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ABSTRACT

A wide range of technologies are commercially available for water purification. However, not all of these technologies are suitable for use in rural, underdeveloped regions. Here, I present a systematic method for selecting the most appropriate technology for a particular community, using rural Ghana as a case study. In Ghana, over half of the population lives in rural areas, and two-thirds of these residents lack access to safe drinking water. Ghana has made significant strides using innovative water treatment techniques; however, there are still many hurdles. Simple and inexpensive, on-site water filtration technologies are a promising method for removing protozoans and other micro-organisms that pose significant health risks in underdeveloped, rural areas. In this review, several of these commercially available on-site water filtration technologies are assessed based on the following factors: effectiveness, cost, energy consumption, environmental impacts, and waste generated. This analysis suggests that for rural communities in Ghana, LifeStraw® and ceramic clay pots are the most appropriate technologies. Implementation of these technologies poses potential benefits in terms of cost effectiveness and economic growth. Although this paper focuses on northern Ghana as a case study, the methodology presented here can be readily extended to specific scenarios in other developing countries.

Keywords: Filtration; Ghana; Public health; Drinking water; Waterborne-diseases

1. Introduction

We are in an era where water scarcity and water quality are of critical importance. Environmental managers, scientists, and government officials have already begun seeking solutions on how to manage water in the midst of global climate change and overpopulation. Although water makes up more than 71% of the Earth's surface, there is an ever-growing struggle to access clean drinking water. Despite freshwater being a renewable resource, the availability of potable water is limited in many regions of the world. Globally, 1.5 million people die each year due to water-related diseases in developing countries [1]. Additionally, the 780 million people who do not have access to clean water represent more than 2.5 times the population of the United States. African countries are among the many developing countries that are plagued by water quality issues, and only 37% have access to hygienic sanitation [1]. Sub-Saharan Africa is a region of the world where the number of people without access to

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drinking water increased by 23% over the period 1990–2004 [1].

Out of all the countries in Sub-Saharan Africa, Ghana provides an outstanding case study for looking at water quality issues. The lack of clean drinking water and sanitation is a severe public health concern in Ghana, contributing to 70% of disease in the country [1]. This is not, however, due to a scarcity of water resources. Ghana is endowed with the Volta River system basin, which has 3.26×10^{13} gallons of water and an average flow rate of 1,210 m/s (42,730 ft/s). Also within the country is a southwestern river system in addition to underground water well supplies. Given the vast water supply available, the primary limiting factor for water consumption is the lack of a water treatment infrastructure.

Here, I discuss the barriers for rural Ghana to establish on-site drinking technology, to evaluate and develop different approaches that could be applied to a series for Ghanaian water supply situations. A general overview of Africa's water problem and the context of Ghana's water crisis will be discussed in detail. The challenges to the current state of rural Ghana's infrastructure are vetted and alternative solutions that will allow communities to access potable water are compared. Lastly, the economic feasibility and political barriers of creating on-site treatment for rural communities in Ghana are acknowledged and addressed. The findings are based on literature reviews of water treatment technology and a 30-day field observation throughout rural and urban areas in Ghana.

2. Background

2.1. General overview

The severe scarcity of clean water has both direct and indirect impacts on Africa's economic development. Direct impacts include waterborne diseases and low agricultural yields. Indirect impacts include impacts on economic activity. For instance, when individuals are frequently sick and spend significant caring for the sick, less time and energy are available for economic activity. The availability of safe and accessible water is a basic requirement for improving economic conditions in any given region. However, this phenomenon is especially acute in Ghana, which is located on the western coast of Africa, bordering the Ivory Coast on the west and Togo on the east. Sub-Saharan Africa has among the highest rates of mortality associated with water-borne illnesses and sanitation. In the year 2000, Ghana had an estimated about 10,000–20,000 deaths due to lack of clean water.

2.2. Ghana's water crisis: general context and overview

Ghana's population is estimated at 20 million people, with 58% living in rural areas and 42% in urban areas [2]. The World Health Organization and Joint Monitoring Program (JMP) for Water Supply and Sanitation define urban areas in Ghana to be areas with populations of 5,000 or more. By contrast, areas with less than 5,000 people are deemed rural [2]. More than half of the rural population in Ghana is susceptible to having contaminated drinking water and water-related diseases like guinea worm and diarrhea [2]. In Ghana, the same water is typically used for washing, bathing, cooking, and cleaning. This means that there are numerous ways for pathogens to be introduced into drinking water supplies and subsequently cause infection.

