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Masters of Engineering Program

Household & Community Water Treatment and Safe Storage Implementation in the Northern Region of Ghana

MIT Ghana Master of Engineer Team
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1.0 Introduction

1.1 The need for improved water and sanitation

Awareness of the direct impact adequate water and sanitation has on the spread of waterborne diseases, revolutionized public health and city planning in major cities in Great Britain and the United States in the late 19th century. Previously the commonly accepted atmospheric theory led people to believe that miasma, or bad air, escaped from the "bowels of the earth" and poisoned people with diseases such as cholera. It was in fact during a London cholera outbreak in 1849 that Dr. John Snow noticed a pattern in the location of cholera victims with relation to a local drinking water well. After careful collection and analysis of epidemiological data, he surmised that cholera was waterborne. As a result, to put a halt to the fatal cases, the handle of the water pump was removed to effectively prevent use of the contaminated source. As Dr. Snow continued his work, not only was the link between ingesting contaminated water and contracting cholera further confirmed, but it became apparent that a key to preventing such illness was selecting the best water source available (Okun, 1996). Finding adequate sources that provide sufficient quantities of uncontaminated water is becoming increasing challenging as the world's population grows, the climate changes, and lands continue to be deforested.

Though high-income countries have significantly improved their life expectancy and curbed the spread of waterborne diseases since the sanitary revolution of the 1800s by extending access to cleaner sources of water, adequate sanitation, and hygiene education, scarce funding, administrative structure, and availability of local technical expertise are some of the factors that limit advances in low or middle-income countries. Many such countries experience water shortages because the cost of accessing cleaner groundwater is prohibitive and surface water that is available often fluctuates seasonally and has high levels of microbial contamination and turbidity[1]. In hope of making clean drinking water accessible globally, in 1977 at the UN Water Conference at Mar del Plata, 1981-1990 was declared the first "International Decade for Clean Drinking Water." Since 1990, a concerted global effort gave an additional billion people access to safe water. Unfortunately, almost an equivalent number of people (1.1 billion) still lack access to potable water. The remaining people without access to potable water may be even harder to reach because those communities with the most accessible, uncontaminated water sources may have been targeted first. Though the job is not easy, the basic need for potable water must be met. Seeking to lessen the disease burden caused by waterborne disease, the UN General Secretary Kofi Annan announced at the 58th Session (A/Res/58/217) that the second "Decade of Water for Life" would begin in 2005 especially striving for greater participation of women as managers of water.

The disparity between the advancement of appropriate drinking water treatment and sanitation in high income countries in comparison to the lack of it in low and middle income countries is apparent in Figure 1 (WHO, 2002). In extremely underserved areas such as sub-Saharan Africa and the Pacific where drinking water coverage rates drop to 58% and 52% respectively, the burden of diarrheal disease is extremely high (UNICEF, 2007). Global leaders in public health considering such high prevalence of diarrheal disease unacceptable, challenged world leaders to meet the UN Millennium Development Goal 7 (MDG); to "half, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation."(UN-NGLS 2006) While much progress has been made in improving access to

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[1] Turbidity is an "indirect measure of the particulate matter in water" which determines the relative amount of particles present (AWWA, 1999). It does not directly measure the type, number or size of particles present but rather the cloudiness as a measure of the amount of light that is able to pass through the fluid. The most common unit used is the nephelometric turbidity unit (NTU) but field experiments are some times completed using a simple instrument which gives turbidity measurements as turbidity units (TU).

drinking water, Figure 2 depicts the numerous countries not on track to meet MGD 7. To meet such an ambitious goal, cost-effective, appropriate, sustainable interventions to improve drinking water quality and sanitation must be considered. Developing water treatment processes appropriate for low and middle income countries is pivotal in beginning to relieve this tremendous burden of disease that very much depends on levels of socioeconomic development (WHO, 2006).

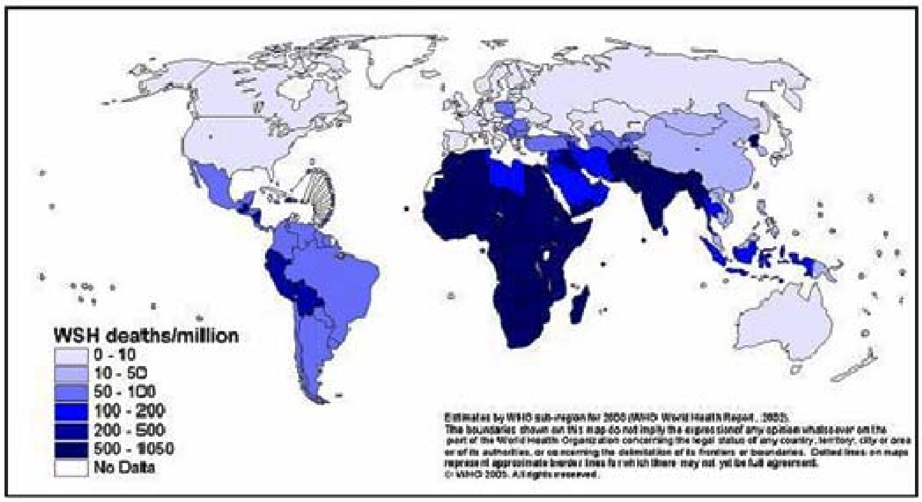

Figure 1 Deaths caused by unsafe water, sanitation, and hygiene for 2000 by Country (WHO, 2002)

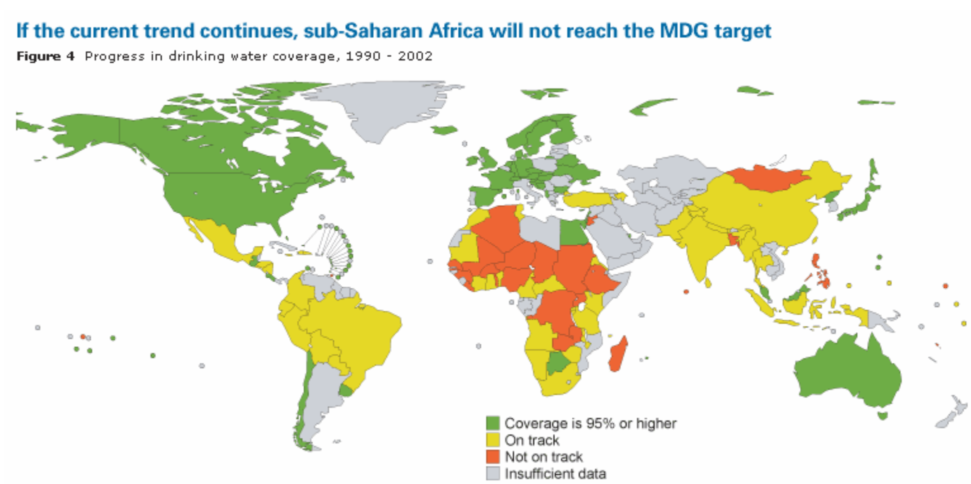

Figure 2 Meeting the MDG target for drinking water coverage (UNICEF and WHO, 2004)

Many rivers, lakes, and streams worldwide exhibit seasonally high turbidities particularly in tropical climates where heavy, rainy season runoff carries silt into the surface water (Okun & Schulz, 1984). Possible turbidity sources include domestic sewage, urban and agricultural runoff, stream bank erosion, wind transport of fine particles, and construction activity (AWWA, 1999). As population growth increases pressure on natural resources through the need to harvest firewood, produce charcoal, expand urban areas, and extend agricultural lands, water worldwide may become more turbid. At the same time, climate changes' effect on the intensity and duration of rainfall and windy, dusty weather can further elevate surface water turbidity levels.

The concern surrounding highly turbid water in developed countries primarily arises from the problem it poses to effective disinfection and secondarily to problem of sediment accumulation in distribution pipes and pipe corrosion. Highly turbid water can reduce the effectiveness of common water treatment methods such as slow sand filtration (SSF) and chlorine disinfection. In addition, turbidity of piped water above 1 nephelometric turbidity unit (NTU) may indicate that the distribution system needs to be flushed and the pipes checked for corrosion (AWWA, 1999). High turbidity is a worldwide challenge. However, turbidities in tropical countries are especially high and may range from 100 NTU to above 1000 NTU. This is true in Northern Region, Ghana, the location of this study, where consumers face limited availability of highly turbid surface water drinking supplies. In this case and in others like it, a sustainable, low-cost, appropriate, first stage of water treatment is needed to reduce the turbidity to acceptable levels.

1.2 WHO Guidelines for Drinking Water Quality

Since 1958, the World Health Organization (WHO) has established and published up-to-date drinking water quality guidelines applicable globally to developed and developing countries. The most current 3rd Edition WHO *Guidelines for Drinking Water Quality* (GDWQ) was published in 2004.

The ultimate goal of drinking water treatment is to provide the beneficiary with safe water free of harmful chemicals and pathogens such as bacteria, viruses, protozoa, and helminthes that spread infectious diseases. Drinking water is an important transport vehicle for pathogens by the fecal-oral route. Other pathways include contamination of food, hands, utensils, and clothing (WHO, 2004). Though the public health and environmental engineering community still debates the relative importance of hygiene, sanitation, water quality, and water quantity in the spread of gastrointestinal infectious diseases, the WHO GDWQ are widely accepted as the foundation for regulation and standard-setting to insure safe drinking water.

1.2.1 WHO turbidity guidelines

While the WHO GDWQ state that the median turbidity should be below 0.1 NTU for effective disinfection, they no longer recommend a health-based guideline value for turbidity in the latest GDWQ (WHO, 2004). Although turbidity influences the microbial water quality, turbidity itself does not necessarily cause adverse health affects. The WHO does, however, recognize a correlation between turbidity and microbial contamination because they observe that, "Sporadic high turbidities in source water can overwhelm treatment processes allowing enteric pathogens into treated water and the distribution system." (WHO, 2004) In addition to water being free of microbial contamination, having an acceptable taste, and appearance are also important parameters for consumers. Consumers usually accept the appearance of water with turbidity less than 5 NTU (WHO, 2004).

1.2.2 WHO microbial contamination guidelines

Because of the tremendous global burden of gastrointestinal infectious diseases, priority is given to ensuring the microbial safety of water. Faecal-oral pathways are not the only mode of transmission. Source water can also provide habitat for water-grown vectors like Guinea worm (*Dracunculus medinensis)* or Schistosomiasis (*bilharziasis*) which are spread respectively by ingestion of a water flea carrying the Guinea worm cyclops or the trematode worm shistosome penetrating the skin of the human host. Another avenue for risk, especially for immune-compromised individuals is bathing because they can develop various skin, eye, ear, nose, and throat infections through having contact with contaminated water (WHO, 2004). From a public health standpoint, important microbial growth factors to consider are the organisms' persistence in water supplies, resistance to chlorine, relative infectivity, and health significance. The most widespread pathogens and parasites are highly infectious and either find water to be a hospitable environment for reproduction or are able to resist decay outside the body. The most common life-threatening, water-borne diseases include typhoid, cholera, and hepatitis A.

WHO guidelines state potable drinking water, treated water entering a distribution system, and treated water in a distribution system must not have detectable *Escherichia coli* (*E. coli)* or thermotolerant coliform bacteria present in any 100-ml sample (WHO, 2004). *E. coli* bacteria, commonly found in the lower intestine of warm-blooded animals, are used as indicators of fecal pollution. Total coliform is not a sufficient indicator of fecal contamination because many bacteria, especially in tropical areas, have no sanitary significance. Total coliform, however, is a good indicator of treatment efficacy. Immediate action must be taken if *E. coli* are present. Keeping *E. coli* out of rural water systems can be challenging in developing countries where fecal contamination is extensive. In this case, a medium-target should be set to encourage progressive improvement of water supplies via the development of water safety plans.

1.2.3 Removal and disinfection of waterborne pathogens

Slow sand filtration (SFF) and chlorination are two of the most common, low-cost and easy-to-maintain water treatment systems for surface waters in developing countries.

1.2.3.1 Slow sand filtration and turbidity

Slow sand filtration is inexpensive treatment method that can be constructed out of mostly local materials, is easily operated and maintained, and has a tremendous ability to improve drinking water quality in developing countries by removing between 2 to 4 log (99 to 99.99%) of microorganisms (Wegelin, 1996). Removal of organic material and pathogenic organisms in SSF (such as protozoa, bacteria, viruses, and helminthes) from low turbidity raw waters depends on the *schmutzdecke*, a thin layer on the top 0.5 to 2 cm of sand where biologically-active microorganisms trap and digest particulate matter. Slow sand filters are cleaned manually by removing the top dirty layer of sand. This process typically takes one to two days and then the filter must ripen before the effluent is safe to use. A SSF can run for several months if water contains low concentration of algae and low turbidities. Conversely, high turbidities and high concentrations of algae can quickly clog the filter resulting in short filter runs and burdensome operation and maintenance costs.

Sensitivity to high turbidities means that SSF requires pre-treatment if the raw water turbidity is greater than 50 NTU for longer than a few weeks (Okun & Schulz, 1984). While Okun & Schultz specify an influent turbidity < 50 NTU for effective SSF, literature differs in what are considered acceptable turbidities for SSF. The usual required influent turbidities range from 5 NTU to 50 NTU (Galvis, Visscher, Fernández, & Berón, 1993). Respectively, Martin Wegelin from the Swiss Federal Institute for Environmental Science and Technology (SANDEC) and Gerardo Galvis from the Centro Inter-Regional de Abastecimiento y Remoción de Agua (CINARA) recommend a 20-30 NTU and 20 NTU limit for the influent of SSF (Wegelin, 1996) (Galvis et al., 1993). Huisman and Wood in 1974 found the optimum purification occurs when the turbidity is below 10 NTU (Okun & Schulz, 1984). More recently, Cleasby (1991) determined that influent SSF turbidity should be no greater than 5 NTU (as cited by Galvis et al, 1993). In other words, SSF requires fairly good influent water and, in general, should not be used for treating highly turbid water > 50 NTU.

Even when turbid water is pretreated, fine particles such as clay can quickly clog the filter bed, cause extreme increases in head loss, and create undesirable conditions in the active biofilm layer in the filter bed (Galvis et al., 2006). Short peaks in turbidity can force the active biofillm deeper into the sand filter bed and, as a consequence, reduce the SSF's removal of pathogenic microorganisms. Although a SSF can be effective, such limitations on its efficacy are important to note and are sometimes buried in the literature.

Other more cited problems, including clogging and reduced filter runs, are common when SSF treats water with a high quantity of very small colloidal particles (Galvis et al., 2006). If the raw water turbidities are lowered, SSF could provide a simple solution for facilities that do not want to use coagulants.

