to ensure that a proper mist eliminator is used.

2.1.4 Cost Estimates

There are three main sources of cost associated with an HDH system: fixed (initial) costs, fuel costs, and maintenance costs. Values for each cost is tabulated in Table 5. Looking at the estimated values, it is clear that the fuel cost dominates both the capital and maintenance costs.

Table 5: HDH Costs

Type	Item	Cost	Total
Fixed	Combustor	\$3457.38	< \$7500 \$4.94/day (\$0.003/$bucket$) (7.5% APR, $5\,yr$ loan, monthly payments)
	Shell and Tube HX	\$1286.86	
	Humidifier	∼ \$1500	
	Pumps, etc.	∼ \$1000	
Fuel	Diesel	\$321/day	\$321/day (\$0.20/$bucket$)
Maintenance	Employee	\$1/day	\$1/day (\$0.0006/$bucket$)

2.1.5 Advantages

HDH requires very simple components and minimal maintenance. It is a reasonably robust system that does not require pretreatment since the product water is condensed vapor (pure). The output water is very pure and can be diluted with brackish water in order to increase the water production rate.

2.1.6 Disadvantages

Without a cheaper form of heat input, HDH can not compete with the current water sources. The only way to make this system a viable option is to find an alternative fuel that is more readily available and at lower cost than standard diesel fuel. Should Haiti have other fuel options, further calculations can be performed to determine whether or not HDH can produce water at a low enough cost.

2.2 Reverse Osmosis

2.2.1 Introduction

Reverse Osmosis (RO), once a very expensive technology, is becoming cost competitive, especially at large scales. RO is a process whereby salty water is forced through a membrane of very small pore size which effectively filters the salt. Because of the effect of osmosis where the pressure of a solution with dissolved solids has a greater pressure than a pure solvent, in this case water, the amount of pumping power can be quite large. While RO systems are characterized by high levels of complexity and large amounts of pumping power, especially for seawater desalination, systems are being developed to work at small scales as well. TSG[6] has been selling $10,000 - 15,000\, gal/day$ day self contained plants to locations in the Caribbean for many years, with a good degree of success. Pumping power can be reduced by desalinating brackish water instead of seawater, or reducing the required flow rate for the system.

2.2.2 Plant Design

Since RO technology is expensive minimizing its use in the overall water solution is critical. A small plant will be used to address the water concerns of the larger village, Phaeton. Phaeton is on the coast, and also has access to a community well of $1200\, ppm$ TDS that can be mixed with the RO plant product stream. Therefore the RO system can be used to produce an overall amount of $20\, m^3/day$ of treated water and mixed with $10\, m^3/day$ of well water to obtain a product at $500\, ppm$ TDS, which is acceptable to people there.

The RO plant itself would desalinate seawater as the draw rates required for the system would be too much for a single brackish well source in the village to handle. The operating parameters of the plant are similar to tired and true plants developed for a similar scale. Table 6 details the specifications of the RO plant to be used.

The calculations that arrive at these values can be found in Apprendix B.

Table 6: RO Plant Operating Parameters

Parameter	Value	Parameter	Value
System Parameters		Energy Data	
Perimate Flow Rate	20 m^3/day	Pump Efficiency	86%
Recovery Ratio	50%	Energy Recovery Efficiency	86%
Intake Flow Rate	40 m^3/day	Pump Power	3.23 kW
Pressure Vessels	1	Pump Power (w/Recovery)	2.06 kW
Membrane Cartridges	1	Diesel Motor	
Operating Temp	30 C	Power Rating	3.35 kW (4.5 HP)
Operating Top Pressure	61 bar	Specific Fuel Consumption	0.240 kWh/kg
Concentrate Rejection Pressure	59.7 bar	Daily Fuel Consumption	5.78 gal/day
Water Concentrations		Fuel Price	$3.00/gal
Intake	35,000 PPM		
Concentrate	69,850 PPM	Fuel Cost	$17.35/day
Permeate	150 PPM		