Of the overall diseases in Ghana, diarrhea is the third most commonly reported disease and it is the most common water-borne infirmity. Diarrheal disease accounts for 25% of cases of infant mortality, which was estimated to be 110 per 1,000 in the year 2000. [1] Water-borne illnesses also affect the life expectancy in Ghana. Currently life expectancy is approximately 56 years.

2.3. Water supply in rural areas of Ghana

In rural areas, the central government generally allocates fewer resources to the low population density areas, delaying development and causing a lack of critical infrastructure. Currently, 56% of the population in the rural areas of Ghana's northern region do not have access to clean drinking water and 92% do not have access to improved sanitation [1]. The availability of potable water in rural areas of Ghana is estimated to be 63% [3]. These regions tend to have lower population density and insufficient infrastructure.

Rural communities in Northern Ghana have attempted to utilize various types of infrastructure to obtain drinking water, including: surface water, hand dug wells, boreholes, spring, rainwater harvesting, and tanker trucks. In some cases, the safest option is to use groundwater. Ghanaians access groundwater through hand dug wells; however, groundwater is a questionable source because direct contamination from fecal matter in upper aquifers is caused by septic tanks. Boreholes, (i.e. *deep wells going down 40 + meters*), are the only way to ensure clean ground water. However, boreholes require proper equipment and are prohibitively expensive for many of these communities.

3. Treatment options

One of the greatest challenges to water quality in underdeveloped countries is the prevalence of microorganisms that causes disease such as *Cryptosporidium*, *Campylobacter*, and rotaviruses. Even though bacteria are larger than viruses (about 0.5–3 μm) they can be difficult to remove by sedimentation. Protozoan parasites are the largest in size and can be removed efficiently by filtration if the effective pore size of the filter medium is small enough.

There are a variety of passive and active methods to improve microbial quality of water. These methods include plain sedimentation or settling, filtration, and chemical treatments options [4]. In areas where clean well water or potable supplies are not available, personal technologies can be used to provide water, purified water for individuals or on-site treatment systems that can be installed to serve small villages up to thousands of people.

3.1. Personal treatment options

Six commercially available drinking technologies for drinking water in Ghana for personal water purification are bottled water, ceramic clay pots (*kosim* filter), LifeStraw®, paper cloth filters, sachet bags, and solar water disinfection. A summary of each technology is provided below.

Bottled water: Bottled water is a burgeoning method of providing clean water to communities in Ghana. The price of a 500 mL water bottle is approximately $1 US.

Ceramic clay pots (*kosim filter*): Ceramic clay pots are highly effective at removing bacteria, viruses, and protozoa. Based on MIT research in Northern Ghana, *kosim* filters are known to remove 92% of turbidity, 9.4% of total coliforms, and 99.7% of *E. coli* from unclean water sources [5]. Typically, ceramic filters hold 8–10 L of water. Filters are produced locally at ceramic facilities and then impregnated with colloidal silver to ensure removal of bacteria in treated water. The price is about $25 US for one ceramic clay pot, which are manufactured locally.

LifeStraw®: LifeStraw® is developed by the European disease control firm Vestergaard Frandsen. This technology is a plastic tube that is 310 mm long and 30 mm in diameter, which can filter out 99% of bacteria and parasites. LifeStraw® utilizes hollow fiber technology that efficiently filters water while it is pulled through the straw. Individuals can put the straw directly into a water source and sip clean water through the mouthpiece. The primary limitation of LifeStraw® is that it has the capacity to filter only 1,600 L, and once exhausted, will clog and not filter as efficiently. Nonetheless, a single straw can meet the needs of a family of five for up to two to three years [6]. The antimicrobial efficacy of LifeStraw® was evaluated by the Department of Soil, Water and Environmental Science, University of Arizona, USA (2010). The LifeStraw® technology has met the US Environmental Protection Agency protocol for microbiological water purifiers testing, which requires a six-log reduction of bacteria and three-log reduction for protozoan parasites. The cost of each LifeStraw® is approximately $24 US.

Paper/cloth filter: Paper or cloth can be used as a filter to remove large particles from the water. Filtration improves the esthetic quality of the water but has unknown levels of the removal of pathogens. Standard filter papers of known efficiency are generally unavailable. Cloth filters can be made from silk, burlap, and cotton, and are essentially free because individuals use cloth that they typically own.

