Exploring Water Filtration Methods for Implementation in Rural Mozambique

Cole Glasson

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Acceptance of Senior Honors Thesis

This Senior Honors Thesis is accepted in partial fulfillment of the requirements for graduation from the Honors Program of Liberty University.

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Thomas Eldredge, Ph.D.
Thesis Chair

____
John Vadnal, Ph.D.
Committee Member

____
Christopher Nelson, M.F.A.
Assistant Honors Director

____
Date

Abstract

Of Mozambicans living in rural areas, nearly two-thirds are without access to clean drinking water sources, leading to waterborne diseases and diarrhea. Thus, a great need exists for an effective and sustainable water treatment solution for rural Mozambicans. Boiling, solar disinfection, and membrane-based processes are analyzed with respect to their effectiveness and economic sustainability in an attempt to propose a solution to those living in rural Mozambique. The most sustainable option is membrane-based processes, with two particular systems showing the most promise: Skyhydrant™ and LifeStraw®. These two ultrafiltration system are extremely effective at retaining almost all forms of bacterial and viral contaminants in source water and provide clean water at a rate of $0.0001/L (Skyhydrant™) and $0.0011/L (LifeStraw®).

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Introduction

According to the National Academy of Engineering (NAE), lack of access to clean water is responsible for more deaths worldwide than war. It is estimated that nearly 5,000 children worldwide die every day from diarrhea-related diseases, all resulting from lack of access to safe drinking water. Due to the extensive nature of this issue, the NAE has classified access to clean water as one of its 14 grand engineering challenges in the 21st century. Over the past few decades, new technology has been developed that seeks to provide sustainable and affordable solutions to those without access to potable water. Three methods that have emerged as viable solutions to this challenge include boiling, solar disinfection (SODIS), and membrane-based water technologies. Through statistical data on microbiological effectiveness and economic analysis, the effectiveness and sustainability of these three methods will be examined with intentions of recommending a sustainable small-scale solution for developing communities living in Mozambique.

Background

Clean Water Crisis in Mozambique

According to World Vision, Mozambique is listed as one of the top ten nations that lacks access to clean water (Reid, 2020). Research has shown that 52.7% of the nation's population lacks access to basic water services and 63% of the rural population is living without improved drinking water sources (Elstrott, 2015; Reid, 2020). According to the World Health Organization, "Improved drinking-water sources are defined as those that are likely to be protected from outside contamination, and from fecal matter in particular." Some examples of improved drinking-water sources include household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater.

A large factor contributing to the clean water crisis in Mozambique is lack of wealth. The nation is listed as one of the 10 poorest countries in the world, with a GDP per capita of only $313 and 78.4% of the population living on less than $2/day (Arnal et al., 2010, p. 614). Additionally, only 60% of the wealthiest rural population of Mozambique have access to improved drinking water and 48% of all rural Mozambicans use other unimproved sources (UNICEF, 2015).

Despite its lack of access to clean water, Mozambique is rich in water supply compared to other nations as it has 104 river basins, some of which are depicted in Figure 1 (Elstrott, 2015). However, rural areas are dispersed and suffer from poverty, resulting in a lack of access to improved water sources and water infrastructure. These factors highlight the importance of a clean water solution that is effective, economical, and sustainable.

Figure 1. Map depicting geography and rivers of Mozambique (Encyclopædia Britannica, 2015)

Boiling

Boiling is one of the technologically simplest methods for treating contaminated drinking water. This method of water decontamination dates back to ancient times and is still a widely practiced method today in many parts of the world (Sobsey, 2002, p. 13). This process involves using a fuel to heat water to temperatures sufficient to destroy waterborne pathogens. In fact, a rolling boil is more than sufficient in terms of temperature to effectively pasteurize contaminated water. The reason water is often brought to a boil is because this is a visual way of knowing that the water has reached a sufficient temperature for decontamination. Heating water to a temperature as low as 60 degrees Celsius (140 degrees Fahrenheit) for a period of ten minutes is sufficient to destroy most dangerous waterborne pathogens. The problem with this method of thermal pasteurization is that not many households that practice boiling for water decontamination have access to or can afford a thermometer to measure the temperature of the water.

There are certain disadvantages associated with the practice of boiling. One of these is the post-treated water's susceptibility to recontamination from hands and utensils (Clasen et al., 2008, p. 407). This is due to the water's lack of residual disinfection as well as the fact that it is commonly stored in open vessels. It is best for boiled water to be stored in the same container in which it was treated and consumed soon after treatment or within the same day (Sobsey, 2002, p. 14).

Despite boiling's effectiveness and ease of use, it is not a sustainable practice for water decontamination. The major reason for this is the cost of fuel: approximately 1 kilogram of wood is necessary to boil 1 liter of water (Sobsey, 2002, p. 14). Fuel is either obtained through purchase or direct labor. Regardless of how it is acquired, it is a major contributor to the cost and effort required to sustain this method of water purification. Despite its ancient heritage, ease of use, and effectiveness, boiling alone is not a viable solution for a sustainable water treatment method for developing countries. However, if the concept of thermal pasteurization can be paired with some renewable energy method, such as solar energy, sustainability could possibly be achieved.