Advantages

The use of SSF in developing countries can be very advantageous and provide another safety barrier prior to chlorination and consumption (Okun & Schulz, 1984):

- Construction costs for SSF are very low in comparison with many other community-based treatment systems.
- The simplicity of the design and operation mean that very little technical supervision is required to run the SSF.
- Maintenance mainly consists of cleaning the beds, which can be completed by unskilled labor.
- Materials and equipment can be purchased locally.
- No chemicals are required.
- If gravity head is available, then the system can be run without power.
- Slow sand filtration can accommodate some fluctuations in the raw water quality and temperature as long as the turbidity does not increase too much and only lasts a short time.
- During the cleaning process, large amounts of washwater are saved.
- If chlorine is applied, SSF removal of organic material allows for a reduced dosage of chlorine and some cost savings.

Disadvantages

In tropical climates disadvantages include (Okun & Schulz, 1984):

- Algae blooms that choke the filter bed;
- Maintenance of the biological layer which sometimes is sensitive to heavy concentrations of colloids and some toxic industrial wastes;
- Filters that only have intermittent flows are more at risk of becoming anaerobic because the stagnant, turbid water sitting on top of the filter inhibits oxygen from reaching the beneficial microorganisms;
- Careful attention needs to be paid to making sure filters do not become anaerobic because this would cause taste and odor issues.

1.2.3.2 Chlorine disinfection and turbidity

Chlorine compounds (hypochlorites) are effective at killing pathogenic organisms, available in most developing countries, and are fairly moderate in cost. An added benefit is that chlorine residual can prevent recontamination of treated water in the distribution system. However, raw waters with high turbidities complicate the disinfection process. More turbid water has a higher chlorine demand because it requires more chlorine to oxidize organic matter present. Therefore, the WHO recommends influent turbidity be less than 0.1 NTU prior to chlorination (WHO, 2004). In emergency situations less than 20 NTU is acceptable (Godfrey, 2005).

Not only does highly turbid water require longer chlorine contact times and the addition of more chlorine compounds, but disinfection may not be effective enough against pathogens within flocs or particles. The WHO states that “high levels of turbidity can protect microorganisms from the effects of disinfection, stimulate the growth of bacteria and give rise to a significant chlorine demand.” (WHO, 2004) Although the presence of organic matter and chlorine could react to form disinfection byproducts, the WHO warns that “disinfection should not be compromised in attempting to control disinfection by-productions (DBPs)” (WHO, 2004). The main goal is to provide pathogen-free drinking water and thereby reduce the incidence of waterborne illness.

2.0 Ghana background

Ghana lies between latitude 4.5°N and 11.5°N and longitude 3.5°W and 1.5°E (Figure 3). Its climate is controlled by three air masses; the Southwest Monsoon, Northeast Trade Winds (Tropical Continental Air Mass) and Equatorial Easterly. The Southwest Monsoon contributes warm, moist air from the Atlantic Ocean while the Tropical Continental Air Mass (locally known as the *harmattan*) carries hot, dry, and dusty air from the Sahara Desert across Ghana. As these two air masses approach the tropics from either side of the equator, they create a low pressure belt known as the Inter Tropical Convergence Zone (ITCZ). Throughout the year, the ITCZ oscillates in response to the changing angle of the sun and creates a dry and wet season. The Northern Region only experiences one rainfall regime from April/May to October with the rainfall reaching its peak in September (Figure 4). Hardly any rainfall occurs during the 5-month long dry season from November to March. Because the ITCZ passes over the southern region twice, it experiences two rainy seasons. Figure 4 shows the unequal distribution and seasonality of rainfall in Ghana. Not only does the North have much fewer raindays but the monthly rainfalls are substantially lower than the South. As a result, the South is a much more water-rich area while the North is water-poor.

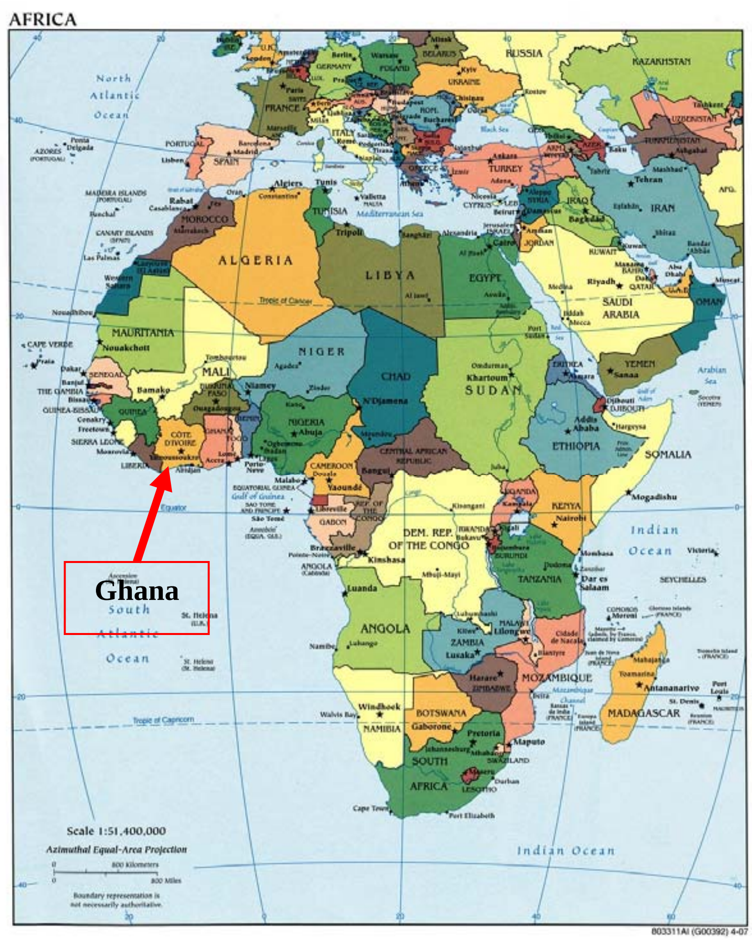

Figure 3 Location of Ghana

(http://www.lib.utexas.edu/maps/africa/africa_pol_2007.jpg)

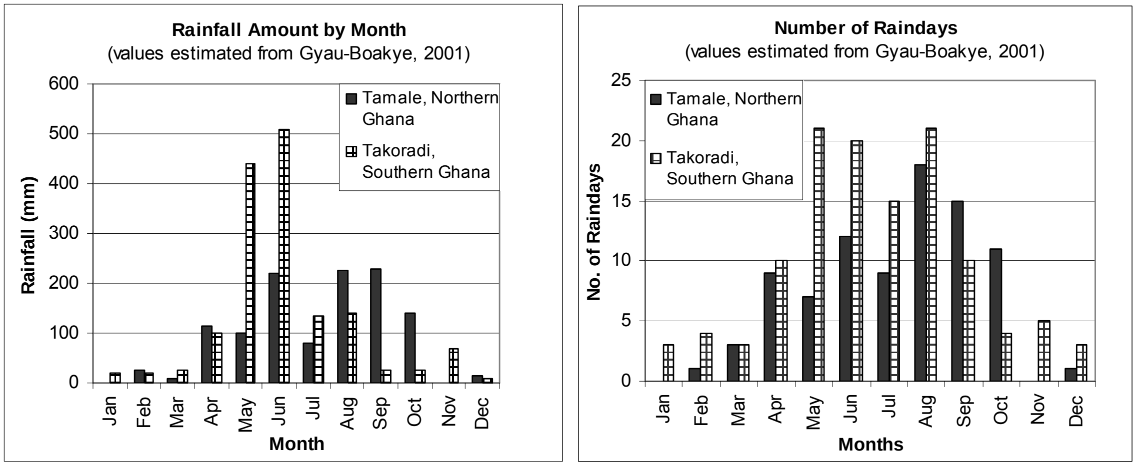

Figure 4 Rainfall chart (left) and number of raindays (right) for Tamale, Northern Ghana and Takoradi, Southern Ghana, 1996 (Gyau-Boakye, 2001)

2.1 History of water supply in Ghana

According to the *Millennium Development Goals (MDG) Mid-Term Assessment* in 2004, only 68% of rural water consumers, the most underserved population in Ghana, had access to an improved source (UNICEF, 2004). To reach the MDG 7 for water, an additional 7.3 million rural people need to gain access to improved water sources through an estimated annual investment of $29 million (World Bank, 2004). Increasing urban and rural populations' access to water is a gradual, resource-intensive process. Progress made since British rule and self-rule should be recognized.

The challenge of water supply in Ghana is not a new one. Before colonial rule in 1844, each public or private entity was responsible for developing and managing their water source and supply. In the early 1900s, due to drought, population growth, the gradual migration into more urban areas, and health problems from the contamination of surface waters, the colonial British government claimed responsibility of public water supply in urban and rural areas. Under British rule, the Public Works Department was created to assess urban water supplies. In 1920, the Geological Survey Division was formed to train local authorities in digging wells, protecting the wells with linings, and preventing the contamination of water supplies (Smith, 1969). Water needs in the Northern and Southeastern parts of Ghana became serious enough that the Geological Survey Department was established in 1937. Their mission was to investigate possible new water sources, advise public medical officers, political administrators, and personnel on the proper well digging and maintenance procedures, and to improve sanitary conditions to prevent further pollution of surface water sources.

In the years prior to independence, there continued to be a large need for the development of rural water supplies. Although by 1942, Hydraulic Branch of the Public Works Department had built 252 dams, ponds and wells, the need for potable water in rural areas was so great that in 1944 a separate Department of Rural Water Supply was formed solely to address rural water supply (Smith, 1969). With limited resources, the new department dug wells, built tanks, and trained and supervised local water administrators. In larger communities, piped systems were sometimes provided from mechanical boreholes. Though this helped, it was not the panacea for Ghana's rural water problems. In the 1950s, concern mounted over the seasonality of groundwater sources. British consultants were invited to advise the Department of Rural Water Supply's work and the potential for groundwater exploitation. Between 1952 and 1959 those working to improve rural water supply partnered with private drilling companies, the

Department of Community Development from the Ministry of Social Welfare and Community Development, and the Department of Agriculture[2]. Ayibotele (1969) described the most common technologies that were utilized and continue to be used today: hand-dug wells that sometimes included hand pumps, protective spring boxes, rainfall harvesting from roofs, infiltration galleries, dug-outs, and small dams (as cited by Gyau-Boakye, 2001).

After gaining independence from British rule in 1957[3], the new Ghanaian government reorganized. In 1965 they finally founded the Ghana Water and Sewerage Corporation (GWSC). Act 310 gave the GWSC the responsibility for "the provision, distribution, conservation, and management of water supply development and installation, and for the coordination of all activities related to the water supply industry." (Gyau-Boakye, 2001) Under this organizational structure, a strong effort was made to develop boreholes instead of surface water due to the cost of a potable water supply using surface water being about twice that of groundwater systems according to Ghanaian study by Bannerman (1975) cited by Gyau-Boakye (2001).

According to the Ghana Statistical Service in Accra, before 1984 50% of the rural population depended on surface water such as streams, rivers, lakes, ponds, impoundments from dams, and dug-outs (Gyau-Boakye, 2001). 1984 was an important year because NGOs and the government concentrated their efforts on drilling boreholes and wells in rural communities. Unfortunately borehole drilling was much more successful in the South than the North and resulted in regional inequity with regards to water access (Gyau-Boakye, 2001). The drier Northern Ghana had to satisfy their water demand with limited groundwater and highly turbid, polluted, traditional surface water sources that are often contaminated from the improper disposal of excrement, chemical from agricultural runoff, and the illegal use of DDT (dichloro diethyl tetrachloroethane) for fishing (Gyau-Boakye, 2001).

Figure 5 shows that despite the challenges in financing, implementing, and training the community to manage rural water supply projects, since 1984 there has been improvement in rural population's access to improved water sources. It is unclear whether this change is sustainable and whether the data takes into consideration systems that are broken and have fallen into disuse. Moreover, it should be noted that the improvement of a source does not guarantee the water is microbially or chemically safe but rather focuses on consumers' access to adequate quantities of water rather than its quality[4]. The combination of UNICEF and governmental data show that access to improved water declined by approximately 8% from 1998 to 2000. The World Bank suggests this is "likely due to the incapability of the data and underlines the need for a review of access figures." (World Bank, 2004) However, some of the data could demonstrate a real decline in water access.

[3] In 1957, the Gold Coast was the first African country to achieve its independence from British Rule and became Ghana.

[4] The MDG define improved access to a water supply as having at least 20 liters per person per day available from a source within one kilometer of the household.

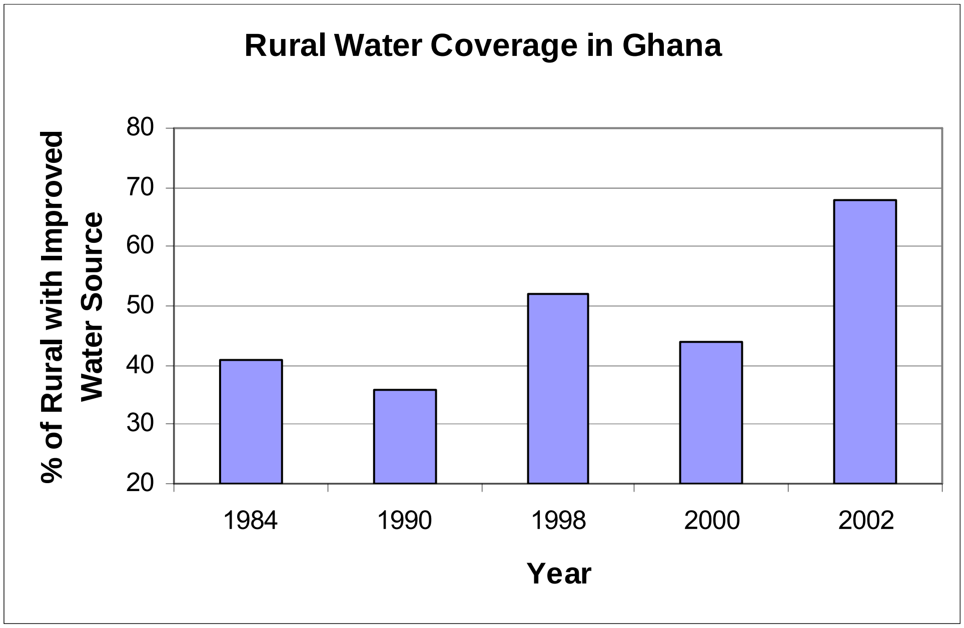

Figure 5 Progress in rural water coverage in Ghana (Gyau-Boakye, 2001; UNICEF, 2004)

Many in Northern Ghana still lack access to improved water sources. Water quantity, source reliability, and the high cost of source improvement projects are challenges that continue to be a barrier to improving water access in Northern Ghana. Figure 6 illustrates that there is a tremendous need to improve access to water (Murcott, 2007).