Sachet bags: Sachet bags are plastic-packaged drinking water bags of 500 mL. The water source for sachets is typically either a well or an on-site drinking water treatment plant. Sachets are sold throughout Ghana by local vendors [7]. The appeal of sachets is their small size, cheap price, as low as $0.08 cents (US) per bag and easy availability. However, large amounts of litter from sachet bags can be observed strewn along the streets (personal observation, 2011). Additionally, a study by the University of Ghana found that out of 27 different brands of 500 mL sachet bags, 75% of the samples contained infective stages of pathogenic parasitic organisms [8]. Furthermore, the study indicated high levels of fecal matter, lead, manganese, and iron.

Solar Water Filtration: Solar disinfection (SODIS) is a technique that was developed in the early 1980s. Transparent bottles are filled with contaminated water. Filled bottles are shaken to oxygenate and the bottles are exposed to the sun by being placed on a roof or rack for about six hours. Bottles will heat faster and to higher temperatures if they are placed on a sloped sun-facing corrugated metal roof. A disadvantage of SODIS is the relatively common use of old bottles. If used bottles have scratches, light transfer and overall effectiveness of SODIS is diminished. Additionally, bottle labels or their residue reduce the clarity of the plastic and the disinfection efficiency of SODIS is reduced. Other major concerns with this method are the leaching of plastic bottle material into the water and regrowth of bacteria previously formed in the water bottle. Thus, proper training in the use of SODIS is required for optimal efficacy.

Slow Sand filtration: Slow sand filtration is a water filtration technology that cleans water as the water flows through the sand. Large microbes cannot pass through the sand pores and clean water filters.

3.2. On-site water treatment plants

A variety of technologies can provide on-site treatment, which vary in complexity and size. These solutions typically require capital investment; training and maintenance but have the greatest potential for long-term, sustainable potable water solutions. The aim of an on-site facility is to provide an affordable system that can be maintained by locals, who in many cases will have limited knowledge and ability. Currently, the Ghanaian government does not provide on-site treatment facilities for rural regions due to the high initial investment that is required. However, in the future, the government may be able to create an investment climate that would foster the installation of on-site treatment facilities in rural areas.

Groundwater wells: Northern Ghana has shallow ground water wells, hand-dug wells, boreholes, and piped systems. Groundwater quality is generally potable but can contain high concentrations of fluoride [9]). In many areas, mining has contaminated groundwater. Locally, dug and maintained wells are a potential longer-term solution but usually require planning and outside assistance.

4. Systematic evaluation of technologies

4.1. Criteria used to evaluate technologies

To determine what water filtration technologies are currently available, the literature was reviewed and concepts from multi-criteria decision analysis (MCDA) were considered. MCDA is the general field of study that provides a framework for decision-making in the presence of two or more conflicting objectives [10]. Furthermore, observations made during a 30-day field study supplement the findings. Personal and community water purification technologies were evaluated based on the following criteria: effectiveness (the likelihood of being used properly and successful in the community), capital cost, operating cost, energy consumption, environmental impacts, and waste generated. Effectiveness was based on the WHO standards for minimal health risks (smhr). Moreover, effectiveness was considered to be the most important of these criteria. The assessment developed in Table 1 should be of general use to individuals or organizations that consider a technology to an appropriate use for their circumstance. This methodology for ranking was judged suitable for the precision of the available data. However, a more sophisticated ranking methodology [11]) could be developed in cases where additional data are available.

4.2. Criteria ranking

(1) *Effectiveness*: Effectiveness was measured according to standards set out by the World Health Organization (WHO). The ranking was based on standards set for minimal health risk to the consumer, measured by levels acceptable for minimum health risks which are: 99.994% for *Cryptosporidium*, 99.99987% *Campylobacter*, and 99.99968% for rotavirus. Effectiveness was weighed significantly higher than the other parameters because avoidance of water-borne diseases is considered to be of paramount importance.
(2) *Cost:* Capital cost: Capital cost reflects the initial cost of the treatment technology. Operating cost: The operating cost reflects the cost of operating and maintaining the technology.
(3) *Energy Consumption:* Energy consumption reflects the amount of energy that is needed to operate the technology per volume of water at maximum efficacy.
(4) *Environmental Impacts:* The environmental impacts focuses on the impacts the water filtration technology has on factors including water quality, air quality, biota, and land.
(5) *Waste generated:* Waste generated focuses on whether or not the technology produces a high level of waste, if the product can be recycled, and if the waste poses a public health risk.