SODIS

Solar disinfection (SODIS) is another technologically simple and widespread method for disinfecting contaminated water. This method utilizes polyethylene terephthalate (PET) bottles (clear plastic water bottles) and exposure to heat as well as the sun's UV rays in order to inactivate waterborne microbes (Sobsey, 2002, p. 15). This is a much more economic alternative than boiling, as the only costs associated with this method are acquisition of water bottles. However, compared to the ongoing cost of purchasing fuel for boiling, this is a very economic option.

The SODIS disinfection process is very simple. If the water that is to be treated is turbid (>30 NTU[1]), it must first be filtered, as this method is not as effective on excessively turbid water (Sobsey, 2002, p. 15). Once the water is of sufficient turbidity, it is then poured into the water bottles, shaken vigorously for oxygenation, and then exposed to the sunlight for about 5 hours (or 2 days if cloudy). While each bottle is only capable of treating 1-2 liters of water, numerous bottles can be exposed to sunlight at a time and thus this method can produce substantial amounts of clean water for drinking purposes.

[1] NTU: Nephelometric turbidity unit, a unit used to measure turbidity, or the amount of suspended particles in water

Membrane-Based Technology

Membrane-based technology comes in many different forms but is characterized by some force that drives filtration such as pressure, temperature, or osmotic differences across a membrane (Mulder, 2010). In relation to boiling and SODIS, membrane filtration processes are a relatively new water treatment method. In recent decades, much research has been given to developing membrane technologies and has resulted in decreased membrane costs and energy requirements (Churchhouse & Wildgoose, 2000).

The advantages of membrane filtration processes are their small footprint and their single-stage treatment (Peter-Varbanets et al., 2009, p. 253). However, these methods are often plagued by membrane fouling and thus require routine maintenance to be kept effective. There is no single membrane filter that works for every situation, but due to the wide variety of options available, a membrane filtration process can be tailored to a specific group of people and thus be optimized for cost and sustainability.

Effectiveness

Boiling

If performed correctly, boiling is one of the most effective water treatment methods for developing countries (Clasen et al., 2008, p. 407). When contaminated water reaches sufficient temperatures, all waterborne pathogens are killed or deactivated, including bacterial spores and protozoan cysts that are not killed off by chemical disinfection as well as microscopic viruses that mechanical filtration fails to remove. Another way that boiling outperforms other treatment methods is that it is independent of turbidity and other dissolved constituents, meaning there is no pretreatment necessary prior to boiling the water. While pretreatment is not a factor that influences the effectiveness of boiling, water of excessive turbidity may be filtered prior to treatment to make it more palatable.

There have been numerous studies conducted in various parts of the world on the microbiological effectiveness of boiling at the household level. Each of these studies varies on multiple fronts such as source water quality, economic demographics, and boiling practices. One particular study that was conducted on an urban population in the developing nation of Zambia showed that water treated by boiling was no more likely to be free of fecal contamination when compared to the source water (Psutka et al., 2011, p. 6099). In this study, 60% of the water samples collected after being treated with boiling fell in the "low-risk" category of less than 10 TTC/100 mL of water, which includes the 38% of samples that were found by WHO to be compliant with safe drinking water recommendations at <1 TTC/100 mL.[2] Moreover, 20% of the drinking samples were considered to be "high" or "very high" risk which corresponds to 100-1000 TTC/100 mL and 1000+ TTC/100 mL, respectively. The remaining 20% of samples fell in the "medium-risk" category of 10-100 TTC/100 mL. Interestingly, 55% of the samples collected at the source were compliant with WHO recommendations, compared to the 38% of compliant samples collected from the treated water. The results of the study showed that drinking water treated by boiling has a geometric mean of 7.2 TTC/100 mL while the source water had a mean of 4.0 TTC/100 mL, meaning that the treated water had a worse microbiological quality than the source water.

[2] Thermotolerant coliform bacteria (also known as fecal coliforms) are often used as representatives of fecal pollution as they behave in a similar manner to most pathogenic bacteria and are easy to identify (Cisneros, 2011, p. 159).

There are some important considerations to keep in mind with this study, however. First of all, the microbiological quality of the source water was quite high at only 4 TTC/100 mL. This shows that the average quality of source water in this scenario was considered by WHO to be "low-risk". Because the quality of source water was comparatively high, this limited the potential improvement from boiling. Additionally, one of the major disadvantages of boiling, which likely played a role in the results of this study, is the possibility of recontamination subsequent to treatment. All the participants in the study reported transferring the treated water once boiled and 51% of participants transferred treated water by directly dipping a vessel into the container and thus exposing the treated water to contaminants. The study found that the number of individuals in a household has a strong correlation with the drinking water quality, suggesting that more individuals may dip their hands into the drinking vessel and contaminating the water. Using a drinking cup to transfer treated water had a strong association with drinking water quality, according to this study.

Another study conducted in rural Guatemala examined the microbiological effectiveness of boiling in a very similar manner to Psutka et al. This study, however, found that boiling resulted in an 86.2% reduction in the geometric mean TTC and 71.2% of stored water samples from self-reported boilers satisfied the WHO guidelines for safe drinking water (0 TTC/100 mL) (Rosa et al., 2010, p. 473). Only 4.9% of the samples fell in the high-risk category and no samples contained more than 1,000 TTC/100 mL, compared to the 20% of sample categorized as high-risk in Psukta et al. On the contrary, 23.7% of the source water samples in this study were free of TTC and 21.4% were classified as high risk, compared to 55% and 10%, respectively in Psutka et al. This demonstrates that in the study conducted in Guatemala, the source water was of considerably poorer microbiological quality, leaving much more room for microbiological effectiveness of boiling. Two other studies conducted in India and Vietnam showed that the practice of boiling had 99% and 97% reduction in microbiological contaminants (Clasen et al., 2008, p. 407; Clasen et al., 2008, p. 4255). The results from studies conducted by Psutka et al. and Roas et al. are given below in Tables 1 and 2, respectively.