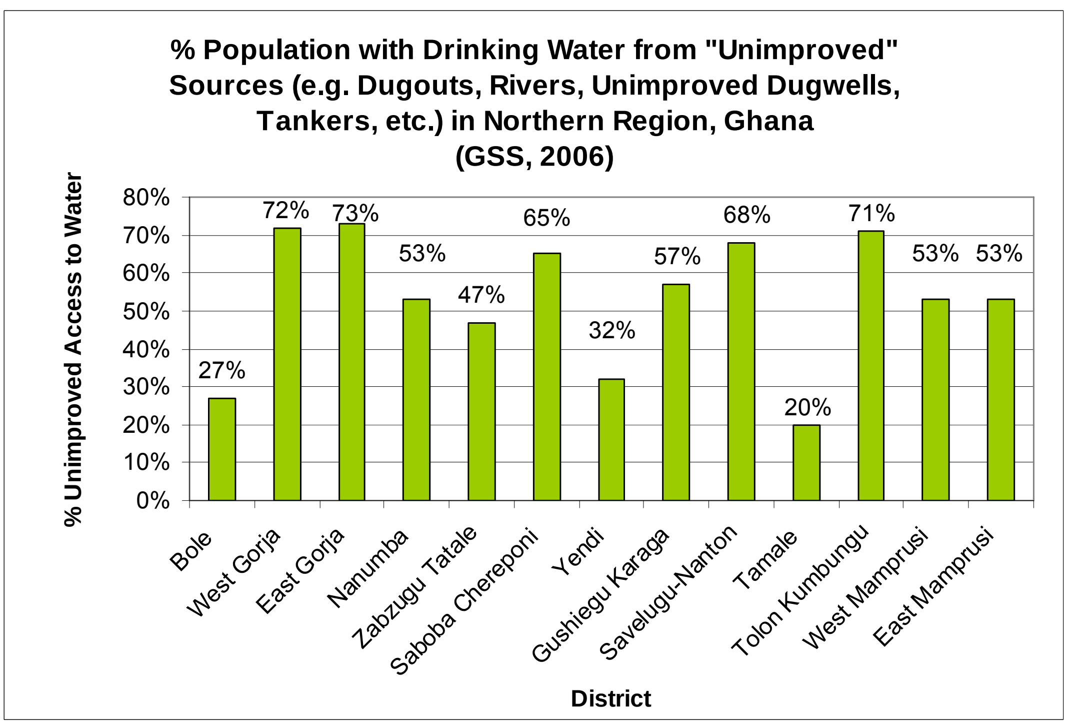

Figure 6 Percent population with drinking water from "unimproved" sources in NRG (GSS, 2006)

2.2 *Common water sources in Northern Ghana*

Common water sources in Northern Ghana include dug-wells, dugouts, ponds, streams, and roof-top rainwater harvesting. Water availability in Northern Ghana is highly seasonal. Streams, hand-dug wells, and dugouts often dry up during the dry season forcing people to travel further in search of water until the aquifers are replenished during the subsequent rainy season.

2.2.1 Boreholes

In areas that have accessible groundwater, boreholes may be the safest, cost-effective long-term solution. Surface water sources can be unreliable because they are transient, seasonal, and at high risk of contamination. On the other hand, drilling rigs and pumps are usually costly, need to be purchased abroad, and require technical expertise. This makes drilling boreholes a challenge in developing countries. Nevertheless, in late 1990s, donor countries such as Canada, Japan, and Germany and a few NGOs such as World Vision International, Oxfam, and UNICEF invested in drilling boreholes in rural communities (Gyau-Boakye, 2001). Like all water treatment technologies, the proper operation, maintenance, and management of boreholes and pumps are essential to sustain a certain treatment standard.

It is difficult to locate viable aquifers, especially in Northern Ghana. The hydrogeology of Ghana has two main formations; the Basement Complex of Precambrian crystalline igneous and metamorphic rocks and the Paleozoic consolidated sedimentary formations. The Basement Complex and Voltaian formations are fairly impermeable and therefore do not store groundwater well though fracturing and weathering allow for some aquifer development. Some success was made when joints and cracks were found using reports, topographic maps, geological and structural maps, survey of existing boreholes and water sources, and talking with community members. In the North, baobab trees, a cluster of big trees or an ant hill can indicate that the water table is closer to the ground level. In other regions of Ghana, borehole drilling was successful in valleys or low areas; however, flat topography inhibits this technique around Tamale. To complicate the situation, dropping water levels in the northern, semi-arid region have sometimes dropped up to 5 meters according to Quist et al, 1988 (as cited by Gyau-Boakye, 2001).

2.2.2 Hand-dug wells

Hand-dug wells are an inexpensive way to access shallow groundwater. Locals can be trained to construct them. There is a great opportunity to further train knowledgeable locals to facilitate community participation so that they are part of the planning, implementation, and management of such projects. Use of an infiltration gallery can reduce the turbidity and general water quality. However, hand-dug wells are limited to areas with accessible groundwater. Most areas in Northern Ghana are not suitable for hand-dug wells. Fifty-four percent of the Ghana has crystalline rocks that make is difficult to dig wells. It is too hard to hand dig below the water table so these wells dry up seasonally. In addition, if they are not correctly capped and sealed with a hand pump added, they can be easily polluted by animals, used domestic gray-water, and water runoff. According to WHO guidelines, hand-dug wells should be located uphill or at least 50 feet (about 15 meters) away from latrines, garbage dumps, and polluted groundwater (as cited by Gyau-Boakye, 2001).

2.2.3 Dugouts/Dams

Dugouts are traditional, earthen basins that catch and store rainwater and interstitial stream flows for long periods of time. Water stored in these runoff harvest ponds is not suggested for potable uses (Ludwig, 2005). However, in the arid areas of Northern Region Ghana and other parts of West Africa where there is limited access to groundwater sources, many communities have few alternative water supplies. These manmade, earthen storage basins are common in rural and urban communities in Northern Ghana where they provide highly turbid surface water to communities with otherwise very limited access to water. In the rural districts of Tolon and Savelugu, over 50% of water sources used by households are dugouts (Figure 7).

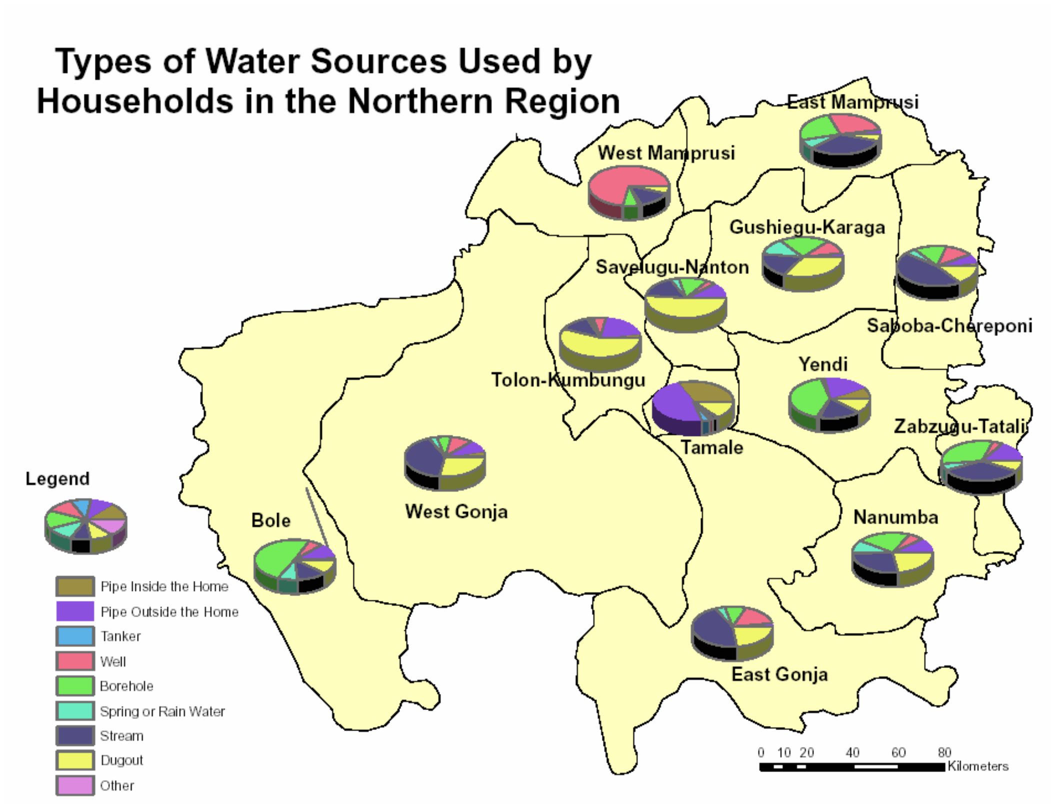

Figure 7 Northern Ghana household water sources (GSS, 2003)

Until all of the dugout water sources in Northern Ghana are identified, protected, and treated, water quality problems will persist at the community and household level. Although a preliminary inventory of dugout location in Northern Region Ghana was completed by Johnson and Doyle (2007), little is still known about the quantity, availability, and quality of dugout water. Only recently has the precise impact the dugouts have on the bacteriological and physical water quality begun to be characterized (Murcott, Doyle, Foran, Johnson, & Yazdani, 2007). In this study physical water quality tests were conducted to characterize the physical water quality of the Gbrumani, Kpanvo, Kunyvilla, and Ghanasco Dams in the Tamale area of Northern Ghana.

MIT Master of Engineering and Harvard Master of Public Health students Johnson (2007) and Foran (2008) were the first to compile water quality data on dugouts in and around Tamale. From Table 1, it is evident that dugouts' high average concentrations of *E.coli* and turbidities greatly exceed the WHO DWQG and are a serious water quality problem that needs a solution. SSF could be a highly effective treatment option for removing 99-99.99% of microorganisms; however, the average dry season turbidity of 248 NTU (Johnson, 2007) and average rainy season turbidity[5] of 931 NTU (690 TU) (Foran, 2007)

[5] The dry season turbidity values were originally measured with the DelAgua® turbidity tube's turbidity units (TU) but were converted to the Hach® 2100 P portable digital turbidimeter's nephelometric turbidity units (NTU) using a correlation determined from data analysis: NTU = 0.7408*(TU); $R^2 = 0.9234$. TU and NTU units were compared

exceed the recommended 20-50 NTU for SSF (Wegelin, 1996). Therefore, a turbidity removal pretreatment step, such as HRF, is necessary prior to SSF.

Table 1 Results from Raw Dugout Samples in Tamale and Savelugu Districts

	Dry Season (Johnson, 2007)	**Rainy Season (Foran, 2007)**
Average *E.coli* (CFU/100 mL)	779	438
Average Total Coliform (CFU/100 mL)	26,357	12,797
Average Turbidity	**248 NTU**	**931 NTU** [5]

Given the high incidence of diarrhea in children under five in the Northern Region[6], improving dugout design in order to reduce the turbidity and make the dugout water more treatable by SSF could help to prevent cases of diarrheal disease. Dugout construction and maintenance also affects the incidence of malaria because stagnant water can be breeding areas for the *Anopheles* mosquitoes. Some potential dugout improvements could be to (Ludwig, 2005):

- Pick a cleaner a source;
- Keep water cool to slow bacterial growth;
- Raise the pH of the water by adding lime;
- Prevent leaks through improved pond-floor lining;
- Place *Gambusia* (mosquito fish) in dugout water to feed on *Anopheles* larva;
- Build natural vegetative barriers to prevent runoff-carried particles from entering the dugout.

When dugouts dry up, many communities are forced to purchase water from water vendors which can be very costly as seen in Table 2 (Okiago, 2007).

Table 2 Cost of Vended Water in Tamale Area (Okiago, 2007)

Water Source	**Quantity (liters)**	**Price (US$)**	**Price per Liter**
Vended	20 L	$0.17	$0.0085
Vended	200 L	$0.94	$0.0047
Tanked water via a third party	1000 L	$3.00	$0.0030
	Average		**$0.0054**

using the student's t-test and linear regression. The t-test gave a p-value of 0.04 which is less than 0.05 so the null hypothesis is rejected and it is likely that there is significant difference between the outcomes of the TU and NTU.

[6] According to the Ghana Statistical Services' data from 2003, 15.3% of children under five years of age have diarrhea.

Alternatively, people are forced to walk longer distances to collect water.

2.3 Water quality of dugout water in Northern Ghana

Long-term water quality data is often lacking because funding is unavailable, workers are untrained and inexperienced with the testing methods, and the correct laboratory and field equipment are inaccessible. Despite these challenges, the WHO GDWQ and engineers working in developing countries emphasize the importance of matching the correct particle removal design with the problem (WHO, 2004) (Wegelin, 1996). According to Howard (2003), communities need to be part of the water quality collection, testing, and analysis of results or at least be informed of results if outside entities complete them. It is particularly important that they learn which water sources are most contaminated, because this might cause positive behavioral change.

Prior to the general hydrogeological and water supply summary done by Gyau-Boakye (2001), very few technical studies explored the quantity and accessibility of Ghana's drinking water supplies. In 1968, Lartey and Smith (1968) published a report investigating water issues from an economic and health standpoint with an emphasis on the impact population growth has on rural water supplies. Smith's rudimentary report in 1969 touched on urban water supply development, potential hydropower development projects, and river basin management but lacked data and conclusive findings especially about drinking water sources and their quality. Ofosu's report (2006) on the *Hydrogeology of the Voltaian Formation of the Northern Region Ghana* explores the limitation of groundwater resources. No report offers in-depth information about surface water problems in the Northern and/or Upper East and Upper West Regions where agriculture, livestock breeding, and human development is greatly limited by highly turbid, seasonal surface water supplies. Neither records of turbidity nor chemical composition were found for dugouts in NRG.

Although, in this study, the community was not part of the water quality surveillance, if a dugout water quality study were expanded, community participation and decision-making would be a key piece of the study. When trying to understand the quality of a water source, the WHO suggests data be gathered about the following subjects, in addition to the actual water quality parameter measurements taken (WHO, 1996, Table 4.1):

- Catchments;
- Geology and hydrology;
- Meteorology and weather patterns;
- General catchment and river health;
- Wildlife;
- Competing water uses;
- Nature and intensity of development and land use;
- Other activities in the catchment that potentially release contaminants into source water;
- Planned future activities.

Currently, most of these steps do not occur in NRG.

2.3.1 Waterborne and water-related disease

Many waterborne diseases come from fecal pollution from human and animal sources that wash into surface water. Defecation nearby or the location of a latrine uphill puts the water body at higher risk of fecal contamination with waterborne diseases such as diarrhea, typhoid, infectious hepatitis and cholera and water-related such as Guinea worm and bilharzias. The incidence of such diseases is very high in communities that drink untreated surface water. The morbidity of such diseases can have serious economic implications for people who are infected and find themselves unable to work or take care of their family. This is particularly true for rural subsistent farmers whose harvests may decrease because they were unable to work during an important point of the crop's growing season.