4.3. Methodological limitations

Cultural adaptability was examined but could not be ranked because there was not enough data available on the views of Northern Ghanaians on each water technology. Further studies should examine whether specific communities would be open to implement new technologies.

4.4. Capital cost and operating cost

For the capital cost and operating cost assessments, each technology was normalized to US dollars per liter. I assumed that a LifeStraw® could filter 1,600 L based on the product information on the LifeStraw® website [6]. A water bottle costs less than a dollar. Therefore, it would take 1,600 water bottles to filter 1,600 L. The operating cost would be $1,600 for 1,600 L.

Table 1
Assessment of personal and on-site water technologies

Treatment technologies	Capital Cost[a]	Operating cost (per liter)[b]	Effectiveness[c]	Energy Consumption[d]	Environmental Impacts[e]	Waste Generated[f]	Advantages	Disadvantages
Bottled water	$0	$1	High	Manufacturing, transportation	Low	Plastic bottles	Individual use	Temporary solution, possibly delaying long term solution, potential supply problem
Ceramic clay pot "*kosim*"	$14	$0	High	None	Low	Exhausted sorbents	Low cost, on-site alternative, potentially useful for families or groups.	Variable quality of locally-made filters, Viruses, no residual protection, recontamination, maintenance
Groundwater Well[h]	Highly variable and site specific	$0	High	None after drilling	Low	None	Potential long-term solution	Maintenance and management required, easily contamination
LifeStraw®	$0	0.015	High	None	Low	Litter	Contains no chemicals, portable	Limited to 1600 liters; one-person only; recurring cost; may delay long term solution
Cloth filter	$5-10	$0	Low	None	Low	None	Individual use or household level, affordable	Microbe removal varies by pore size
Slow sand filter	$16-25	$0	High	Pump, vents, and drain	Low	None	Simple to use, Small scale and community level.	Requires technical knowledge and training; Constant maintenance
Solar water disinfection (UV) (size)	$0	$1	Moderate, Function of sunlight, cloud cover	None	Low	Litter	Low cost, no energy required, on site	Leaching of bottle material, regrowth of bacteria, toxic chemicals still in the water; training
Water satchet	$0	$0.008	High	Manufacturing and transportation	Plastic waste, litter	Plastic bags	Individual use	Temporary solution, possibly delaying long term solution, potential supply problem
Water treatment plant	$7,000-$40,000	parts	High	Significant	Land required, potential pollution	Water treatment plant sludge	Long term water supply, May lead to economic growth, improved health	Requires capital investment, dedicated land, good quality source water, and competent management with training.

[a]Capital cost of $0 is colored green, moderate range is yellow, high is orange, and significant expenses are coded red. These judgments were made based upon capital cost to per capita income of individuals in developing countries.
[b]Same as above.
[c]High effectiveness is colored green.
[d]No energy consumption is colored green.
[e]Low environmental impacts are colored green.
[f]No waste is colored green.
[g]30-50 feet.
The colors key indicates the level of acceptability for each parameter. Green is high acceptability, yellow is neutral, orange is moderate, and red is for low acceptability.

Kosim filters: The assumptions made were that it filter can pass through water at a rate of 3 L/h. So at 9 L it would be $5. Then calculations were adjusted to go from 9 to 1,600 L. The ceramic clay filter (*kosim*) costs approximately $14 (US). The operating cost is about $885/1,600 L.

Shallow groundwater wells: The cost is highly variable and is dependent on the depth of the well and location.

LifeStraw®: There is no capital cost. The operating cost is $24/1,600 L. [6].

Cloth filters: The capital cost for cloth filters is the bucket and the cloth material. The operating costs takes into account how often the cloth needs to be replaced, which depends on how many liters of water are being passed through it.

Slow sand filter: The capital cost for slow sand filtration is between $16 and $25 (US) (low to moderate). The operating cost depends on how long the sand is clean and how clean the water is.

Solar water disinfection: Operating cost is negligible if water bottles are reused.

Water sachet: The capital cost for a sachet is about 8 cents per sachet or $12.80 (US) per 1,600 L.