Table 1: Geometric Mean TTC Counts in 100 mL Samples of Drinking and Source Water (Psutka et al., 2011, p. 6099

		drinking		source		Drink:Source geometric mean ratio[a]		
	N	mean	95% CI	mean	95% CI	ratio	95% CI	p-value
week 1								
all	52	4.1	(2.4−7.0)	9.1	(5.0−16.7)	0.5	(0.3−0.8)	<0.01
boiled on day	33	2.8	(1.6−4.8)	14.5	(6.83−30.6)	0.2	(0.1−0.4)	0.0001
week 2								
all	50	7.2	(3.5−14.6)	5.3	(2.8−10.0)	1.4	(0.73−2.5)	0.33
boiled on day	33	4.3	(1.9−9.8)	4.4	(2.01−9.43)	1.0	(0.4−2.4)	0.98
week 3								
all	49	10.7	(5.1−22.3)	2.4	(1.6−3.7)	4.3	(1.9−9.6)	<0.001
boiled on day	30	12.0	(4.3−33.6)	2.4	(1.4−4.3)	4.6	(1.4−14.9)	0.01
week 4								
all	49	10.2	(5.1−20.3)	3.4	(1.9−5.9)	3.0	(1.3−6.8)	<0.01
boiled on day	28	10.9	(4.2−28.5)	2.6	(1.4−5.0)	4.1	(1.5−11.6)	<0.01
week 5								
all	49	6.4	(3.2−12.9)	2.4	(1.5−4.0)	2.7	(1.5−4.8)	0.001
boiled on day	25	5.0	(2.0−12.6)	1.7	(1.1−2.9)	2.9	(1.1−7.6)	0.04
all[b]								
all	249	7.2	(5.4−9.7)	4.0	(3.1−5.1)	1.8	(1.3−2.5)	<0.001
boiled on day	149	5.9	(4.0−8.6)	4.0	(3.1−5.1)	1.5	(1.0−2.3)	0.08

[a] Drink:Source geometric mean ratio indicates the difference between contamination levels observed in drinking vs source water. A contamination level >1 indicates that drinking water was more contaminated than source water. [b] Reporting the ratios of all water samples were adjusted for clustering.

Table 2: Geometric Mean TTC Counts in 100 mL Samples of Drinking and Source Water (Rosa et al., 2010, p. 476)

	Source water			Drinking water			Log reduction of TTC			
	N	Mean	95% CI	*N*	Mean	95% CI	*N* pairs	Mean difference	95% CI	*P* value
Round 1	48	17.1	9.23–31.74	44	1.8	1.17–2.67	44	1.02	0.74–1.31	< 0.001
Round 2	48	13.6	7.04–26.24	45	2	1.21–3.22	45	0.81	0.51–1.12	< 0.001
Round 3	44	12.2	6.40–23.21	41	2.1	1.32–3.34	41	0.71	0.38–1.04	< 0.001
Round 4	44	22.8	11.89–43. 77	41	2.3	1.40–3.92	41	1.01	0.66–1.36	< 0.001
Round 5	40	15.3	7.53–31.14	35	2.8	1.56–5.03	35	0.84	0.49–1.18	< 0.001
All	224	15.8	11.88–21.04	206	2.1	1.73–2.65	206	0.88	0.74–1.02	< 0.001

*TTC = thermotolerant coliforms; CI = confidence interval.

Each of these studies shows that the effectiveness of boiling is highly dependent on the source water quality and the measures used to store and transfer the treated water. If practiced properly, boiling does have the potential of being a safe water treatment method, especially for those in developing nations such as Mozambique.

SODIS

Overall, SODIS is a very effective method at treating microbiologically contaminated water. There are, however, many factors that influence the effectiveness of this method: type of microbe, water vessel, environmental effects such as sunlight and ambient temperature, vessel placement and orientation, mixing of vessel, solar collection/reflection, water quality, water aeration, and exposure time (Sobsey, 2002, p. 17). The main factor that drives the effectiveness of this method is the synergistic effects of both UV radiation in the UV-A range (320 to 400 nm) and heating to temperatures of 50-60° C. Temperatures of this degree alone are high enough to inactivate 99.9% of most enteric viruses, bacteria, and parasites in a matter of a few hours. The combined effects of UV radiation and heat produces a greater inactivation of harmful microbes than each agent alone.

Studies have shown that various bacteria (fecal coliforms, E. coli, and enterococci) and viruses (coliphage f2, rotavirus, and EMC) are reduced by several orders of magnitude when exposed to UV rays from sunlight for several hours and sufficiently high temperatures are reached (Sobsey, 2002, p. 16). Additionally, oxygenation is a very important factor in the effectiveness of SODIS. For example, Reed demonstrated in *Solar inactivation of faecal bacteria in water: the critical role of oxygen* that aerated water experienced a 99.9999% reduction in E. coli and enterococci while an unaerated bottle only experienced a 90-99% reduction in the same bacteria (1997, p. 278). It has also been shown that periodically vigorously shaking the water increases exposure of microbes to oxygen molecules and increases microbial inactivation.