2.2.3 Cost Considerations

Fixed Cost The largest barrier to operation in Haiti is cost, particularity the fixed cost of the system. However the cost can be spread over time using financing at a fixed interest rate. The fixed cost can be obtained by calculating the cost of a plant per gallon per day of installed capacity. Costs for this came from two sources, a paper on desalination costs by Miller (2003)[7], and from proposals by TSG Water to build plants in Anguilla[8] and Peter Island[9]. Additional cost data were obtained from TITAN, a skid mounted RO plant manufacturer[10]. The costs are normalized to per day installed capacity and then averaged over all the systems. This average is $4.48 per gpd installed. This is multiplied by the required capacity of $20\,m^3/day$ or $5284\,gal/day$ to obtain the total cost. This cost is then multiplied by 1.25 to factor in importation costs to give the total in Table 7 below.

This cost is too high to be paid for up front, unless such a system would be donated. The cost would then need to be financed. The period of finance was chosen to be 10 years to minimize the cost impact on the water that is eventually sold to pay back the loan. An nominal interest rate of 7.5% APR was chosen based on current interest rates for fixed term loans and taking into account the increased risk involved in deploying such an expensive investment in a relatively unstable county. This is then figured into the daily cost of operation, which will be discussed below.

Daily Costs Daily costs consist of several key components These include: loan repayment, membrane replacement (once every 3 years), chemicals and maintenance, labor, and fuel for the pump. Table 8 details our daily costs.

The cost per bucket at the bottom is assuming the entire plant output of $20\,m^3$ diluted with $10\,m^3$ of well water resulting in a total sale-able quantity of $30\,m^3$. In

Table 7: Fixed Costs of a 20 m^3 per day RO Plant

Component	**Cost/gpd [$/(gal/day)]**	**Total Cost [$]**
Membrane and Pressure Vessel	$1.00	$5,284.00
Pre-Treatment	$0.30	$1,585.20
Post-Treatment	$0.30	$1,585.20
Installation	$0.48	$2,536.32
Miller - Capital Cost Estimation	$2.08	$10,990.72
TITAN Small Scale Plants (with Installation)	$1.45	$7,636.89
TSG Plant Figures		
TSG Anguilla Plant - 10,000 gpd	$5.83	$58,262.00
TSG Anguilla Plant - 15,000 gpd	$4.30	$64,492.00
TSG Peter Island - 100,000 gpd	$5.72	$571,890.00
Average Capital Cost w/Markup	**$2.20**	**$14,552.82**

Table 8: Daily Operational Costs of a 20 m^3 per day RO Plant

Reoccouring Expense	Lifetime Total	Cost Per Day
Membrane Replacement (Miller)	$3836.77	
Membrane Replacement (KMS)	$1500.00	
Membrane Replacement - Average	$2668.39	$0.73
Treatment Chemicals and Spare Parts	$10,414.09	$2.85
Fuel Cost		$17.35
Fixed Cost Loan Repayment		$5.76
Total Daily Operating Cost		$26.97
Water Cost Per 5 gal bucket		**1.7 cents**

order to meet the cost per bucket all the water produced must be sold.

2.2.4 Sociopolitical Considerations and Operation Risk

While the implementation of RO seems very feasible from a cost perspective, as it easily competes with the pumped water source now there are significant risks associated with operating in Haiti.

The first is that RO is complex technology that can be prone to sabotage if not properly guarded and maintained. There is evidence that the hand pumps on community wells were intentionally broken by saboteurs. This is why our daily costs include labor of an additional person to guard the plant.

The second is that the pump stations the bring "sweet" water into the town are being operated at a profit, whereas our system has to sell water at cost to be competitive with the current pumped water price. Therefore the RO plant could be easily undercut by the pump station operators which would make it had to sell all the water produced. The high fixed cost and required loan repayments make it necessary to sell most of the water produced. This risk could be ameliorated by a lump sum donation for the capital cost of the plant, or working with plant furnishers, like TSG, to provide a plant at significantly reduced cost as part of a charitable activity. This would also allow plant furnishers to test their products in harsh third world settings as the continue to develop cheaper plants.