2.3.1.1 Guinea worm

*Dracunculus medinensis*is, also known as Guinea worm disease, is an ancient parasitic disease that was once widespread and is still endemic in Ghana and Sudan. It mainly affects poor populations in remote, resource-limited communities in Africa where there is inadequate access to potable water, health care, and education. This debilitating helminthes disease was called the "empty granary" disease in Mali because it left subsistent farmers incapacitated for such long periods of time that they lost part or all of their harvest. In 1986, it was estimated that 3.2 million people in 20 endemic countries in Africa and Asia were infected and 125 million were at risk of infection[7]. Eradication became a recognized target of the World Heath Assembly in 1991(WHO, 2004). The success of a global eradication campaign is mainly attributed to adequate funding and the strong leadership of the Centers for Disease Control, UN's Children Fund (UNICEF), the WHO, and the Carter Center which persuaded National Ministries of Health, local NGOs, the private sector, village volunteers, and infected individuals to make eradication of this debilitating disease a priority. Despite initial skepticism about the effectiveness of a behavior-based intervention plan, the Guinea Worm Eradication Program has become an example of the possibility of using cost-effective methods of controlling and even eliminating a disease at a national level.

The Guinea worm disease cycle begins when a person drinks contaminated water from a stagnant source that contains copepods[8] capable of transporting the Guinea worm larvae. Inside the human body, the copepods are killed by strong stomach acid and disperse larvae which travel into the small intestine. Sixty to ninety days later the male and female larvae mate. During the next year the female grows to be two to three feet long. Symptoms include a burning sensation in the infected area, fever, and occasionally diarrhea. As the female worm reaches full maturation, she burrows out of the skin in search of a water source where she can lay her larvae. Instinctively, individuals submerge the infected area in cool water to sooth the pain. Unfortunately, the cool water stimulates the blistered skin to rupture and release hundreds of thousands of larvae. There is no vaccine to prevent or medication to treat guinea worm disease, however, simple filtration of contaminated water with a cloth, sand, or ceramic filter will remove the copepods, which are approximately 1 mm in size and visible to the naked eye (Figure 8 and Figure 9).

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[7] The 20 countries where guinea worm disease was endemic are Benin, Burkina Faso, Cameroon, Chad, Cote d'Ivoire, Central African Republic, Ethiopia, Ghana, India, Kenya, Mali, Mauritania, Niger, Nigeria, Pakistan, Senegal, Sudan, Togo, Uganda, and Yemen

[8] Copepods small crustaceans, 1-2 mm long, present in the ocean and most freshwater habitats. Pathogens such as the cholera bacteria and guinea worm larva are ingested by the crustaceans. Those who consume contaminated unfiltered water are at risk of ingesting a copepod carrying a pathogen. http://en.wikipedia.org/wiki/Copepod

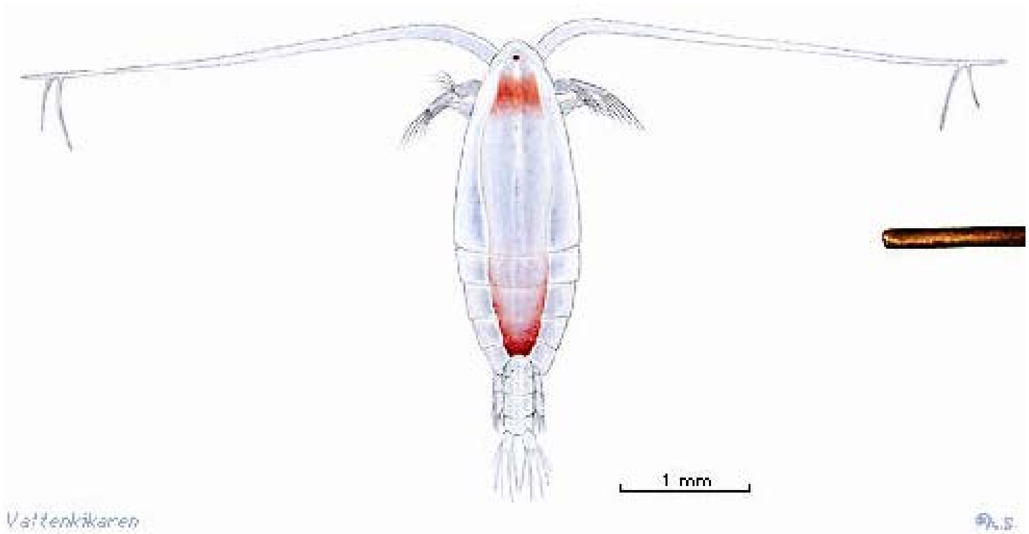

Figure 8 Copepod size in comparison to a magnified hair (http://www.vattenkikaren.gu.se/Fakta/arter/crustace/copepoda/copese.html)

Figure 9 Guinea worm educational poster (left) and Guinea worm cloth filter (right) Kpanvo, Northern Region Ghana

The main burden from the disease arises from debilitating pain and infection that can last 12 to 18 months after the worm's emergence. Although Guinea worm disease impacts all age groups, it is equally devastating to children because they miss educational opportunities and but also to adults who cannot assume the agricultural and household responsibilities which can lead to poverty and food scarcity.

The key factor in eradication of Guinea worm disease is to interrupt the transmission for one year through case identification and treatment, treatment of unsafe sources with Abate® larvicide, case containment, cloth filters, and education campaigns. Reaching remote communities most at risk of Guinea worm disease has proved to be a challenge when the affected communities are poor, illiterate, and difficult to access. The behavior change intervention promotes disease prevention education in remote communities and the improvement of their water treatment and storage. Over the years, the most cost-effective intervention proved to be 200μm monofilament nylon filters and health education and social marketing. In fact in Ghana, studies show an 80% decrease in cases in communities participating in health education and social marketing campaigns, such as US Peace Corps "worm week," the radio, T-shirts, posters, banners, stamps, painted vehicles, and video interventions, versus the 45% reduction in villages without such programs. However, because public education campaigns depend on the voluntary participation of residents and sometimes are not well received by traditional people who have their own indigenous explanations of Guinea worm, many still remain skeptical about their effectiveness. Improvement of communities' water source, though important in the long-term, was difficult to implement on a large scale due to the exorbitant per capita cost of more than $40/per person plus maintenance costs.

As a result of these coordinated efforts, the world saw a 99% drop in Guinea worm prevalence. In 2005, the majority of remaining cases were in Sudan (5569 cases) and Ghana (3981 cases). An average of 3.5 million cases has been prevented annually (Levine, 2007). This sums to 63 million cases of Guinea worm disease prevented since 1987. According to economic analysis, between 1987 and 1998, the global campaign received $87.5 million from governments and private sector donors. One notable donor in 2000 was the Bill & Melinda Gates Foundation for $28.5 million. The cost per case prevented ranged from US$5-8. This success illustrates the power of coordinating across agencies and governments to achieve a specific disease burden reduction (Levine, 2007).

Though successful, the campaign's work is not yet complete. In Sudan, progress is stalled by civil unrest. A political solution is required before any systematic intervention can be implemented. As the first African endemic country to implement a national Guinea worm disease prevention program in 1986, Ghana should have seen much more progress especially because they created a successful village volunteers' monthly reporting system that trains community health promoters to reach remote areas and allows data in rural areas to be collected. Because of its voluntary nature, it is questionable whether such a program will be effectively managed long enough to eradicate the disease. Such volunteer programs require continued organizational attention and resources to distribute, replace, and monitor the use of the nylon filters, identify and treat cases, contain cases, apply Abate® to infested dugouts, and run educational campaigns.

Other interventions focused more on improve the water source because until the supplied water is free from contamination, health problems at the household level will persist. When Guinea worm was endemic in places like Mafi Kumase in the Volta Region of Southern Ghana, horizontal roughing filtration and slow sand filtration were successfully implemented as community interventions to remove copepods from the contaminated dugout water.

3.0 Household water treatment and safe storage technology

As part of this research has been designed to help present and future Household Water Treatment and Safe Storage (HWTS) interventions better target their activities and programs in Northern Ghana, it is important to clearly define the range of existing HWTS options under consideration for the region.

3.1 History of household water treatment

Throughout the 1990s, water quality received relatively little attention among interventions to reduce the diarrheal disease burden in the developing world. The lack of investment in water quality generally was significantly influenced by a meta-analysis by Esrey et al. (1991) that concluded that sanitation and hygiene education yielded greater reduction of diarrheal disease than water supply or water quality interventions. However, more recently, a study by Fetwell & Colford (2004) commissioned by the World Bank found that hygiene education and water quality improvements have a greater impact on the incidence of diarrheal disease (42% and 29% respectively), than sanitation and water supply 24% and 23% respectively. Currently, there is evidence to suggest that safe water in the home can reduce diarrheal disease by 6-50%, independent of improved sanitation or hygiene (Nath et. al., 2006). Furthermore a recent review of more than 38 studies covering 53,000 people found that household water quality interventions were nearly twice as effective in preventing diarrheal disease 47% as community infrastructure such as improved wells and standpipes 27% (Clasen, 2006). The new research on the health benefits of household water treatment has helped draw international attention to HWTS; however, a consensus has not emerged about which treatment option is most effective. Furthermore, for any given community product appropriateness will also depend on site and cultural factors, so technology options must be assessed in the context of the local environment.

This research considers four core HWTS technologies and processes: 1) UV/solar disinfection; 2) chlorine disinfection; 3) particle removal (filtration or flocculation); and 4) combined treatment (particle removal and disinfection). In addition, we chose to consider bagged "sachet" water in this assessment. Although it is not a water treatment method, 'sachet' water provides a safe drinking water option for target, and has emerged as a popular water choice throughout Northern Ghana (Okioga, 2007).

3.2 Overview of HWTS product options

This section provides a brief overview of available HWTS options. Additional information on the cost and benefits of these technologies can be found in the fact sheets section offered by HWTS Network Tools (MIT, 2008) and the Wilson Center's "Household Water Treatment and Safe Storage in Developing Countries: A Review of Current Implementation Practices" (Lantagne et. al., 2006). The results of specific HWTS interventions have been consolidated by the International Scientific Forum on Home Hygiene in a report entitled, "Household water storage, handling and point-of-use treatment" (Nath et. al., 2006)

3.2.1 SODIS / UV

Solar disinfection is a simple and cost effective household treatment option in which clear plastic bottles are filled with low-turbidity (<30 NTU) water, shaken vigorously for oxygenation and then left outside, typically for six hours if it is sunny and two days if it is cloudy (EAWAG, 2008). After the set UV disinfection time defined for the local region, the UV radiation will have disinfected the water and it can be safely consumed. At this point, the plastic bottle acts as a safe storage container helping to protect the disinfected water from recontamination. Several recent studies have demonstrated a significant reduction of diarrheal disease using this method, especially among children under five (Conroy et al., 1996). Despite its ease of use and demonstrated effectiveness in other markets, SODIS was not considered in this research as both polyethylene (PET) and SolAqua products have been shown to be relatively ineffective in Northern Region Ghana given the turbidity of local water sources and reduction of solar radiation due to extremely high atmospheric dust during the harmattan winds, November-March (Foran, 2007; Yazdani, 2007).

3.2.2 Chlorination (disinfection only):

Disinfection through chlorination has been a known water treatment method since at least the early 1900s; however point-of-use chlorination did not emerge as a scalable HWTS option until the 1990s. During this period, the Pan American Health Organization (PAHO) and U.S. Centers for Disease Control (CDC) developed the Safe Water System (SWS) based on chlorination with dilute sodium hypochlorite solution, safe storage and hygiene education.

Effective chlorination requires the user to place the correct dose of the chlorine solution in a storage container (a larger dose is required for turbid water), agitate the water and then wait for 30 minutes before consumption. Chlorination is less effective in highly turbid water (>30 NTU) as the microbial contaminants are somewhat protected by the particulates in the water (Nath et.al. 2006). Across a number of randomized control trials, SWS has been shown to reduce diarrheal disease by as much as 44-84%. Population Service International (PSI) is a NGO that has utilized a social marketing model to implement SWS in a number of developing world countries. For example, in Zambia, PSI branded the chlorine product (Chlorin) and generated demand through behavior change communications such as radio and TV spots and point-of-sale materials (Lantagne et.al., 2006). However, despite some success, PSI has not been able to increase the price to cover full costs.

One alternative to liquid chlorine has been developed by Medentech, an Irish company. In addition to other products, Medentech markets chlorine tablets called Aquatabs[9] that come in a variety of doses including a 20 liter HWTS dose (Figure 10). Aquatabs have recently been introduced in Ghana and may be easier for consumers to transport and use than the liquid chlorine product traditionally used in the Safe Water System, but they are relatively more expensive per liter. In addition they must be used in a 20 liter container, so a product-specific protocol must be developed to stimulate effective and sustained use.

Figure 10: Chlorine disinfection - Sodium hypochlorite (CDC, 2008) and Aquatabs (Medentech)

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[9] Aquatabs are effervescent (self-dissolving) tablets which, when added to unsafe drinking water, make the water safe to drink. Aquatabs utilize the active ingredient sodium dichloroisocyanurate (NaDCC), also known as sodium troclosene and sodium dichloro-s-triazine trione. The NaDCC used in Aquatabs is approved by the US EPA and NSF International for routine treatment of drinking water for human consumption (MIT Watsan, 2008)

3.2.3 Particle removal options (filtration and flocculation)

Household scale filtration uses inexpensive local materials such as clay or sand to treat water, making it an attractive HWTS option for low income communities. However, filtration products often require some technical expertise to build and maintain, and lack of residual protection remains a key concern. There have been various studies on the efficacy and health impact of household filtration systems, including several researchers have shown positive results including: Peletz, 2006; Johnson, 2007; Brown, 2007, Stauber, 2007; and Kikkawa, 2008.

Four distinct household filtration options have been developed: 1) cloth filter, 2) biosand filter, 3) ceramic pot filter , and 4) candle filter (Figure 11). The first, and simplest, is a cloth filter which does not reduce turbidity or microbial contamination, but is effective in the removal of larger disease vectors such as the cyclops, which is responsible for the transmission of guinea worm disease. The second filtration option is the biosand filter. This slow-sand system was originally developed for centralized treatment at the community scale, but has been modified to provide a HWTS option. Biosand filters are relatively easy to use, and the flow is immediate and substantial enough to provide water not only for drinking but also for cooking and washing. Biosand filters have been shown to reduce bacteria and viruses by as much as 90% (HWTS Network Tools); however, recontamination remains a significant concern. Furthermore, biosand efficacy has not yet been demonstrated in the extremely turbid waters seen in Northern Ghana, although local studies are currently underway (Kikkawa, 2008). Ceramic filters offer a third filtration option. The ceramic products help limit recontamination as they are combined with a safe storage container, but they also have a slow flow rate with a maximum of only 1-4 liters / hour. One of the most well-known and widely distributed ceramic filters is the "Potter's for Peace" model which is shaped like a flowerpot and impregnated with colloidal silver. It has been shown to remove 99.9% of bacteria (Johnson, et.al. 2008), but must be cleaned regularly to ensure a continuous flow. The "Potter's for Peace" style filter provides a safe storage container with a tap, which helps to limit recontamination; however, as there is no residual chlorine protection the user must be trained to clean the ceramic filter element frequently. PHW's primary product, the *Kosim*, is a ceramic pot filter which has been distributed to 10,000 households to date in Northern Ghana. More expensive versions of the ceramic filter are also available on the market (e.g., British Berkefeld; Katadyn). These higher-end models tend to have cylindrical ceramic "candles" sometimes containing colloidal silver or additional media such as activated carbon. Candle filters are primarily used by high-income households and foreign travelers in Ghana, but have not reached a price point where they are an option for wide-spread distribution. Overall, household filtration is an attractive HWTS option; however, there is some variation in efficacy, ease of use, and cost between filter types and designs, so site specific product assessments should be conducted before introduction in a new market.