Another study by Sobsey et al. (2008, p. 4262) shows that SODIS effectively reduces bacteria, viruses, and protozoa by a log-reduction value (LRV) of 3, 2, and 1, respectively (99.9%, 99%, and 90%) under baseline conditions. According to Sobsey et al. baseline conditions are those “typically expected in actual field practice when done by relatively unskilled persons who apply the treatment of waters to varying quality and where there are minimum facilities or supporting instruments to optimize treatment conditions and practices.” When performed in idealized conditions, where treatment is optimized by skilled laborers with instrumentation that is capable of maintaining high levels of performance in waters of varying quality, SODIS is capable of realizing a 5.5+, 4+, and 3+ LRV in bacteria, viruses, and protozoa, respectively. Regardless of idealized or baseline conditions, SODIS has shown to be very effective at significantly reducing the possibility of illness from drinking microbiologically contaminated water.

One factor that has a significant influence on the effectiveness of SODIS for water decontamination is turbidity. SODIS is not nearly as effective at inactivating harmful contaminants when its turbidity is greatern than 30 NTU. In these instances, SODIS can be coupled with some mechanical filtration method to reduce the turbidity of the source water to a level in which SODIS becomes effective. Reed (1997, p. 185) in *Innovations in solar water treatment* suggests that when water is of excessive turbidity, one should perform small-scale rapid sand filtration on the water before carrying out the SODIS process. This pre-treatment process is depicted in Figure 2. This process will remove a portion of the harmful microbes, but its primary purpose is to clarify the colored water so that subsequent solar photo-oxidation will be effective.

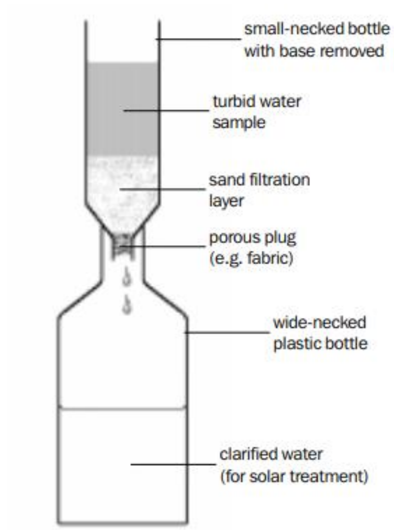

Figure 2. Simple small-scale rapid sand filtration system (Reed, 1997)

Membrane-Based Technology

Membrane-based technology can be characterized by the type of force that creates separation and drives filtration, such as pressure, osmotic, or temperature. This paper will look only at pressure-driven membrane processes, while other types of membrane-based systems have applications in areas such as disaster relief and other short term water filtration requirements. Pressure-driven membrane processes can be further broken down into the size of filter they utilize. These include microfiltration (MF), ultrafiltration (UF), nanofiltration (NF), and reverse osmosis (RO) (Mulder, 2010; Fane et al., 2011). Figure 3 breaks down the various membrane separation processes by pore sizes, molecular weight cut-off (MWCO) and sizes of solutes/particles, and Table 3 demonstrates the various properties of pressure-driven membranes by their pore size.

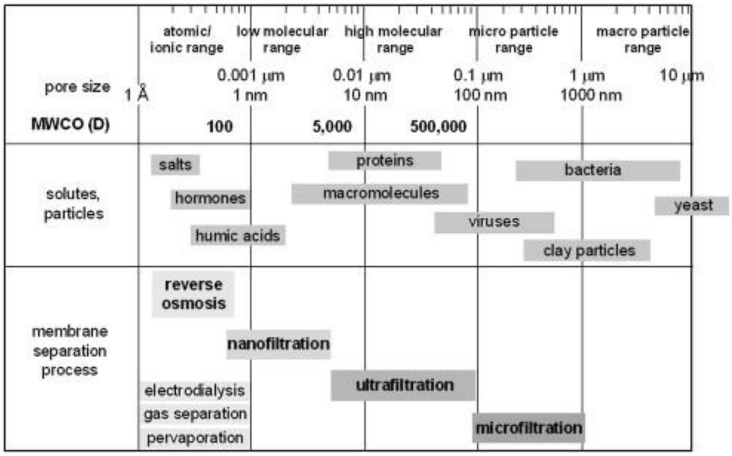

Figure 3: Driving forces and applications size range for membrane processes (Peter-Varbanets et al., 2009, p. 254)

Table 3: Pressure-driven membrane properties (Fane et al., 2011, p. 303)

	Microfiltration	*Ultrafiltration*	*Nanofiltration*	*Reverse osmosis*
Pore size (nm)	50–10 000	1–100	~2	<2
Water permeability ($l\,m^{-2}\,h^{-1}\,bar^{-1}$)	>500	20–500	5–50	0.5–10
Operating pressure (bar)	0.1–2.0	1.0–5.0	2.0–10	10–100
MWCO (Da)	Not applicable	1000–300 000	>100	>10
Targeted contaminants in water	Bacteria, algae, suspended solids, turbidity	Bacteria, virus, colloids, macromolecules	Di- and multivalent ions, natural organic matter, small organic molecules	Dissolved ions, small molecules
Membrane materials	Polymeric, inorganic	Polymeric, some inorganic	Thin-film composite polyamide, cellulose acetate, other materials (Schafer *et al.*, 2005)	Thin-film composite polyamide, cellulose acetate