2.3 Other Processes

Several other desalination technologies exist and are commonly used throughout the world. Unfortunately, many of them are not appropriate for applications in Haiti and other third world countries do to cost, power requirements, and maintenance issues. Table 9 summarizes these technologies as well as the reasons why they are not being considered for Phaeton and Paulette.

3 Rainwater Collection and Treatment

3.1 Introduction

Rainwater collection and treatment provides a low cost alternative way to produce clean salinity-free water for human consumption only. Given that Haiti's other renewable resources such solar energy are low, rainwater would provide a sensible alternative considering the raininess of the region. While rainwater collection will not satisfy all of the area's demand, it will certainly help improve the situation.

Table 9: Desalination Technologies

Technology	Driving Force	Reason not appropriate
Nanofiltration	Pressure	Too much NaCl present in brackish water. NF can not remove ions from solution.
Electrodialysis	Electricity	Requires a stable and reliable electricity source. Consumes too much power.
Multi-Effect Distillation	Steam	Too expensive for small scale production.
Multistage Flash	Steam, Vacuum	Too expensive for small scale production.
Vapor Compression	Pressure, Heat	(Low) pressure vessels are difficult to produce and maintain inexpensively.
Forward Osmosis	Pressure, Heat	Unproven technology. System is likely to be too complex.

3.2 Nature's Water Distiller

The large amount of diffuse solar energy and resulting tropical weather patterns produce a great deal of rain in Haiti, which essentially acts as a natural distillation process. The North Central Basin, where Phaeton and Paulette are located, receives an average yearly precipitation of 1.6 m[11]. No accurate monthly distribution of rainfall was available, however it is known that the rainy season comes to north-central Haiti between September and June with a peak in November-December. In the summer when it is drier, the water has to be stored. For this we would make use of a pre-existing cistern. If no rain fell from the end of June to September, a period approximated to 70 days, the cistern would have sufficient capacity to store excess water. This is detailed in Table 10. Rainwater is clean when it falls from the sky but will pick up contamination upon collection and sitting in the cistern therefore it is necessary to treat it with chlorine to prevent pathogenic contamination.

Table 10: Data for Rainwater Collection

Parameter	**Value**
Average Yearly Rainfall	$1.6\,m$
Average Daily Rainfall	$4.38\,mm$
Collector Area	$289\,m^2$
Averaged Output	$1.27\,m^3/day$
	$334.44\,US\,gal/day$
Cistern Capacity	$100\,m^3$
Days of Storage Capacity	$78.75\,days$

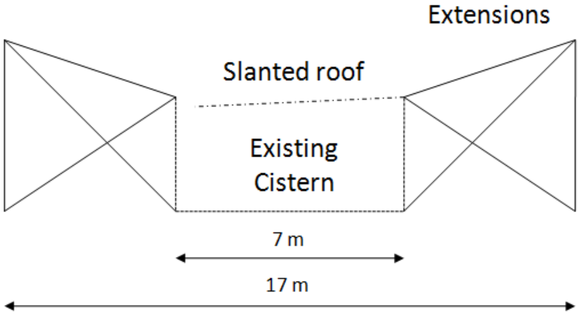

Figure 1: Proposed Cistern Design

3.3 Collection and Cistern Retrofitting

Perhaps the most important aspect of rainwater collection is proper collection and storage. One of the two villages currently has an existing cistern that can store approximately $100\,m^3$ of water (dimensions are about $7\,m \times 7\,m \times 2\,m$). Unfortunately, this cistern is in a state of disrepair - there are cracks in the concrete walls which result in water seepage and the pumps are broken. However, given adequate renovation, this cistern can be made into a a proper water storage system.

From the picture and information provided by Amy Smith, it appears that the cistern structure is sound and that the main issue is small cracks. These can be sealed using common commercially available sealants that are fairly low cost[12].

Once the cistern cracks are taken care of, the entire structure can be completely water sealed by installing a pool vinyl liner. Standard swimming pools (both above ground and in ground) use vinyl liners to protect the pool itself as well as to prevent water seepage into the concrete structure (in ground) or to the pool wall (above ground). Installation of the vinyl liner could be done by local workers and the primary cost would be that of the liner. Assuming that cost of the liner is proportional to the amount of material, an estimate can be made by comparing to a standard pool liner. Note that many liners are custom made to fit a given pool so getting one made to fit the cistern should not be an issue and should not alter the cost substantially.