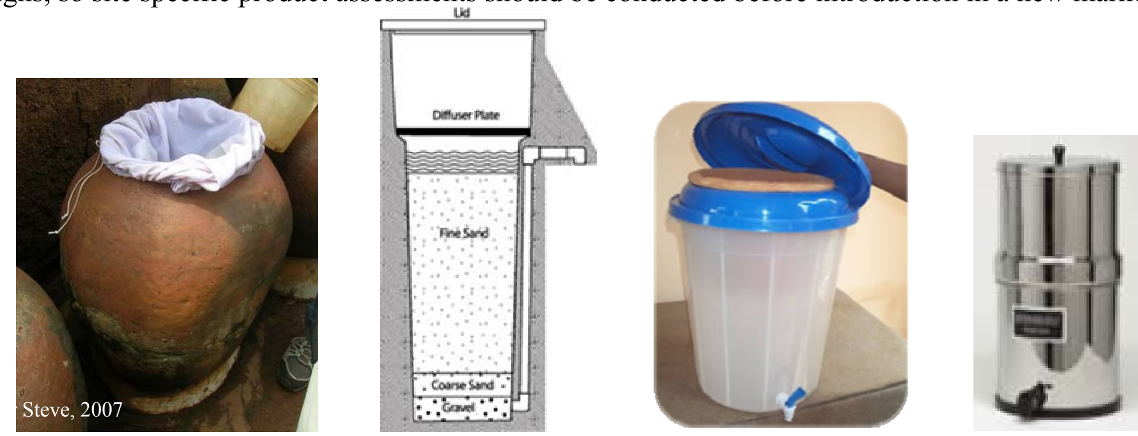

Figure 11: Household filtration options - Cloth, biosand, ceramic pot, and candle filter

Particle removal may also be achieved by using a flocculent such as moringa seed or alum[10]. Such products are locally available in Ghana and have traditionally been used to manage water with very high turbidities. Flocculants are known to effectively remove suspended particles and improve microbial quality. Preliminary research on alum coagulation in Northern Ghana has demonstrated 99.7% removal of total coliforms and 99.4% removal of *E. coli* (Foran, 2006). This removal rate is comparable to that achieved with biosand or ceramic filters. However, as flocculants do not remove all the microbial contaminants during the treatment process, they are not being considered here as a stand-alone HWTS option.

3.2.4 Combined system (particle removal + disinfection) options

Combined particle removal and disinfection options have recently been developed to more effectively manage the highly-turbid, microbially contaminated surface waters being used as household drinking water sources in many parts of the developing world.

The best-known combined treatment product on the market is PuR™, a single-dose product produced and widely marketed by Proctor and Gamble (P&G) as a part of a collaborative effort with the United States Centers for Disease Control (Figure 7). PuR™ is sold in sachets designed to treat 10 liters of water, and includes a flocculent (ferrous sulfate) as well as chlorine disinfectant (calcium hypochlorite). PuR™ is sold at cost for $0.035 cents per sachet to non-profit organizations, such as PSI, who are currently engaged in product testing and distribution in East Africa. In addition, PuR™ can be bought commercially by retailers and travelers for $0.05-$0.11/sachet. PuR™ has been extensively tested and shown positive health impacts in Pakistan (Luby et.al., 2006), and Kenya (Crump et.al., 2005). However, PuR™ is not currently being considered as an option for Northern Region Ghana in part because of its relatively high cost but also because it is not currently available in the region.

An alternative option for combined treatment is to use two distinct products in combination such as a *Kosim* ceramic pot filter or alum followed by a chlorine product, such as Aquatabs (Figure 12). Such combinations using two distinct HWTS methods in separate steps have received very limited research to date. However, water quality impacts of combining *Kosim* with Aquatabs has recently been studied in northern Ghana (Swanton, 2007), and a few experiments using alum as a flocculent followed by chlorine have shown the positive impacts on diarrheal outcomes (Reller et.al. 2003). Therefore, such products may offer a locally relevant solution for the low-income communities with highly turbid water seen in Northern Ghana. However, widespread implementation will require the development of an effective model for dosing and effective use.

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[10] Alum is aluminum sulfate (Al2 (SO4)3).H2O which is perhaps the most commonly used coagulant worldwide. A coagulant is a chemical which, when added to water, enables small particles to aggregate into larger flocs. Coagulation is a widely applied process in urban water treatment plants around the world, and is also sometimes applied at a household scale, for example, in India parts of Southeast Asia and China (MIT WatSan, 2008)

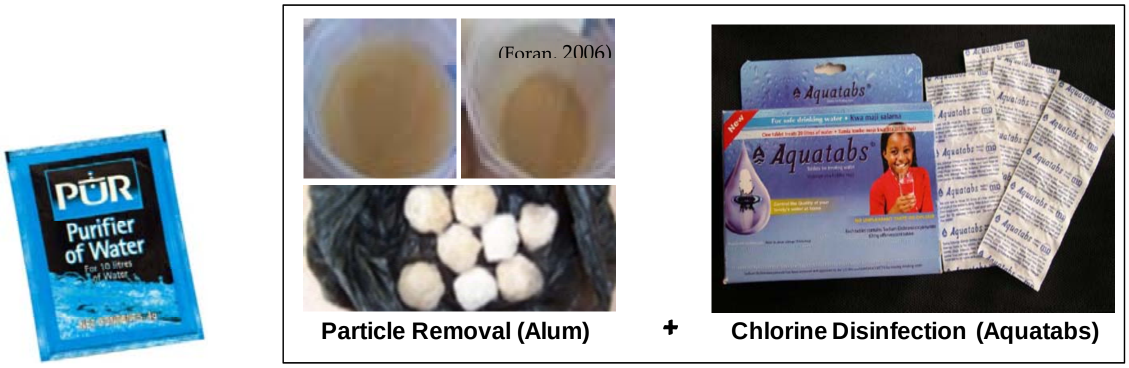

Figure 12: Combined treatment options - PuR^{TM} sachet or Alum + Chlorine Disinfection

3.2.5 Sachet water

Finally, sachet water has emerged as a popular choice among urban populations in cities and town throughout the developing world. In Ghana, there are two types of sachet water: hand-tied and factory-produced. These products tend to be produced in bulk in a centralized location, and then sold in individual units in local markets and road-side stands. The sachet product has demonstrated commercial viability in Ghana, and thus it offers an interesting benchmark and microenterprise model. For a detailed description of the production and water quality seen in sachet water in Tamale, Ghana the reader is referred to "Water Quality and Business Aspects of Sachet-Vended Water in Tamale, Ghana" (Okioga, 2007).

3.2.6 HWTS tradeoffs: role of consumer preference

As highlighted in the high-level product overviews above, efficacy of HWTS interventions varies by geographic region, source water characteristics and community type. HWTS adoption rates and project sustainability depend heavily on the cultural relevance of the HWTS solution selected, the implementation strategy and the local ability and willingness to pay. Therefore, consumer understanding along with assessments of product appropriateness for local conditions and relative cost are needed to determine which products have the greatest potential for long-term sustainable impact in a given region.

4.0 Pilot Study of Horizontal Roughing Filtration in Northern Ghana as Pretreatment for Highly Turbid Dugout Water

Tamar Rachelle Losleben

4.1 Abstract

In Northern Region Ghana (NRG), earthen dams called dugouts collect highly turbid rainwater runoff and intermittent stream flow. These dams serve as many communities' main source of drinking and domestic water despite their physical and microbial contamination. Slow sand filtration (SSF), a low-cost technology for treating microbial contaminated drinking water is only recommended for water < 50 NTU. Two research objectives were established to address this issue: to characterize dugout particle sizes and distribution and to test a pilot horizontal roughing filter's (HRF) effectiveness at removing turbidity from highly turbid dugout water. Among the four dugouts tested in NRG, they typically have high concentrations of non-setttleable colloidal (< 1µm) and small supracolloidal particles (< 10µm). In addition, a pilot HRF at Ghanasco Dam in Tamale, NRG was conducted using three 7m tubes filled with three sizes of granite gravel, local gravel, and broken pieces of ceramic filters arranged by decreasing size. The pilot study was run for 52 days to test if HRF could reduce the high turbidity (305 NTU) to < 50 NTU to make SSF a viable option. There were a number of promising outcomes: the best performing media, the granite gravel, by removing an average 46% of the influent turbidity, produced an average effluent turbidity of 51 NTU which almost achieved the goal of < 50 NTU. The granite gravel HRF removed twice as much turbidity (46%) as plain settling (25%). Overall, the granite gravel removed 76% and 84% of the influent turbidity according to the settling test and pilot HRF data respectively. Three recommendations derived from this pilot HRF study are (1) to monitor dugout water quality, (2) to investigate media and particle properties to enhance colloidal particle removal (3) to modify the HRF to effectively remove very high dry season turbidities and likely even higher rainy-season turbidities from dugout water.

Keywords:

Roughing filtration, horizontal roughing filtration, slow sand filtration, turbidity, Northern Region Ghana, dugouts, drinking water sources, physical water quality

4.2 Introduction

Approximately 50% of the population in Northern Region Ghana (NRG) collects drinking water from unimproved sources such as dugouts[11], rivers, unimproved dugwells, and tankers (GSS, 2006). Dugouts are manmade rain harvesting ponds that are an unreliable source and of poor microbial quality averaging 779 *E. coli* CFU[12]/100 ml in the dry season (Johnson, 2007) and 438 *E. coli* CFU/100 ml in the rainy season (Foran, 2007). The average dugout turbidity in NRG is extremely high ranging from 248 NTU

[11] Dugouts will be used synonymously with dams or rain harvesting ponds that catch and store runoff and water from intermittent streams.
[12] CFU stands for colony forming unit and refers to viable cells.

(Johnson, 2007) in the dry season to 931 NTU[13] in the rainy season (Foran, 2007). Many waterborne diseases such as diarrhea, typhoid, cholera, and infectious hepatitis come from fecal pollution from human and animal sources that wash into this surface water. Other water-related diseases such as Guinea worm and bilharzias are also prevalent. The incidence of these diseases is very high in communities that collect and drink untreated dugout water. The morbidity of such diseases can have serious economic implications for people who are infected and find themselves unable to work or take care of their family.

Difficulties arise in the microbial treatment of highly turbid water because particulate matter can enhance microbial growth, inhibit clear detection of microorganisms, and interfere with SSF and disinfection processes, making them less effective and more expensive (Health Canada, 2001). The World Health Organization (WHO) suggests that more turbid water creates greater risks of acquiring a gastrointestinal illness (WHO, 2004). Water of 5 NTU or lower is acceptable in taste and appearance to most consumers (WHO, 2004).

Although rainwater usually carries few particles, rain runoff carries suspended particles into the dugouts worsening the water's physical water quality. Other sources of turbidity include algal growth, erosion of loose soil, deposition of dust from the air, wind advective mixing of lake sediments, water collection, fishing, and humans and animals entering the dam. Characterization of particle size and distribution greatly vary depending on the climate, soil type, the slope of the area, and land use practices.

High turbidity negatively impacts the effectiveness and durability of low-cost community and household scale drinking water treatments such as slow sand filtration (SSF), ceramic pot filtration (*Kosim* filters[14]), and chlorination. While dugouts can and should also be improved as storage basins, effective and appropriate technologies that do not rely on chemical treatment to treat and reduces raw dugout water to < 50 NTU are needed at the community level.

This problem was approached with two objectives:

1. To improve dugouts as a surface water source to decrease the cost of treatment.
2. To reduce the turbidity of dugout water to make slow sand filtration a possibility.

The first objective was approached by testing four dam's physical water quality in order to better understand the suspended particles' sizes and settling behavior. The second objective was targeted by constructing and testing a pilot horizontal roughing filter (HRF) at Ghanasco Dam in the semi-urban area of Tamale, NRG, to determine its effectiveness at reducing the dugout turbidity to a level adequate for SSF.

4.3 Removal and disinfection of waterborne pathogens in highly turbid water

SFF and chlorination are two of the most common, low-cost and easily maintained water treatment systems for surface waters in developing countries. To extend the runtimes of SSF, literature guides suggest SSF influent be less than 50 NTU (Galvis, Visscher, Fernández, & Berón, 1993). Not only does highly turbid water require longer chlorine contact times and the addition of more chlorine compounds,

[13] The dry season turbidity values were originally measured with the DelAgua® turbidity tube's turbidity units (TU) but were converted to the Hach® 2100 P portable digital turbidimeter's nephelometric turbidity units (NTU) using a correlation determined from data analysis: NTU = 0.7408*(TU); R^2 = 0.9234. TU and NTU units were compared using the student's t-test and linear regression. The t-test gave a p-value of 0.04 which is less than 0.05 so the null hypothesis is rejected and it is likely that there is significant difference between the outcomes of the TU and NTU.
[14] *Kosim* filters are household ceramic filters fabricated the local NGO Pure Home Water according to the NGO Potters for Peace's design.

but disinfection may not be effective enough against pathogens within flocs or particles for turbidities > 0.1 NTU (WHO, 2004). The presence of particles can create a habitat for bacteria that stimulates their growth. Organic matter and chlorine could react to form disinfection byproducts; however the WHO prioritizes the provision of pathogen-free drinking water and reduction of the incidence of waterborne illness above the control of disinfection by-productions (WHO, 2004).

4.4 Horizontal roughing filtration pretreatment

A horizontal roughing filter (HRF) basically acts as a large sedimentation tank where the settling distance is reduced by the presence of a coarse media such as gravel allowing colloidal particles to settle. HRF can effectively remove colloidal-size particulates without the addition of coagulant chemicals and also provide a large solids storage capacity at low head loss. Sedimentation and adhesion to media particles are the main particle removal mechanisms (Schulz & Okun, 1984).