The smaller the pore size, the smaller the molecules that the filter will remove and thus the more effective the membrane process will be. However, as the pore size decreases, the energy requirements, in this case, the pressure, increases. Thus, systems like reverse osmosis may not be sustainable for rural parts of developing countries. Microfiltration and ultrafiltration will be of particular interest in the scenario of providing clean water to the rural parts of Mozambique, since these types of systems can be operated based on static pressure due to gravity.

It can be observed from Figure 3 that microfiltration does not totally entail the complete range of viral bacteria in terms of pore size. Most ceramic membranes utilized by developing countries have a nominal pore size of about 0.2 μm (Clasen et al., 2004). This provides complete protection from bacteria, but only partial protection from viruses, which range in size from 30-300 nm. While microfiltration membrane processes can provide considerably cleaner and safer water, it does not have the ability to provide a complete disinfection and protection against viral bacteria.

Ultrafiltration membrane processes are of much more interest in developing countries. According to Peter-Varbanets et al. (2009, p. 255), "most water-quality problems are due to pathogens, which are completely retained by ultrafiltration membranes." These filters do require greater energy needs due to their pore size and associated flow resistance but provide much greater protection against harmful viruses. There are many field studies that have been conducted that explored the effectiveness and cost of ultrafiltration membrane systems in developing countries. While the details of each of these small-scale systems differed in their design and construction, they all removed virtually all coliform from the feed water (Pryor et al., 1998; Hagen, 1998; Arnal et al., 2001; Arnal et al., 2002; Arnal et al., 2010). In terms of effectiveness at removing harmful microbiological contaminants, ultrafiltration membrane processes provide the best results of the presented methods in this paper.

Economics

Boiling

Despite boiling's ease of use and satisfactory microbiological removal effectiveness, it is a rather expensive method for treating contaminated water. While it has no investment cost other than a vessel for heating the water in, it has ongoing expenses that come in the form of purchased fuel or opportunity cost resulting from gathering fuel. The cost of fuel is going to depend on the method used for heating as well as the local fuel prices specific to the location of interest. Mozambique is about 77% forest and forest resources as well as charcoal make up about 80-90% of the energy consumed (Uamusse, 2019, p. 19). Additionally, only 18% of Mozambican households have access to electricity and 90% rely on traditional energy sources such as charcoal and firewood for domestic use (Mahumane et al., 2012) Thus, for this analysis, the cost of boiling will be based on local prices of charcoal, the most commonly used source of fuel for cooking purposes.

According to Vesterberg, the average price of a 75 kg bag of charcoal is $21 in Matola Rio, a sub-urban community located approximately 20 km west of the capital city of Mozambique (2014, p. 14). Of course, prices will vary depending on location and scarcity, but this serves as a baseline approximation of the price of boiling in Mozambique. By considering the average energy content of charcoal to be 30 MJ/kg, simple calculations can be done using heat capacity formula given below.

$$Q = mc_p\Delta T = \rho V c_p \Delta T \tag{1}$$

Equation (1) can be used to solve for the energy required to heat a given amount of water, in this case 1 liter, to 100°C from an assumed starting temperature of 20°C. The remaining parameters and results are displayed below in Table 4. From these calculations, it would cost on average $0.0207 to boil 1 L of water with charcoal in Mozambique.

Table 4: Calculations for Determining Unit Cost of Boiling in Rural Mozambique

Cost to Boil 1 L of Water Using Charcoal Calculations	
Energy Content of Charcoal [J/kg]	3.00E+07
Density of Water [kg/m^3]	997
Volume of Water [m^3]	0.001
Specific Heat of Water [J/kg-°C]	4181
Starting Temperature [°C]	20
Ending Temperature [°C]	100
Efficiency of Open Fire	0.15
Energy Required to Boil 1 L of Water Using Charcoal [J]	2223177
Mass of Charcoal Required to Boil 1 L of Water [kg/L]	7.41E-02
Average Price for 75 kg Bag of Charcoal [$]	$ 21.00
Unit Price of Charcoal [$/kg]	$ 0.280
Price to Boil 1 L of Water Using Charcoal [$/L]	$ 0.0207

With the average daily water needs per person for hydration and cooking being around 8 liters (Zuane, 1997, p. 575), this would mean that for the average household size of a family in Mozambique of 5.46 people (Global Data Lab), each family would spend about $0.73/day on boiling water. For the vast majority of rural Mozambicans, this amounts to almost a single day's earnings, which cannot all be spent on disinfecting water. Because of this, boiling is by no means a sustainable method of water purification when using fossil fuels or some other nonrenewable energy source.