Water treatment plant: The cost ranges from $7,000 to $40,000 (US) depending on the sq. ft. of the facility and the location

4.4.1. Effectiveness

The range of effectiveness was measured based on the capability the technology had to filter 99% of bacteria, parasites, and or toxic chemicals. If it met the requirement, the technology was given a high ranking and if the technology did not meet this requirement; it was given a low ranking.

4.4.2. Energy consumption

Energy consumption was evaluated by considering whether the technology had a high or low impact to the air, water, and land. If plastic waste was produced or there was a potential for contamination by multiple users, then the technology was ranked as low energy consumption. However, a high ranking was given to technologies that had low or no environmental impacts.

4.4.3. Waste generated

This parameter was evaluated based on the amount of waste material by each technology and was ranked from high to low. Of all the technologies, bottled water and LifeStraw® create the most waste in the form of litter.

5. Discussion

The findings show that the most advantageous short-term solution to the water crisis in rural Ghana would be the utilization of a combination of personal options such as the LifeStraw® and *kosim* pots (Table 1). However, long-term water security in rural Ghana will require government efforts and will depend upon the development of infrastructure such as a groundwater infrastructure, water treatment plants with distribution systems or on-site water filtration. Observational studies and local interactions have indicated that groundwater wells and *kosim* filters are more readily available and currently being adopted by small villages.

Ghana's water crisis needs a holistic approach because a variety of water filtration technologies are needed to confront the diverse and complex nature of Ghana's water dilemma. In choosing a holistic approach, each filtration technology would supplement each other's limitations. Alternatively, rural areas in Ghana should have access to a water treatment facility. LifeStraw® filters are particularly effective for villagers that need to travel throughout the day, allowing them to stop at a water source and drink clean water as needed. The disadvantage of focusing on personal options is that doing so may delay implementation of longer term, more sustainable solutions. If drinking water can be obtained through vendors, even at high cost, the incentives for new treatment plants or wells are reduced.

The technologies that are not recommended for use in rural Ghana are water sachets, cloth-filters, solar filtration, and water bottles. These approaches do not meet adequate drinking water standards. Water sachets in particular, generate excessive waste and have been shown not to meet WHO standards for clean water in studies.

5.1. Implementation of solutions: the role of the government in improving human welfare

In the face of surging populations without water and the economics involved with clean water supplies, Ghana's governmental agencies have the potential to play a significant role in making water easily accessible. However, the unwillingness of the government to support water facilities' effectiveness prevents for small rural communities and villages to have a way to mass-produce drinkable water. An infrastructure provision is necessary to improve the effectiveness of water quality. However, the government has not provided an initial investment for on-site water treatment facilities that would address basic water and sanitation needs. As a result, the private sector (small water systems), charitable organizations, and a small group of individuals, the

Informal Service Providers, have stepped in but cannot provide area-wide supplies. Thus, Ghana's governmental agencies, that have greater financial resources, are not providing rural areas with infrastructure that would alleviate their drinking water problems.

Similarly, global organizations such as the United Nations have made goals to halve the population without sustainable access to safe drinking water and basic sanitation by 2015. Clean water issues were identified and addressed by the creation of the United Nations' Millennium Developmental Goals (MDG) in the year 2000. MDG is a series of eight international goals that serves to improve the quality of life in developing countries (MDG). Nevertheless, individual communities are still involved in combating the water problem. For example, rural water needs are being supplemented by boreholes and hand-dug wells with pumps made by locals. Sustainable long-term solutions will depend upon the development of supporting infrastructure that can maintain existing facilities, train operators, and provide growth as needed.

6. Conclusion

This study analyzes the known alternatives for rural Ghana. Safe drinking water is needed at present and short-term solutions are important. Of the identified solutions, only the personal water treatment alternatives are available short term. Of these, LifeStraw® is immediately available and requires virtually no training. The disadvantage is the cost; each person needs to spend approximately $US 25 per straw. For long-term solutions, the government and other agencies need to focus on creating on-site water treatment facilities. While there are barriers to this long-term solution, such as cost, politics, and cultural adaptability, its emphasis on location-based treatment has the benefit of providing high-quantity clean water to the community. For Ghana to reap the economic and social benefits of a nation with access to clean, potable water, the country's leaders must focus on creating water infrastructure for rural regions. Future work should focus on reducing the level of waste generated from personal water treatment.

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