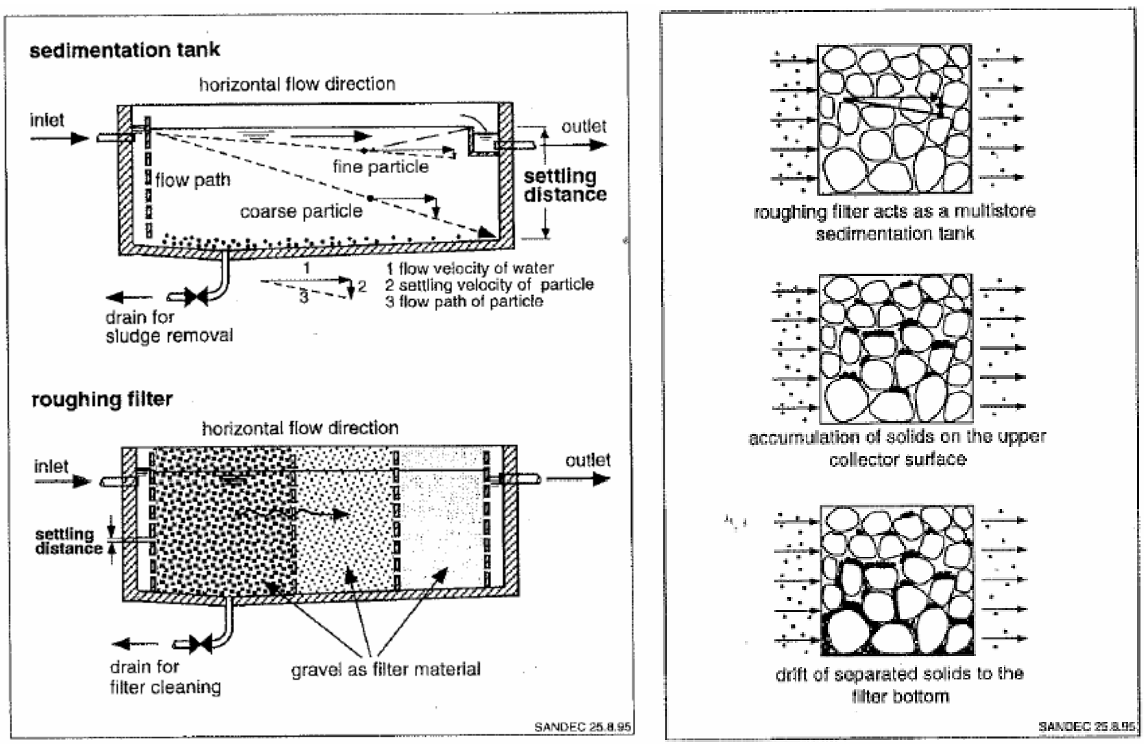

Figure 13 Solids removal in HRF (Wegelin, 1996)

Allowing a granular media filter to ripen and form a biofilm strongly influences the quality of water produced because fine particles adhere to and accumulate on the media (Amirtharajah, 1988). With time, as the HRF stores more particles, the filter efficiency increases until the filter flow is inhibited by the accumulated particles and the filter media must be cleaned.

In the 1980s, Water and Sanitation in Developing Countries (SANDEC) and the Centro Inter-Regional de Abastecimiento y Remoción de Agua (CINARA) received funding to promote HRF and standardize its design, operation, and maintenance practices (Wegelin, 1996) (Galvis, Latorre, Sánchez, & Sánchez, 2006). Since then, roughing filters have been implemented in more than 25 countries[15] (Wegelin, 1996). The first HRF in Ghana was built in the Volta Region in Mafi Kumase in the mid-1990s as part of SANDEC's surface water treatment program for roughing filter (RF) pilot projects in rural areas headed by Martin Wegelin and supported by a team of local Ghanaian engineers including Afrowood Consulting Ltd. led by Dorcoo Kolly from Mafi Kumase (Figure 14).

Figure 14 Mafi Kumase HRF: dirty gravel media (left) and view of HRF from the inlet (right)

To maximize the particles collected, HRF requires a low filtration rate of 0.5-2 m/h (Boller, 1993, Wegelin, 1993). For maximum and average turbidities of 650 and 84 NTU respectively, CINARA suggests a filtration rate of 0.3 m/h (Galvis et al., 1993). Because maximum turbidity values in NRG are over 1000 NTU during the rainy season, the filtration rate may have to be as low as 0.3 m/h to achieve an effluent of 50 NTU.

When properly operated and maintained, HRFs have performed well. According to the WHO Drinking Water Quality Guidelines (2004), RF can remove 50% of bacteria from raw water and up to 95% if the system is protected from turbidity spikes by a dynamic filter or if it is only utilized when ripened. In Sudan's Blue Nile Health Project (BNHP), the gravel and brunt brick media in the HRFs respectively removed 87% and 77% of the influent turbidity that ranged from 40-500 NTU (as cited by Wegelin, 1996). In contrast, a pilot HRF system at the International Institute for Water and Environmental Engineering (2iE) in Ouagadougou, Burkina Faso produced a HRF 4-19 NTU effluent with only a 32% mean turbidity reduction (Figure 15)(Sylvain, 2006). The difference between the BNHP and 2iE HRF is the raw water quality; the later turbidity was ten times higher than the former allowing for a greater percentage of the turbidity to be removed. Given the turbidity range in NRG, a HRF needs to reduce the influent turbidity by 80-90% to produce a 50 NTU effluent.

[15] In 1995, HRFs were in use in Costa Rica, Colombia, Peru, Bolivia, Argentina, Burkina Faso, Ghana, Cameroon, Sudan, Ethiopia, Kenya, Tanzania, Malawi, Zimbabwe, Swaziland, Madagascar, South Africa, Pakistan, India, Sri Lanka, Burma, China, Thailand, Malaysia, and Indonesia, and Australia.

Figure 15 2iE HRF pilot study, Ouagadougou, Burkina Faso (Sylvain, 2006)

4.3 Materials and methods

4.3.1 Sampling techniques

Water samples were collected from the shore of four dams near Tamale from customary collection points. Daily samples from the pilot HRF were taken to monitor it for 52 days from January 13, 2008 to February 28, 2008. If a filter valve clogged, the valve was readjusted and water was allowed to flow for 3-5 minutes before sampling.

Microbial samples from the dam and the tanks were collected by dipping the 100 ml Whirlpack® bag below the water surface. Pilot HRF system microbial sample were collected from the effluent tubes in Whirlpack® bags. The microbial samples were stored in a cooler with ice packs and processed within six hours of their collection. One surface soil sample was taken from the periphery of Ghanasco Dam.

4.3.2 Physical water quality tests

The Simple Methods for Water Quality Analysis from SANDEC's *Surface Water Treatment by Rouging Filters: A Design, Construction, and Operation Manual* was used (Wegelin, 1996). These water quality tests use durable, inexpensive equipment to make water quality monitoring and filter performance possible in low-income communities. They were used to characterize the physical particle properties of four dams in the Tamale area and monitor the performance of the Ghanasco Dam pilot HRF.

Turbidity[16]

In the field turbidity was measured with a DelAqua® turbidity tube[17] in turbidity units (TU). For all other lab procedures, turbidity was measured in nephelometric turbidity units (NTU) using a Hach® 2100 P portable digital turbidimeter.

Fitrability

The filterability test is a low-cost substitution for suspended solids, but it only yields relative values of solid matter removal. One-hundred milliliters of water was added to a 250ml cylinder of a filter set[18] with

[16] Suspended solids are not to be confused with turbidity. While turbidity is a measurement of the cloudiness or haziness of water due to particles blocking light as it tries to pass through the sample, suspended solids are the measure of the actual particle mass per mass of water.
[17] The DelAqua® turbidity tube measures: 25.5cm long, outer diameter of 2.8cm, and inner diameter 2.3cm.
[18] The filter set includes a 250ml cylinder, 250ml filter support, and filter disk.

a 1.5µm polycarbonate capillarpore membrane filter (Hach® FT-3-1101-047). The filtrate volume was recorded at 1, 2, and 3 minutes.

Solids Settleability

One liter of water was added to an Imhoff cone. The amount of settled solids (ml) was recorded after 15 minutes, 30 minutes, 1, 2, 4, 8, and 24 hours.

Suspension Stability

One liter of water settled for two days. The settled water turbidity was measured at 0, 15, 20, 60, 90, and 120 minutes and 4, 8, 24, 32, and 50 hours with a turbidimeter.

Sequential Filtration

The influent and effluent turbidity of separate water samples that filtered through 1µm, 8-12µm, and 20-30µm filter papers[19] on a filter set was measured using a turbidimeter.

4.4 Physical water quality of dams

The physical water quality of four dams close to Tamale in NRG was tested: Ghanasco Dam (also the site of the pilot HRF), Gbrumani Dam, Kpanvo Dam and Kunyevilla Dam (Figure 16). These dams differed in the way water is accessed and their level of watershed protection.

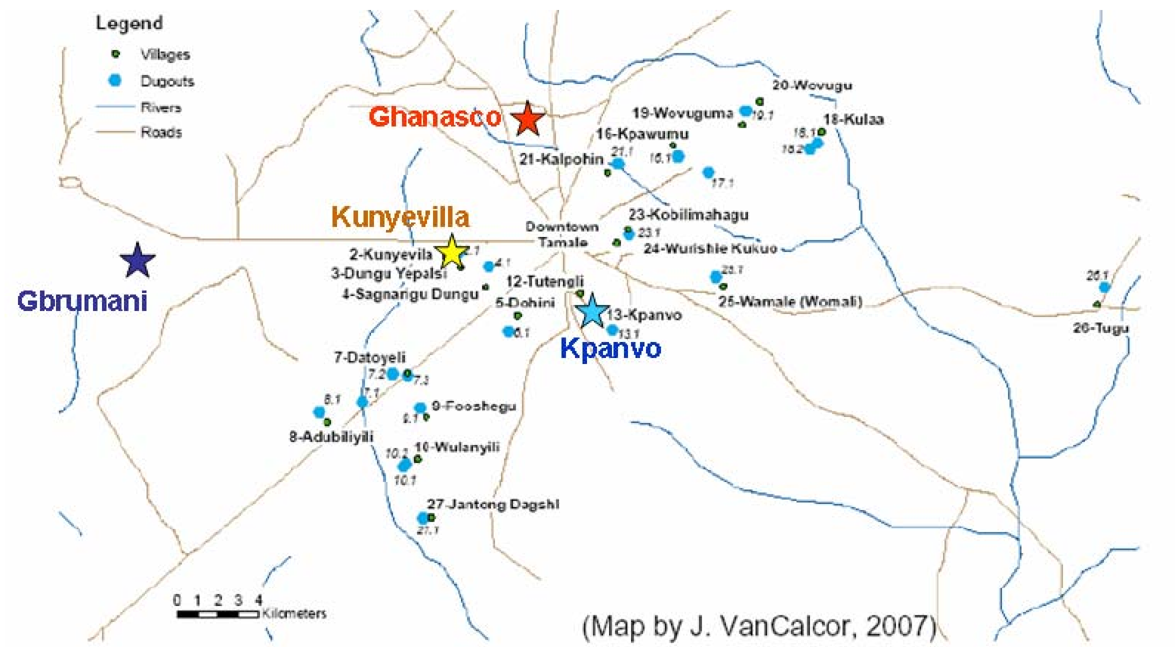

Figure 16 Map of Tamale and locations of dugouts

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[19] Polycarbonate capillarpore membrane, 47mm filter papers were used (ZB921, Schleicher & Scull)

4.4.1 Description of dam sites

Figure 17 Ghanasco Dam (pilot HRF site) (left) and Gbrumani Dam and hand pumps

Photo Credit: Susan Murcott, 2007

Ghanasco Dam is a large dugout that does currently not dry up. Water is collected directly from the muddy shores of the dam. It does not have a fence, reeds, or grasses around its periphery (Figure 17).

Gbrumani Dam is surrounded by a natural barrier of tall grasses and a fence. It has five hand pumps with gravel infiltration galleries[20]. One sample was taken from the hand pump water and one directly from the dugout (Figure 17).

Figure 18 Kpanvo Dam with treadle pump (left) and Kunyevilla Dam (right)

Kpanvo Dam[21] surface area is smaller than Ghanasco Dam and its periphery is also denuded of reeds and grasses. We were informed that it would dry up with the next 1-2 months at which point the community would need to purchase water (Figure 18).

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[20] These improvements were built by Rotary International and the Carter Foundation.

[21] Kpanvo Dam received five treadle pumps from the Guinea Worm Eradication Campaign (GWEC) so individuals would no longer wade into the dam to collect water. The treadle pump spouts were covered by Guinea worm cloth

Kunyevilla Dam has a large surface area, no periphery fence, and very little grass along its clay-packed periphery. It was drying up very quickly at the time of the visit on January 21, 2008. Women purchase water from Tamale once the dam dries up (Figure 18).

4.5 Ghanasco Dam pilot HRF system details

Ghanasco Dam's average turbidity during the test was 374 NTU. The dugout's proximity to the Peace Corps Tamale Sub Office (TSO) and to the Tamale market made purchasing and transporting materials, taking water samples back to the TSO (where the laboratory was located), and monitoring the system convenient.

Figure 19 Ghanasco Dam, Tamale, Northern Region Ghana

4.5.1 Design and construction

The construction of the HRF was completed with locally available PVC pipe and two 700L polytanks according to the design in Figure 20. Four tubes were assembled with different media inside (Figure 21). The ends of the 7 meter 4" PVC pipe were capped with a 90º elbow angled upward to keep the tubes full of water.

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filters to ensure that any water collected was free from copepods. After three days of use, two of the five treadle pumps were already in need of repair. Beneficiaries were using the remaining three pumps. All individuals also received free pipe filters from the GWEP while free biosand filters were disseminated by International Aid.

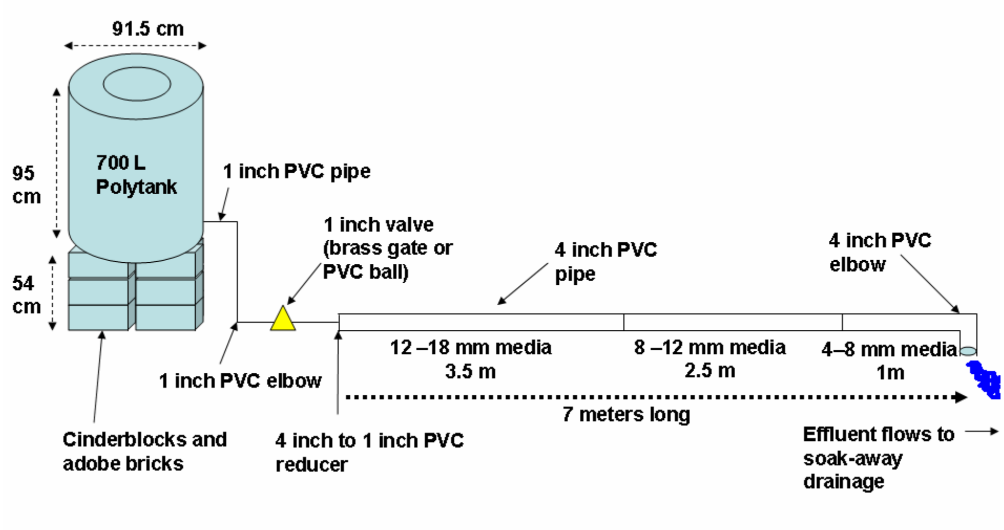

Figure 20 Detailed design of the Ghanasco Dam pilot HRF

The granite gravel (G), local gravel (D), and broken pottery (P) media were cleaned and sorted by size. A small amount was placed in a plastic sieve and plunged in clean water three times. The sieve basket was then passed to the next water bucket and plunged into the water three times. Finally, this was repeated a third time or until further plunging did not dirty the water. Once washed, mesh screens with 5 mm openings were used to separate the 4-8 mm pieces. Mesh sieves with 13 mm openings were used to separate the 8-12 mm media. The largest media came from what remained on the 13 mm screens.