SODIS

Compared to boiling, SODIS is an extremely economical water treatment method, with little to virtually no cost associated with the process. The only costs that might be associated include acquiring an initial supply of PET bottles and replacing those bottles as necessary. Supplies of PET bottles can come in many different forms, but in the context of rural areas, they are often treated as a commodity and thus sold in local markets anywhere from $0.02-0.20 (Luzi et al., 2016, p. 41). Assuming the worst-case scenario of a price per bottle of $0.20 and that this bottle holds 1 L of water, a family of 5 with necessary water needs of 8 L per person per day, this would amount to an initial cost of $8 per family. This $8 investment would provide enough clean water for the average family's daily cooking and hydration needs. Assuming a lifetime for each bottle of 12 months (SODIS, 2009), this investment would result in a price per liter of clean water of $0.0004. This is significantly less than the price per unit liter of water by boiling and does not require the constant purchase/collection of charcoal/fuel wood.

The SODIS process can be utilized year-round, as it is still effective even in cloudy conditions. However, under cloudy conditions, studies have shown that bottles need to be exposed for a period of about 48 hours in order to see similar effectiveness to that under sunny circumstances (Borde et al., 2016, p. 4). Thus, in Mozambique, which experiences a rainy season during the months of January to March, more water bottles would need to be supplied to make up for the longer disinfection periods or an alternate water treatment method would need to be utilized during this season.

Membrane-Based Technology

As discussed above pertaining to the effectiveness of membrane-based water treatment technology, ultrafiltration systems provide the best protection against microbiological contaminants for a small level of energy input (considering most UF systems are gravity fed). For this reason, only UF systems will be analyzed in terms of the economic sustainability of the system. In recent years, the cost of membranes has decreased significantly, making systems much more affordable and thus applicable to decentralized areas of developing nations like Mozambique (Hoa & Lesjean, 2008, p. 5). However, cost is still a significant factor in determining the feasibility and sustainability for a small-scale ultrafiltration system for a rural population.

There are two specific ultrafiltration membrane technologies that are of particular interest for implementation in rural areas of Mozambique. The first technology is called Skyhydrant™ by Skyjuice™ Foundation and is a portable ultrafiltration device weighing just 13 kg that, according to the product brochure, is capable of producing 10,000 L of clean water each day, sufficient for the domestic water needs of 500-1000 people (SkyJuice™ Foundation). This system can operate at 1 m of gravity head and does not require any electricity for operation. Unlike boiling and SODIS, this method of water filtration is a small-scale system capable of providing clean water to entire communities and villages. The filters in this system last up to 5-10 years without replacement. Some of the regular cleaning and maintenance procedures include a daily mechanical backwashing process that cleans membrane surfaces as well as a weekly/monthly chemical cleaning process that removes residual fouling and limits biological growth in the system. A single unit costs $3,500; however, with a lifetime of 10 years and virtually no maintenance cost, this unit is capable of providing clean water at a rate of $0.50 per person per year (Butler, 2009, p. 628). In other words, over its 10-year lifespan, this system is capable of producing clean water at a rate of $0.0001/L. The typical configuration of the Skyhydrant™ water filtration system is shown in Figure 4.