The internal surface area of the cistern, neglecting the roof, is approximately $105\,m^2$. This surface area corresponds closely to a pool of dimensions, $16' \times 32' \times 6'$, and a corresponding vinyl liner costs approximately \$900[13]. Adjusting for custom size as well as import, it can be estimated that the liner will cost \$1000.

Further modifications can be made to improve the effectiveness of the cistern. First, in order to increase the amount of water collected, extensions can be built around the top of the tank. Five meter long (horizontal distance) planks can be installed around the sides (see Fig. 1). These extensions would be supported with a simple wooden truss and corregated metals sheets, which can be built using local materials and labor.

These extensions increase the effective dimensions of the cistern to $17\,m \times 17\,m$, which increases the amount of water that can be collected by nearly a factor of 6.

Overflow is not a problem since the rate at which people would be withdrawing water would be more than sufficient to ensure the cistern does not exceed capacity.

The roof of the cistern should also be modified. The existing roof should be replaced with a simple corregated metal structure that would be installed at an angle to force all of the collected water to enter the cistern from a single location. This closed roof design helps prevent large debris from entering the cistern. Also, a small opening is easier to filter than a large opening.

Cleaning of the cistern and wood extensions would be necessary, but this could be done prior to rainy season when the cistern is empty.

3.4 Treatment: Chlorination and Filtering

3.4.1 Chlorination

When water enters the collection area it is routed to a small entrance fitted with a particulate strainer, that can me made of a cheesecloth or something similar. After passing through the cloth the water moves through a chlorination column where solid chlorine is dissolved in a controlled amount based on the volume flow rate of water that passes through it. There are a number of commercial products available for this purpose which allow fine control of chlorine concentration in the incoming water. One such product is the Chemilizer HN55 Water Powered Chemical Injector available from Genesis Water Tech for $250[14]. This device is particularly suited for this application because it allows metering without electricity.

According to the American Society of Hygiene and American Public Health Association, the highest level of bacterial contamination requires a level of free chlorine of at least $1.5\,ppm$ to kill the most resistant viruses in $30\,min$[15]. To kill the most resistant protozoa in that time requires $1.36\,ppm$[16]. Therefore our system needs to maintain a concentration of free chlorine in the water up to $2.0\,ppm$. This concentration will kill most contaminants and is also safe for drinking consumption as recommended by the US EPA[17].

The total amount of chlorine per year is measured by taking the total mass production of rainwater per year from Table 10 and multiplying it by the concentration required. Since chlorine comes as liquid sodium hypochlorite, which contains 12% free available chlorine the amount needs be divided by 0.12. The total chlorine in liquid form required is $7.7\,kg$ per year, taking into account a safety factor of 1.25 and an average residence time of the chlorine of $30\,mins$.

3.4.2 Filtering

When the user is ready to consume water from the cistern. It needs to be removed from the bottom of the cistern to maximize the residence time of the free chlorine. Since small debris the water may not have completely settled by the time the water is needed, it needs to be run though a sand filter. Sand filters are commonly available and easy to clean and maintain. To overcome the pressure drop in a sand filter a hand pump can be used to remove the water and filter it before being dispensed into a bucket. Because the pressure of sand filtration is very low, hand pumping would be possible. Commercial Sand Filters are widely available and can be purchased easily, perhaps even in Haiti. One such a device is the Hayward E3307 High Capacity Sand Filter[18], which has a maximum pressure drop of $3.34\,bar$ when it is dirty. These filters are easy to backwash and maintain, as they require no electronics, and can use beach sand as a filtration material.

3.4.3 Costs

Table 11 summarizes the costs of the filtration and purification system.