Figure 21 Pilot HRF media: granite gravel (G) left, local gravel (D) center, broken pottery (P) right

4.5.2 Operation and maintenance

The HRF system flow rate, tank levels, and turbidity were monitored daily. The two storage tanks were filled daily and stirred four times a day. Turbidity measurements were taken before and after mixing the tanks. Mixing helped re-suspend the particulate matter that had settled and accumulated. Filter performance is affected by turbidity and particle size. The relative particle size characterization shows how each process alters the particle sizes present.

4.6 Results and discussion

4.6.1 Physical water quality of dams

Knowledge about the type, size, and behavior of suspended particulate matter in the dams is pivotal to determining the main source of particles, how to prevent them from entering the dam water, and how to remove them from dugout water.

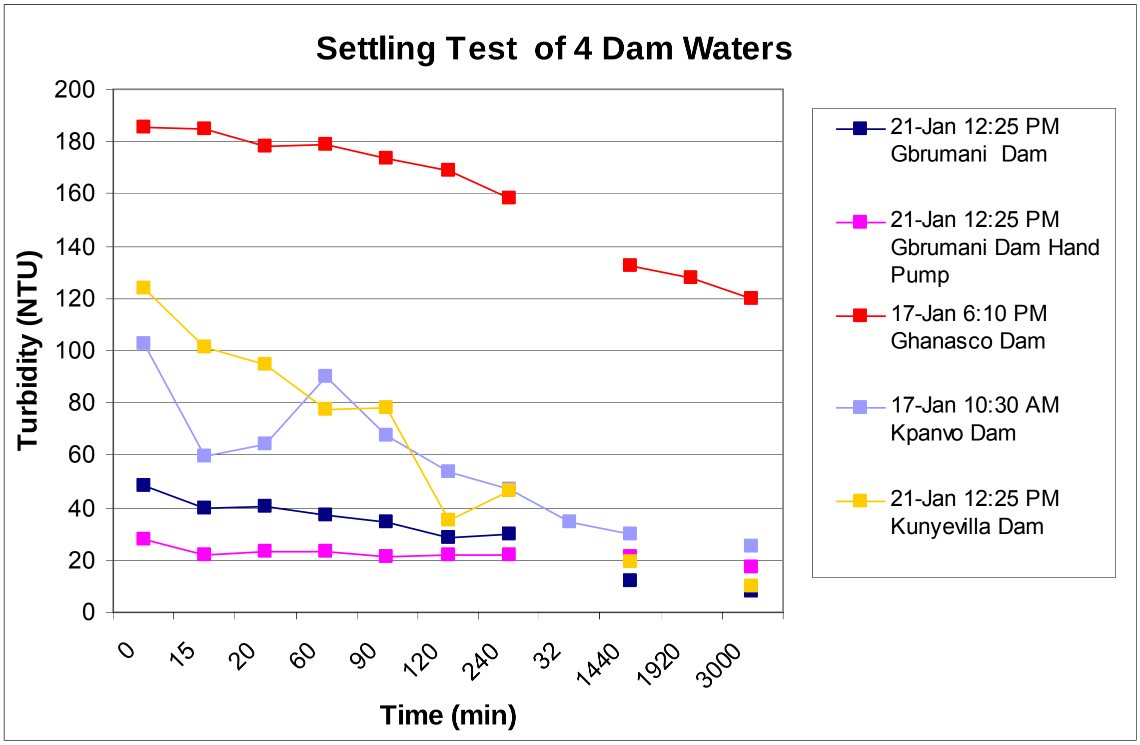

Figure 22 Settling Test of 4 Dam Waters

A water sample's relative particle size and concentration can be determined from the dam settling test shown in Figure 22. The Gbrumani Dam and hand pump samples had the fewest particles. Kpanvo Dam and Kunyevilla Dam followed a similar settling trend that shows they have larger sized particles than Gbrumani Dam because, respectively, 77% and 92% of their turbidity settles out. In comparison with Kpanvo Dam and Kunyevilla Dam, Ghanasco Dam started at the highest turbidity, but only half of its turbidity settled, leaving its settled turbidity at 125 NTU, 75 NTU higher than the maximum recommended for SSF. Water with very low turbidity reduction through settling could require a turbidity removal step such as HRF prior to SSF.

4.6.2 Pilot study – HRF performance evaluation

Turbidity removal was the main indicator of the pilot HRF's efficacy and overall, the pilot HRF at Ghanasco Dam performed well. Through gravity sedimentation in the tank, the average turbidity percent removal was 59% in the G tank and 55% in the P tank. The average effluent turbidity[22] from all of the tubes was between 51 NTU and 72 NTU (Table 3). This range of average effluent turbidities from the HRF tubes nearly satisfies the 20-50 NTU requirement for water being treated by SSF. However, unfortunately, the best performing coarse media, the granite gravel, that removed an average of 84% of the turbidity was also the most expensive at $79.67 per cubic meter (Table 3).

[22] This turbidity data was initially measured in TU with a turbidity tube and was converted to NTU according to the correlation found between TU and NTU.

Table 3 Comparison of HRF media average turbidity removal effectiveness

	Average HRF effluent turbidity	Average filtration rates (ml/min)	Media cost ($ per m^3)	Average total % turbidity reduction by HRF system	Filtration coefficient λ (min^{-1})
G granite gravel	51 NTU	220 (1.6 m/hr)	$79.67	84%	0.002
D local gravel	72 NTU	170 (1.3 m/hr)	$8.16	76%	0.0007
P broken pottery	61 NTU	200 (1.5 m/hr)	Free except for transport	80%	0.0006
Goal:	< 50 NTU	41-270 (0.3-2.0 m/h)	---	---	---

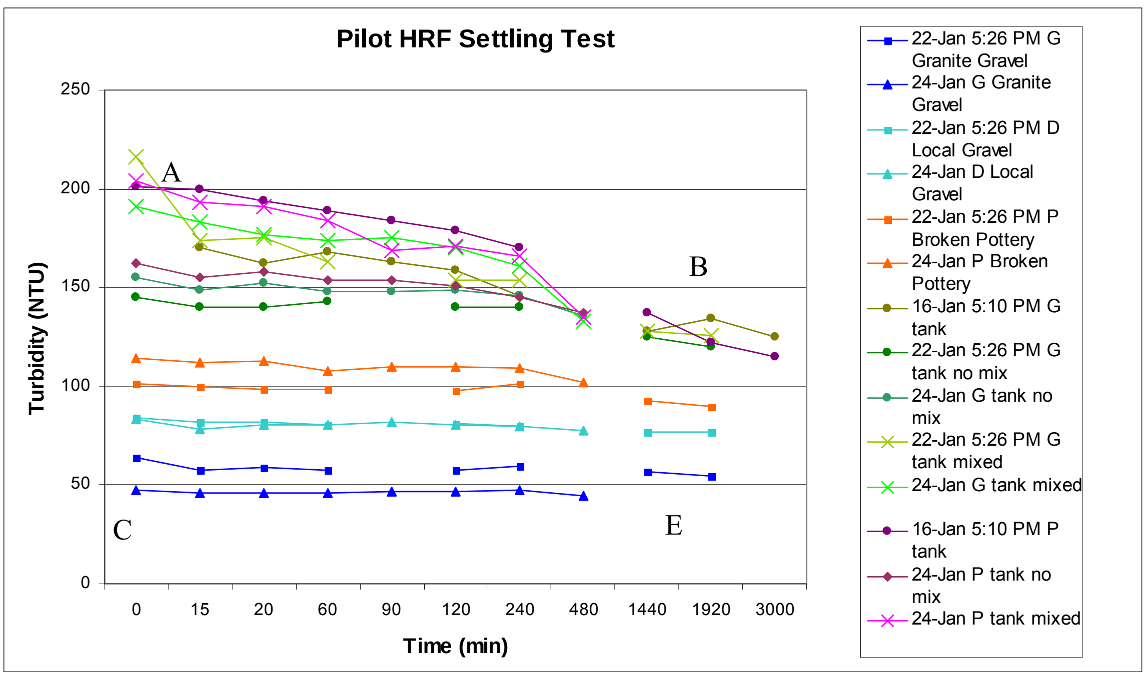

Figure 23 Settling tests for HRF tanks and effluents (G, D, and P)

Figure 23 illustrates the turbidity settling trends of two parts of the pilot HRF: the upper portion of the figure shows the settling behavior of tank water (A – maximum turbidity in fully mixed tank; B – most settled turbidity in tank) and lower portion shows the settling behavior of the HRF effluents (C – maximum turbidity of pilot HRF effluent; E – most settled turbidity of pilot HRF effluent). The settling tests showed that about 30% of the turbidity settled out of mixed tanks in 24 hours.

After two days, the mixed tanks' turbidity (A) leveled out at the settled tanks' turbidity values (B) (Figure 23). Allowing the settled tank samples to settle further showed very little reduction in turbidity. Similarly, allowing the G, D, and P effluents (C) to settle longer barely improved their turbidity (E). The amount of unsettleable particles represents the turbidity introduced by very small, colloidal particles such as clay. Therefore, the improvement that the roughing media makes on turbidity percent removal is the difference between B and C and is 46%, 30%, and 19% for the G, D, and P tubes respectively (Table 4). Including the effects of settling and the pilot HRF led to 71%, 58%, and 47% average total turbidity removals respectively for the three tubes (Table 4). Subtracting the HRF percent turbidity removal from the total percent turbidity removals yields the percent turbidity removals from plain settling: 25%, 28%, and 28% for G, D, and P respectively.

Table 4 Turbidity Removal Results from Ghanasco Dam Pilot HRF Settling Tests

	Settling test initial* tank turbidity (A)	Average settled HRF effluent turbidity (E)	Average % turbidity removal by HRF after settling in tank based on…		Average total % turbidity removal by HRF system according to the settling test
			Settling test	Turbidity records	
G granite gravel	219 NTU	52 NTU	46%	61%	71%
D local gravel	193 NTU	77 NTU	30%	47%	58%
P broken pottery	193 NTU	96 NTU	19%	55%	47%
Goal:	---	< 50 NTU	---		---

* Initial turbidity is the averaged settled and mixed tank turbidities from the settling test.

4.6.3 HRF channel design

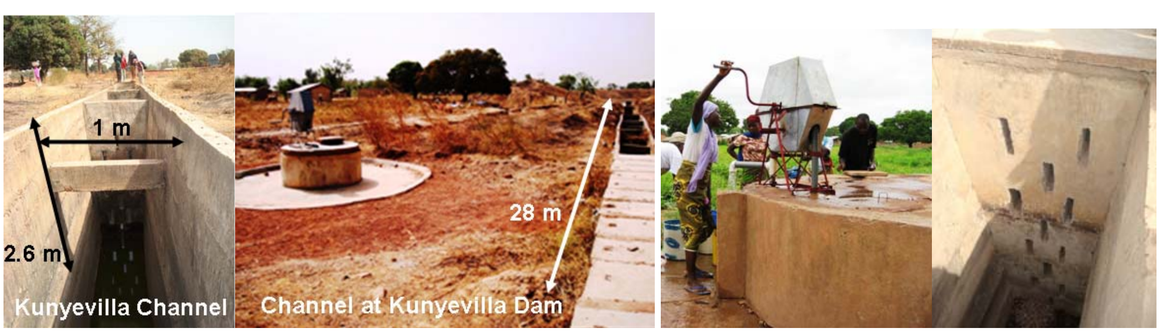

Figure 24 Kunyevilla Dam channel in the rainy season (left) and dry season (center and right)

In 2002, the local NGO Village Water built a 28-meter long covered concrete-lined channel and cistern with two rope and washer hand pumps at the Kunyevilla Dam near Tamale, NRG (Figure 24). The dugout water flows through three 4-inch diameter pipes, a 28-meter long, concrete-lined channel partially filled with large gravel, a covered 16-meter long concrete channel filled with sand, and finally reaches the sunken cistern. The channel was in a state of disuse and many of the channel coverings have been removed. It was unclear whether the channel was designed to be a HRF.

Using the filter coefficient calculated for the granite gravel (G), the best performing but most costly Ghanasco Dam pilot HRF media, a theoretical HRF was designed to be built in a concrete-lined or plastic tarp-lined channel that transported the raw water through the HRF and SSF by gravitational flow, eliminating the need for mechanical pumping. At the end of the channel, the water enters a partially underground cistern equipped with rope and washer pumps. Not only would this design simplify the system by reducing the cost of mechanical pumping, but it would also limit the amount of mechanical parts that could break and need to be repaired and improve easy access to the media for cleaning.

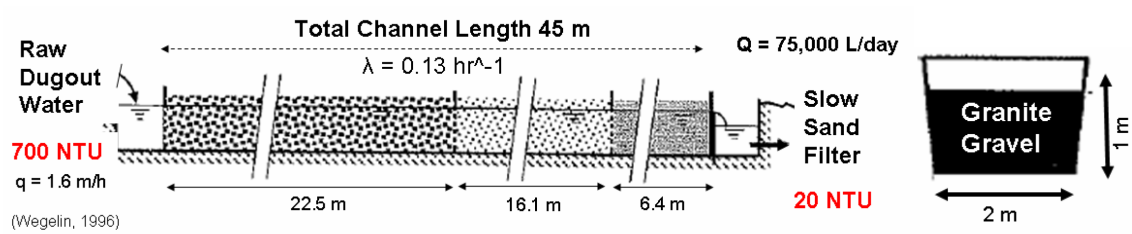

Figure 25 HRF channel design based on granite gravel filtration coefficient, side view

A number of assumptions were made:

• Beneficiary population	10,000 people
• Water demand	7.5 L/pp/day Q = 75,000 L/d or 3.12 m3/h
• Rainy season dugout mean turbidity	T = 700 NTU
• Flow rate	q = 1.6 m/h
• Cross-sectional area	A = 1.95 m^2
• Depth	z = 1 m
• Width	y = 2.m

The length of the channel HRF was determined by varying the length (x) of the channel until the effluent turbidity, $T_{0,}$ reached 20 NTU, a turbidity adequate for SSF. The channel has the same proportions of large (50%), medium (36%), and small media (14%) as in the Ghanasco Dam pilot test. The depth is only 1 m for easy removal and cleaning of the filter media. The design length of the HRF channel, 45 m, is about double the length of the 28 m Kunyevilla Dam channel. From the dam settling test, it was evident that the Ghanasco Dam particles are not as settleable as those in Kunyevilla Dam. Thus, the Ghanasco Dam HRF channel must be longer than Kunyevilla's. This suggests the Kunyevilla Dam may have been initially built to be a HRF.