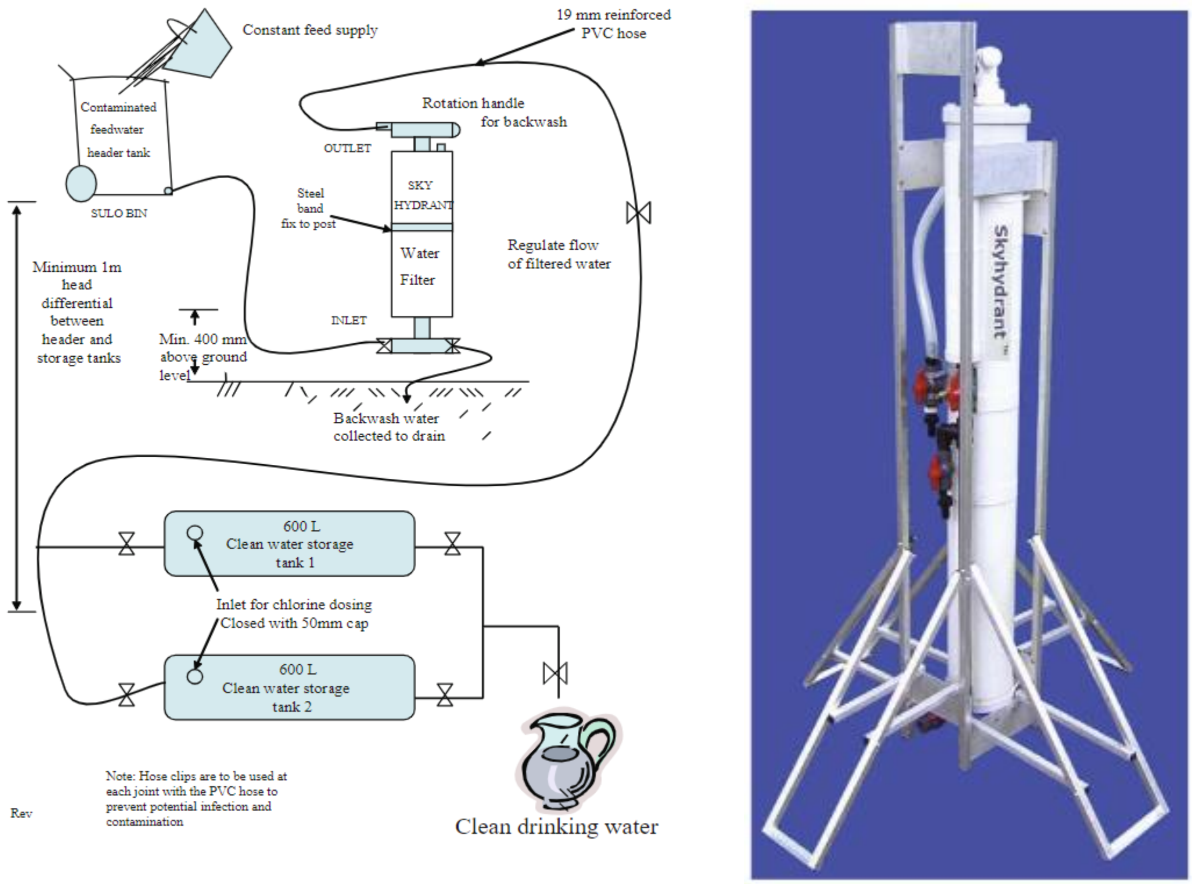

Figure 4: Configuration of Skyhydrant™ Water Filtration System (Butler, 2009, p. 625-625)

Another ultrafiltration device that shows great promise for providing a sustainable solution to low-income rural areas of Mozambique is the Vestergaard Fransen S.A.'s "LifeStraw® Family" (see Figure 5). Unlike Skyhydrant™, LifeStraw® is a point-of-use system (POU) that is applicable to providing individual households with clean water in the home. Similar to the Skyhydrant™, LifeStraw® is a gravity-fed system that is designed to meet internationally recognized levels for microbiological water purifiers and is capable of treating water of high turbidity (Clasen et al., 2009, p. 819). This system produces about 150 mL/min (9 L/hour) and has a lifetime of 18,000 L. In large quantities, this product is available for $20.00, and without any replacement parts or operational costs, is capable of producing clean water at a rate of $0.0011/L.

Figure 5: LifeStraw® schematic (Clasen et al., 2009, p. 820)

Proposed Solution

The water treatment method that is most effective will change from location to location. Each scenario has its own set of geographic and demographic factors that will render some solutions more effective and sustainable than others. For rural populations of Mozambique, specifically small communities and villages with populations ranging from 50-1000 inhabitants, it is necessary that a proposed solution is able to provide ample amounts of safe drinking water that is feasible economically over a long period of time. All of the methods discussed in this paper have shown to be very effective at treating microbiologically contaminated water when performed as intended. For boiling, this means bringing the water to a high enough temperature for a certain period of times and being careful not to re-contaminate the treated water through unsafe transfer methods. For SODIS, this means ensuring water has sufficiently low turbidity before exposing it to the sun by pre-treating it by filtering and exposing it to UV radiation for a sufficient amount of time. For membrane-driven processes, this means regular flushing and maintenance of filters to prevent clogging and to provide sufficient bacterial and viral removal.

While each of these methods can significantly decrease microbiological contamination and provide safe drinking water, not each of these methods is sustainable economically and socially. Despite its ease of use and long-standing reputation, the recurring cost of fuel for boiling renders it the most expensive alternative and thus least sustainable method of water decontamination presented. However, it is still a viable method in emergency situations when no other option for water treatment is available.

SODIS is a very economical alternative for water decontamination, as its only incurred cost is acquisition of inexpensive PET water bottles. However, this method is not the most sustainable when it comes to volume of water produced and social sustainability. When SODIS is implemented, it often requires educational training and promotion. Meierhofer and Landolt (2009) and Gurung et al. (2009) have highlighted key factors for success when implementing SODIS with sustainability in mind: commitment and authority of promotors, promotion frequency, visibility of SODIS in the community, availability of bottles, promotion materials, and an enabling environment. While SODIS is effective and economical, it is often times hard to sustain on a social level and therefore difficult to implement long-term.

The most promising of the methods presented are membrane-filtration technologies. This method of water decontamination has a reputation of being very costly; however, continued research and advancements related to this treatment method has led to decreased costs, increased effectiveness, and greater applicability to developing parts of the world. The type of membrane-filtration method varies significantly and is highly dependent on the local conditions of the area of implementation. Hoa and Lesjean (2008, p.11) state, "In order to provide sustainable access to safe water, membrane systems should then be well-adapted to local conditions, that is to say, low-cost, easy-to-maintain, robust and as far as possible independent of chemicals and energy supply." The two methods presented, namely the Skyhydrant™ and LifeStraw® Family both achieve sustainability according to the standards mentioned by Hoa and Lesjean. The Skyhydrant™ system is ideal for supplying clean water to a larger group of people, making it great for implementation in small villages of 250-1000 inhabitants. LifeStraw®, on the other hand, is a POU system that is ideal for supplying clean water to individual families in their own homes. This would be ideal for very remote areas of small communities less than 250 people. Each of these products have lifetimes of up to 10 years and little to no maintenance required. The LifeStraw® requires frequent backflushing, but this is performed by simply closing off the tap side, squeezing the hand pump three times, and opening the cock at the bottom of the cartridge to allow the backwash to be released (Clasen et al., 2009, p. 820). Both of these methods can be implemented at very low costs: $0.0001/L for Skyhydrant™ and $0.0011/L for LifeStraw®.