Table 11: Cost of A Rainwater Filtration and Purification System

Item	**Cost**
Concrete Sealant	< \$70.00
Wood and Corregated Metal Sheets	local cost
Vinyl Liner	\$1000
Sand Filter	\$300.00
Chlorinator	\$250.00
Hand Pump	\$50.00
Piping, Misc	\$25.00
Chlorine - Per kg	$0.55\,kg$
Percetage Free Chlorine	12%
Chlorine Reqired Per Year	\$7.70
Cost Per 10 years	\$42.35
Total - 10 year lifetime	**\$1737.35** +local materials

Costs are taken from market prices for most components as well as estimations for the cost of locally available materials. The only components that would need importation would be the chlorinator and filter, and perhaps the liquid chlorine stock. Since the cost of this system is low this could be provided in a single lump sum as a charitable activity.

4 Conclusions and Recommendations

Given the extreme poverty of Haiti and the fact that cost is the primary barrier to desalinating water, designing a free freshwater source to serve the entire population is not possible. It is however possible to purify acceptably clean water for a lower cost than what is currently being provided to residents at the pump stations. To accomplish this goal RO is clearly the best technology. Thermally driven processes rely on an abundance of natural resources, such as coal, or abundant renewable resources like the sun. However, Haiti lacks these resources forcing any thermal process to be driven by expensive imported diesel fuel. RO is not thermally driven and is much more energy efficient when compared to thermal processes, making diesel fuel use in this process very cost competitive. The main risks for RO are the large capital expense which requires financing and long pay-off times, as well as being very technologically sophisticated necessitating replacement parts from outside of the country. Therefore an RO plant needs sustained operation for a long time to be financially viable. If the establishment of a high capacity RO plant is outside of the price range of an organization wishing to create pure water, making use of rainwater collection and treatment is also easily possible. Haiti, is a very rainy country and storage of water has been attempted in the past. Making use of an existing cistern by repairing it and expanding its collection area with a simple structure, as well as putting in a cheap treatment system in place will result in a source of fresh water to meet the drinking needs of part of the population. This is a more cost effective solution that does not meet every need but is a definite step in the right direction to provide clean water for Phaeton and Paulette.

A HDH Calculations

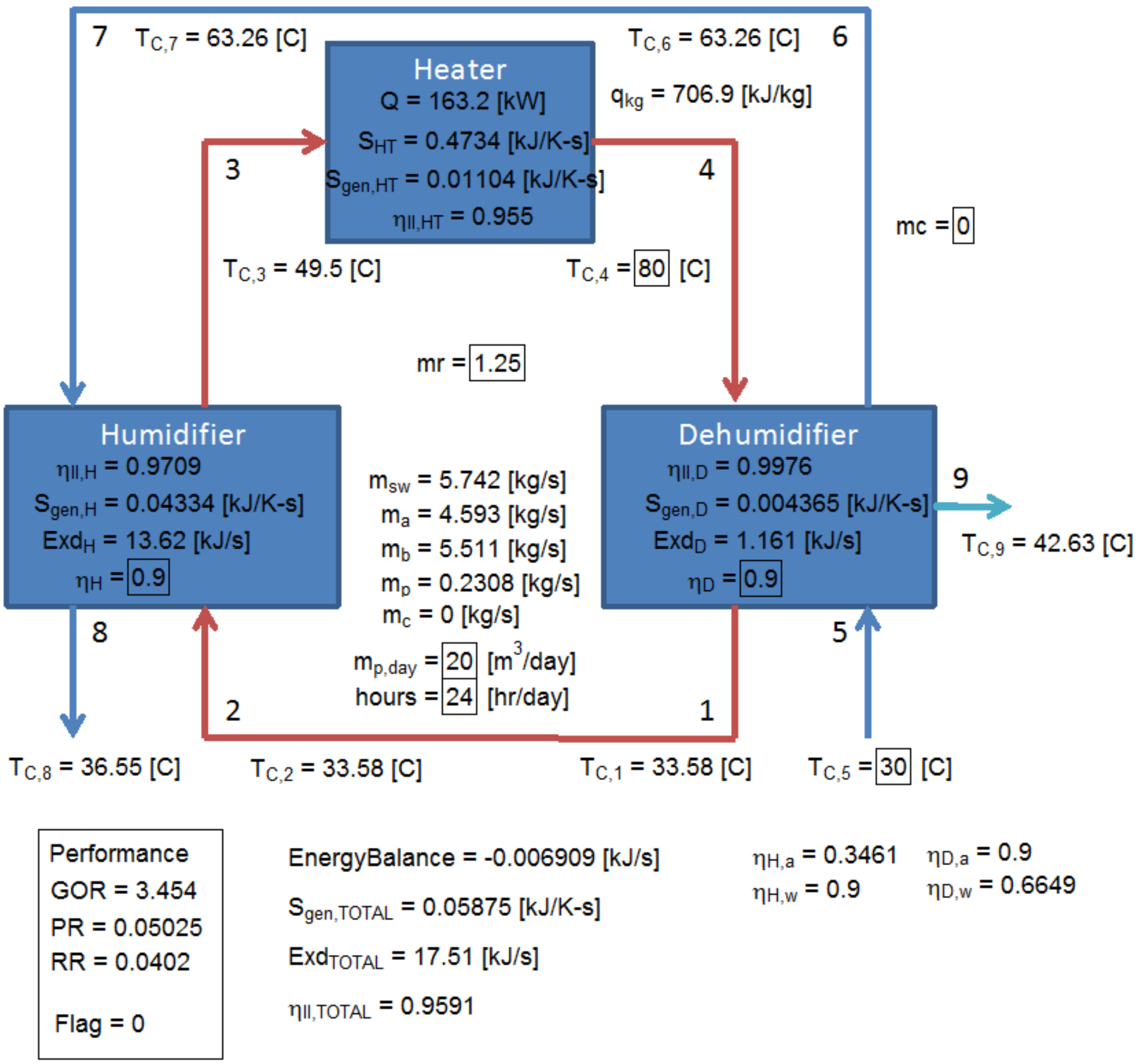

Figure 2: Closed Air, Open Water, Air Heated (CAOW-AH) Cycle

The above figure and calculated values was created using Engineering Equation Solver (EES). The cycle is solved on the assumption that it will be running 24 *hours* a day, which is accomplished by using a diesel generator to provide the required heat input. Streams 1-4 are humid air, streams 5-7 are sea water, stream 8 is brine and stream 9 is product.

B RO Calculations

SWRO Calcs

System Data

$p_2 := 61 \cdot \text{bar}$

$p_3 := 59.7\text{bar}$

$p_1 := 1.\text{bar}$

$p_4 := p_1$

$PPM_{feed} := 35000 \frac{\text{mg}}{\text{kg}}$

$V_{dotp} := 20 \frac{\text{m}^3}{\text{day}}$

$R_p := 0.50$

$\eta_p := 0.86$

$\eta_t := 0.86$

$\eta_m := 0.94$

$n_{modu} := 1$

$A_m := 36.8\text{m}^2$

$A := 1.3 \frac{\text{L}}{\text{m}^2 \cdot \text{hr} \cdot \text{bar}}$

$SR_{spec} := 0.998$

assume constant density $\rho := 1000 \frac{\text{kg}}{\text{m}^3}$

$T_{mix} := 303 \cdot \text{K}$

$J_{test} := 34 \frac{\text{L}}{\text{m}^2 \text{hr}}$

$B := (1 - SR_{spec}) \cdot J_{test}$

Temperature Correction Factor

$$TCF := \exp\left[-2700 \cdot \text{K} \cdot \left(\frac{1}{T_{mix}} - \frac{1}{298 \cdot \text{K}}\right)\right]$$

$TCF = 1.161$

$B := B \cdot TCF$

$A := A \cdot TCF$

multiply the given membrane parameters by the TCF

membrane parameters (temp corrected)

$\boxed{B = 7.897 \times 10^{-5} \cdot \frac{\text{m}}{\text{hr}}}$

$\boxed{A = 1.51 \times 10^{-3} \cdot \frac{\text{m}^3}{\text{m}^2 \text{hr} \cdot \text{bar}}}$