Government Programs and Implementation

It is one thing to research and propose a water treatment solution to those without access to clean water; however, the implementation of such strategies is often a very involved and can be a difficult process. In recent decades, many government and nonprofit projects have been undertaken that attempt to reduce poverty and improve access to clean water in the nation of Mozambique. The Millennium Challenge Corporation (MCC) enacted a five-year, $506 million project in 2007 that aimed at increasing the nation's economic growth and reduce poverty by investing in water supply, sanitation, and drainage projects (Elstrott, 2015, p. 8). As a result of this project, more than 614 rural water points were put in place, two municipal draining systems were upgraded and expanded, rural boreholes with hand pumps were established as improved water sources, and small-scale solar purification systems were made. This work resulted in a 23% increase of the rural population with access to improved water sources. Additionally, the consumption of improved water increased by 15.1 liters per person per day and the average trip time to a primary water source decreased by over 60 minutes.

One key entity that was established as a result of MCC's Water Supply and Sanitation project was the Administracao de Infra-estruturas de Agua e Saneamenta (AIAS). This government organization manages water supply and sanitation assets in 134 towns. While the Water Supply and Sanitation project concluded in 2013, the AIAS still exists and continues to manage water supply and sanitation assets (Elstrott, 2015, p. 8).

As of 2020, Mozambique had a population of about 31 million people, 62% of which lived in rural areas, or about 19 million people (Worldometer, 2020). With capabilities of producing up to 20,000 L of clean water each day, the Skyhydrant™ system would be able to support the drinking needs of up to 2,500 people. This would mean that 7,600 units would be necessary to support the total rural population of Mozambique. At $3,500 per unit, this equates to $26.6 million. This is simply the cost for acquiring the systems, and additional costs would be required for distributing the systems to villages around the nation as well as funding for educational programs required on operating and maintaining the system.

The LifeStraw® is capable of producing up to 9 L/hour of clean drinking water, which is more than enough for the average household's daily drinking needs in Mozambique. Assuming an average household size of 5.46 and a price per unit of $20.00, it would cost $69.6 million to acquire enough LifeStraws® to supply clean water for the rural population of Mozambique. These are very crude estimates, of course, but they give a good idea of the scale of funding necessary to implement these solutions for the rural population of Mozambique.

Points of Further Research

The research presented here is just the tip of the iceberg when it comes to exploring the various water decontamination methods available for developing nations. There are so many ways that each of the methods presented here can be made more effective and/or more sustainable; however, it is beyond the scope of this research to go into detail about all of the ways that this can happen. Instead, a brief overview will be given for a few alternatives to the methods presented here that can provide points of further research. One of the major drawbacks of boiling is the energy requirement necessary to reach microbial inactivation temperatures. However, it is possible to utilize renewable sources, particularly solar energy, to obtain temperatures that effectively provide safe drinking water. In a study conducted by Kang et al., (2006) a commercial solar water heating system, shown in Figure 6, was examined for its effectiveness in providing clean water in emergency situations. This system was capable of reducing water seeded with 10^7 TTC/mL of E. coli to 0 TTC/mL in a matter of 2 hours at a temperature of 55°C on a sunny day and 100 TTC/mL in a matter of 4 hours at a temperature of 45°C on a cloudy day. This system is capable of producing 125 L of water per day, sufficient for the drinking needs of 50 people all while requiring no fuel or electricity. Additionally, the estimated unit cost for providing clean water is $0.01/L (Kang et al., 2006, p. 865).

Figure 6: 125 L Capacity Solar Water Heater (Kang et al., 2006, p. 864)

Another point of future research, presented by Boutilier et al. (2014), involves utilizing plant xylem, a porous material that transports fluid in plants, as a mechanism of filtration. Figure 7 shows the experimental setup of this type of filter. The pores found in plant xylem range in size from a few nanometers up to 500 nm depending on the species of plant (Boutilier et al., 2014, p. 1). This pore size is comparable to most UF systems and is capable of filtering out pathogens, making for an extremely inexpensive water filtration device. This study shows that for a xylem cross section of 1 cm^2 and a pressure head of 3.5 meters, this method is capable of producing up to 4 L of water per day with a bacteria rejection rate of 99.9%. The study showed, however, that the xylem filters being tested were unsuccessful in filtering out gold colloids of size 20 nm, which is comparable to the size of the smallest viruses. The author did suggest further research on whether certain conifer species existed that have pore sizes small enough to filter out viral species.

Figure 7: Construction of Filter Using Plant Xylem (Boutilier et al., 2014, p. 4)

Conclusion

The number of people dying each day from waterborne illness due to lack of access to clean water is why the United Nations has identified as one of their Millennium Development Goals (MDGs) to halve, by 2015, the proportion of the population without sustainable access to safe drinking water and basic sanitation (UN.org). While significant progress has been made in bringing more effective and economical solutions to those without access to clean water, there is still much more research to be done to realize a world where no person lacks access to safe drinking water. This paper endeavored to determine an effective and economical solution to bringing clean water to rural populations living in Mozambique. Of three commonly utilized water treatment methods in place today in developing countries, namely boiling, SODIS, and membrane-filtration technology, membrane-filtration technology has been identified as the most sustainable option for water treatment in rural Mozambique. Specifically, the Skyhydrant™ system and the LifeStraw® system have shown to provide clean water at very low costs. However, with more research, it is likely that there will be many more ways of providing clean water to those without access in the near future.

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