Flow Rates

$$V_{dotIN} := \frac{V_{dotp}}{R_p} = 40 \frac{\text{m}^3}{\text{day}}$$

$$c_{sf} := \frac{PPM_{feed}}{M_{NaCl}} \cdot \rho \qquad c_{sf} = 598.905 \frac{\text{mol}}{\text{m}^3}$$

$$c_{sc0} := \frac{V_{dotIN} \cdot c_{sf}}{V_{dotIN} \cdot (1 - R_p)} \qquad c_{sc0} = 1.198 \times 10^3 \frac{\text{mol}}{\text{m}^3}$$

find concentration at the end (retentate) assuming no salt in permiate (this will be checked later)

$$mNaCl_c := \frac{c_{sc0}}{\rho} \qquad mNaCl_c = 1.198 \frac{\text{mol}}{\text{kg}}$$

retentate molality

Osmotic Coiefficient

osmotic coieff from table

$\phi_f := 0.933$ $\qquad \phi_c := 0.933$

OR

lookup osmotic coiefficent from table and inerpolate

$$\phi_{m0.5} := \left(\frac{0.923 - 0.921}{200\text{bar} - 1\text{bar}}\right) \cdot (p_2 - 1\text{bar}) + 0.921$$

$$\phi_{m0.75} := \left(\frac{0.929 - 0.926}{200\text{bar} - 1\text{bar}}\right) \cdot (p_2 - 1\text{bar}) + 0.926$$

$\phi_{m0.5} = 0.922$

$\phi_{m0.75} = 0.927$

interpolate between pressures

$$\phi_f := \left(\frac{\phi_{m0.75} - \phi_{m0.5}}{0.75 \frac{\text{mol}}{\text{kg}} - 0.5 \frac{\text{mol}}{\text{kg}}}\right) \cdot \left(\frac{c_{sf}}{\rho} - 0.5 \frac{\text{mol}}{\text{kg}}\right) + \phi_{m0.5}$$

$\phi_f = 0.924$

...and then between molalities

$$\phi_{m1} := \left(\frac{0.938 - 0.934}{200\text{bar} - 1\text{bar}}\right)\cdot\left(p_3 - 1\text{bar}\right) + 0.934$$

$$\phi_{m1} = 0.935$$

interpolate between pressures

$$\phi_{m2} := \left(\frac{0.986 - 0.979}{200\text{bar} - 1\text{bar}}\right)\cdot\left(p_3 - 1\text{bar}\right) + 0.979$$

$$\phi_{m2} = 0.981$$

$$\phi_c := \left(\frac{\phi_{m2} - \phi_{m1}}{2\frac{\text{mol}}{\text{kg}} - 1\frac{\text{mol}}{\text{kg}}}\right)\cdot\left(\frac{c_{sc0}}{\rho} - 1\frac{\text{mol}}{\text{kg}}\right) + \phi_{m1}$$

$$\phi_c = 0.944$$

...and then between molalities

Osmotic Pressure and Permeate Flux

$$\Pi_f := \phi_f\cdot R_{gas}\cdot T_{mix}\cdot\left(2c_{sf}\right)$$

$$\Pi_f = 27.872\cdot\text{bar}$$

$$\Pi_c := \phi_c\cdot R_{gas}\cdot T_{mix}\cdot\left(2\cdot c_{sc0}\right)$$

$$\Pi_c = 56.985\cdot\text{bar}$$

$$\Delta\Pi := \frac{\Pi_f + \Pi_c}{2}$$

$$\boxed{\Delta\Pi = 42.429\cdot\text{bar}}$$

$$\Delta P := \frac{p_2 + p_3}{2} - p_4$$

$$J_v := A\cdot(\Delta P - \Delta\Pi)$$

$$J_v = 25.545\cdot\frac{\text{L}}{\text{m}^2\text{hr}}$$

New Salt Rejection and Salt Flow in Permiate

$$SR := 1 - \frac{B}{J_v}$$

$$SR = 0.9969$$

$$c_{spA} := \left(\frac{c_{sf}}{R_p}\right)\left[1 - \left(1 - R_p\right)^{(1-SR)}\right]$$

$$c_{spA} = 2.564\frac{\text{mol}}{\text{m}^3}$$

salt concentration

$$J_s := B\cdot\left(c_{sf} - c_{spA}\right)$$

$$J_s = 1.308\times10^{-5}\frac{\text{mol}}{\text{m}^2\cdot\text{s}}$$

Number of Membranes

$$J_{vessel} := n_{modu}\cdot A_m\cdot J_v$$

$$J_{vessel} = 22.562\cdot\frac{\text{m}^3}{\text{day}}$$

$$\frac{V_{dotp}}{J_{vessel}} = 0.886$$

$$n_{vessel} := 1$$

to obtain number of pressure vessels

$$J_{Svessel} := n_{modu}\cdot A_m\cdot J_s$$

$$J_{Svessel} = 41.591\cdot\frac{\text{mol}}{\text{day}}$$

$$A_{tot} := n_{vessel}\cdot n_{modu}\cdot A_m$$

$$A_{tot} = 36.8\,\text{m}^2$$

total membrane area

Outgoing Salt Concentration

$$PPM_p := \frac{c_{spA}}{\rho}\cdot M_{NaCl}$$

$$PPM_p = 149.826\cdot\frac{mg}{kg}$$

final concentration of salt in permiate
yes it meets requirements

$$c_{sc} := \frac{V_{dotIN}\cdot c_{sf} - V_{dotp}\cdot c_{spA}}{V_{dotIN}\cdot\left(1 - R_p\right)}$$

$$c_{sc} = 1.195\times 10^{3}\,\frac{mol}{m^{3}}$$

concentration of salt in retentate
(constant densities cancel)

$$PPM_c := \frac{c_{sc}}{\rho}\cdot M_{NaCl}$$

$$PPM_c = 6.985\times 10^{4}\cdot\frac{mg}{kg}$$

$$m_{sc} := \frac{PPM_p}{M_{NaCl}}$$

$$m_{sc} = 2.564\times 10^{-3}\,\frac{mol}{kg}$$

$$\Pi_p := 0.934\cdot R_{gas}\cdot T_{mix}\cdot\left(\rho\cdot 2\cdot\frac{PPM_p}{M_{NaCl}}\right)$$

$$\boxed{\Pi_p = 0.121\cdot bar}$$

this is the osmotic presure contrib from the small amount of salt in the permiate is 3 orders of magnitude below the osmotic pressure therefore we can neglect

Energy Usage Calcs

$$P_{rqd} := \left(p_2 - p_1\right)\cdot V_{dotIN}$$

$$P_{rqd} = 2.778\cdot k\cdot W$$

required to pressurize the inlet stream

$$P_{avail} := \left(p_3 - p_4\right)\cdot V_{dotIN}\cdot\left(1 - R_p\right)$$

$$P_{avail} = 1.359\cdot k\cdot W$$

available from the pressurized concentrate stream

$$P_{shaft} := \eta_t\cdot P_{avail}$$

$$P_{shaft} = 1.169\cdot k\cdot W$$

at turbine shaft

$$P_{pumpRqd} := \frac{P_{rqd}}{\eta_p}$$

$$P_{pumpRqd} = 3.23\cdot k\cdot W$$

power required at the pump shaft

$$P_{motor} := P_{pumpRqd} - P_{shaft}$$

$$P_{motor} = 2.061\cdot k\cdot W$$

$$P_{electric} := \frac{P_{motor}}{\eta_m}$$

$$P_{electric} = 2.193\cdot k\cdot W$$

net electric power consumption
of system

Diesel Motor Calcs

$$SFC := 0.240\,\frac{kg}{k\cdot W\cdot hr}$$

Average diesel engine specific fuel consumption

$$USD := 1$$

$$\rho_{fuel} := 0.85\,\frac{kg}{L}$$

deisel density

$$VFC := \frac{SFC}{\rho_{fuel}} = 0.282\cdot\frac{L}{k\cdot W\cdot hr}$$

volumetric fuel consumption

$$\boxed{DFC := P_{pumpRqd}\cdot VFC = 5.782\cdot\frac{gal}{day}}$$

daily fuel consumption for RO system - wthout energy recover to elimnate complexity - motor connected directly to pump shaft

$$F_c := 3.00\cdot\frac{USD}{gal}$$

$$FuelRate := DFC\cdot F_c = 17.346\cdot\frac{USD}{day}$$

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