4.7 Conclusions

With poor groundwater accessibility, water quantity, quality, and accessibility will become a growing problem and potentially also a source of social tension, conflict, and economic burden in Northern Region Ghana and other water scarce regions of Sub-Saharan Africa. While millions of donor dollars fund interventions provide boreholes, one complimentary long-term solution also lies in improving and protecting dugouts. Solutions that grant communities improved access to potable water must be multidimensional and focused on developing community ownership and leadership of the project and creating financially sustainable O&M systems.

The first step is to better understanding dugout water quality and their physical and chemical properties as water sources. Until this occurs, problems with treating highly turbid water will persist. In turn, as more is learned about the physical water quality of dugouts, HRF and other technologies can be modified to more effectively remove suspended particles from highly turbid waters. For the extremely turbid water in NRG, using design parameters from Wegelin (1996), the best performing media, the granite gravel (G) barely met the target turbidity of < 50 NTU with its average effluent of 51 NTU. The filtrability and sequential filtration results confirmed that the majority of turbidity remaining in the HRF tube effluents was from colloidal (< 1μm) and small supracolloidal particles (< 10μm). Given that this pilot study was run during the dry season when NRG dugout turbidities are typically lower (250 NTU), the results suggest the HRF design needs to be modified further to remove colloidal particles such as clay and to be effective treating more turbid rainy season NRG dugout water (931 NTU) (Foran, 2007).

In this pilot HRF study at Ghanasco Dam, plain settling in the HRF tanks removed an average of 57% of the turbidity, while a laboratory settling test showed about 30% reduction of turbidity through settling. The coarse media in the pilot HRF enhanced turbidity reduction by removing an average of 55% of the turbidity of raw dugout water (average 350 NTU) entering the HRF tubes from the HRF tanks. Out of the three coarse media, granite gravel (G), local gravel (D), and broken pottery (P), the granite gravel media on average removed the most turbidity at 84% turbidity removal and a filter coefficient of 0.002 min^{-1}. The results from the settling test emphasize the importance of HRF in particle removal because, on average, the granite gravel (G) media removed 46% of the initial turbidity, twice as much as plain settling, which removed an average of 25% the turbidity.

Overall, with average 80% turbidity removal and an average effluent turbidity of 61 NTU, HRF has potential as a pretreatment option for the dugouts in Northern Region Ghana. Therefore, with more investigation of the HRF effectiveness at removing turbidity from even more turbid, rainy seasons dugout water, using SSF could be a viable, low-cost treatment option in a multi-stage filtration system that first treats the raw water with HRF.

5.0 Modification of a Biosand Filter in the Northern Region of Ghana

Izumi Kikkawa

5.1 Abstract

Household water treatment is an effective approach to supply clean and safe drinking water to those who lack it, especially in developing countries. The biosand filter (BSF) is one well-known household treatment that has been successfully implemented in approximately 25 countries. However, a limitation of this filter is that it is not effective for treating highly turbid waters. A local plastic design (LPD) BSF was constructed in Northern Region, Ghana, and an experimental modification of the LPD BSF was tested to see if the modification would effectively treat highly turbid influent water. Modifications were made in order to provide an additional "biolayer," the core layer where most removal and degradation of pathogens occur. Along with two unmodified LPD BSFs, two modified LPD BSFs were built: one with an additional 5-cm sand layer, one with an additional 10-cm sand layer, which were designed to develop as the biolayer. Filter ripening was confirmed through an increase in turbidity removal after 13 days. All four LPD BSFs removed turbidity by an average of 92-95 % after Day 13. The modified BSFs showed slightly higher removal of turbidity after 27 days of operation. This could be indications that the modified BSFs possibly withstands greater operational variation, or that the modified BSFs require less frequent cleaning. Quantitative microbial results were not obtained after the filter ripening. However, the average percent removal of total coliform for the four LPD BSFs was 86 % for Day 11, with an average effluent concentration of 430 cfu/100 ml.

30 HydrAid™ BioSand Water Filters that were installed in a local village, Kpanvo, one month prior to the author's arrival in Ghana, were also evaluated. The HydrAid BSFs had an additional layer of superfine sand and were tested for evaluating the treatment of turbid water. However, the turbidity of the influent water used in the village was not extremely high (average of 32 NTU). These HydrAid BSFs showed an average of 87 % removal of turbidity, and an average of 95 % removal of total coliform, with average effluents of 2.9 NTU for turbidity and 710 cfu/100 ml of total coliform. Further research, such as testing the BSFs with water with higher turbidity which is typical to Northern Region, Ghana, is recommended to evaluate the effectiveness of the HydrAid BSF.

Keywords: biosand filter (BSF), developing country, household water treatment and safe storage

5.2 Introduction

Lack of access to safe water is a pressing issue worldwide. According to the United Nations, more than one billion people do not have access to safe drinking water and approximately 1.8 million children are dying from diarrheal diseases each year (WHO, 2004). In the Millennium Development Goals (UN, 2005), the United Nations have set Target 10 (Goal 7) to "Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation". Thus, national governments, local and international non-governmental organizations (NGOs), private enterprises, communities, and individuals have been trying to increase access to safe water and sanitation.

For water supply, the United Nations has reported good expectations to meet the MDGs (UN, 2005). However, it has also been recognized that there are serious gaps between the results in rural and urban areas. Among the population without access to an improved source of drinking water, 84 % live in rural areas (WHO & UNICEF, 2006). Lack of safe drinking water in rural areas is more profound since water distribution systems cannot be easily and cost-effectively extended. Therefore, greater effort is required to provide water to the poor and those living in the rural areas.

In the past decade, household water treatment and safe storage (HWTS) has been gaining in recognition as an effective way to provide clean water to the developing countries, especially in rural areas, but also to any household seeking an additional barrier of safe water protection[4]. Different types of HWTS systems have been developed including technologies based on disinfection, coagulation, filtration, and other water treatment processes.

The Biosand Filter (BSF) is a renowned household filter that is an intermittently operated slow sand filtration unit. Approximately 270,000 BSFs have been successfully installed in 25 countries reaching more than 2.5 million people (Nichols, 2007). The BSF effectively removes giardia cysts, cryptosporidia oocysts, water-borne parasites, bacteria, viruses, iron (and iron bacteria), manganese, sulphur smell and other obnoxious odors, color, poor taste, and small particles (silt, clay and organic materials) from source waters (Lee, 2001). Laboratory studies have indicated that the BSF is capable of removing more than 5 $\log_{10}$ units of Giardia, 99.98 % for Cryptosporidium, 99.5 % of bacteria (Lee, 2001; Stauber, 2007). For physical quality, Buzunis has reported filtrate quality of less than 1NTU (Buzunis, 1995).

The purification mechanism of the BSF generally follows the mechanisms of slow sand filtration. As water is slowly passed through a bed of sand, the clay particles, microorganisms such as plankton, diatoms, protozoa, rotifers, and bacteria and some of the inorganic ions get strained out or attached to the surface of the sand grains. After the filter is mature and the *schumutzdecke* and biofilm are developed, microorganisms that get captured in this biologically active layer are predated or naturally die due to lack of food and are biodegraded into simpler inorganic forms (Huisman & Wood, 1974).

However, the efficacy of BSF under conditions of highly turbid influent water is largely unknown. Center for Affordable Water and Sanitation Technology (CAWST) recommends that the turbidity of the influent water should not exceed 50 NTU (CAWST, 2008) since the operation with highly turbid influent water will clog the filter, thus compromising performance and requiring more maintenance. Surface water in developing countries can easily exceed this limit. For example, some of the dugouts (man-made earth dams that collect rainwater and intermittent stream water) in Northern Region, Ghana show turbidities as high as 1000-2000 TU (1350 – 2700 NTU) (Foran, 2007). Extending the BSFs' abilities to treat highly turbid water would enable provision of household water treatment to many areas that only have highly turbid water.

This research focuses on enhancing the treatment capacity of the BSF, so that it would suite treatment of highly turbid water. BSFs that were constructed with a local plastic design (LPD) were also modified by the author, and were evaluated in Northern Region, Ghana. In addition, HydrAid BSFs (provided by International Aid) that were concurrently installed in Ghana were also evaluated.

5.3 Methods

5.3.1 Local Plastic Design (LPD) BSFs

A local plastic design BSF was constructed following the construction and installation manual for a plastic BSF (Ngai, Murcott, & Dangol, 2006) with some minor changes due to availability of equipment in Ghana. Modified LPD BSFs were designed so that they would have an additional biological layer, the core layer where most removal and degradation of pathogens occur. This was enabled by inserting an additional diffuser basin with a sand layer in it, between the BSF container and the original diffuser basin (Figure 27). Two BSFs were constructed unmodified (BSF A and A'), one LPD BSF was constructed with an additional sand layer of 5 cm, and another was constructed with an additional sand layer of 10 cm. The design flow rate of these BSFs was 15-20 L/hr. Maximum and minimum limits of the design flow rate are 30 L/hr and 5 L/hr, respectively (Ngai et al., 2006).

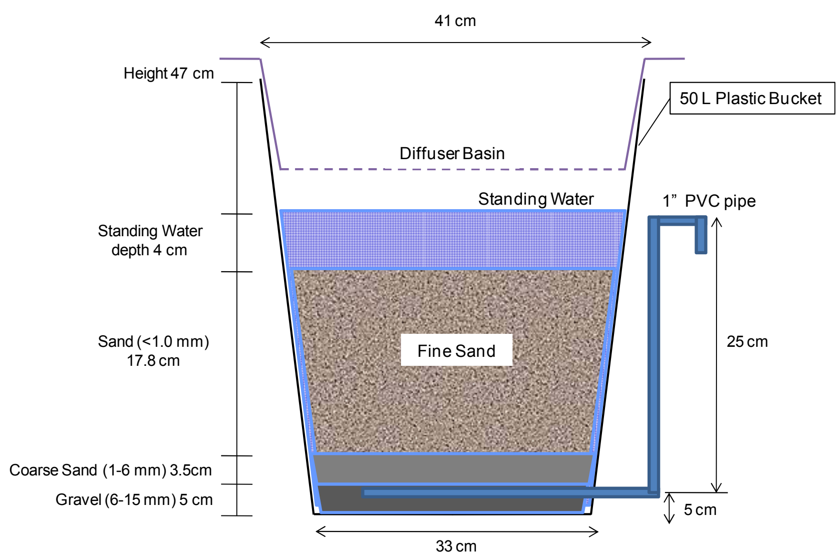

Figure 26 Schematic of a LPD BSF

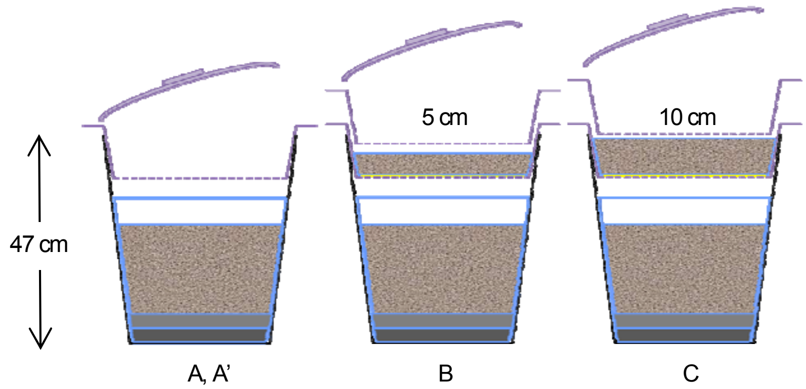

Figure 27 Schematic of the unmodified (BSF A & A') and modified (BSF B & C) LPD BSFs

All four LPD BSFs were fed 20-30 L of water from the Ghanasco Dam, a dugout in Northern Region, Ghana, every day. Before operation, the additional basins with sand were put in place on BSF B and C. First, all four BSFs were added 10-15 L of water. After letting the water flow for 3-5 min, the effluent was sampled for microbial testing and turbidity measurements. Finally, additional water was poured into the filters, so that the water level would reach the top of the filter. Flow rates were measured when the water level was maximum, thus providing a consistent head when measuring flow rate.

5.3.2 HydrAid™ BSFs

Approximately 200 BSFs (HydrAid™ BioSand Water Filter) that were provided by the NGO, International Aid, were installed in a local village, Kpanvo, one month in advance of the sampling and testing results reported here. The design flow rate for this unit is approximately 47 L/hr (International Aid, 2007). The HydrAid BSF also has a modification from the conventional BSF. While a conventional BSF has three layers: gravel, coarse sand, and fine sand, the HydrAid BSF (Figure 28) has an additional layer of superfine sand at the very top.

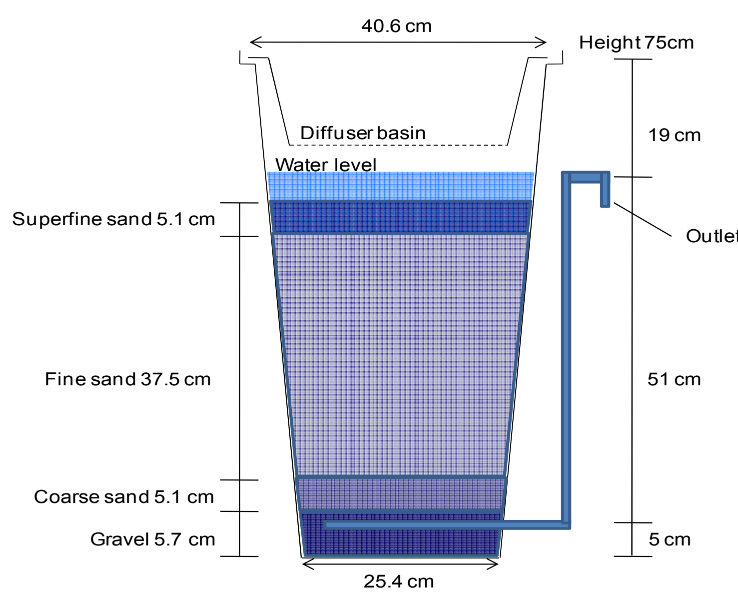

Figure 28 Schematic of the HydrAid BSF

Sampling of the influent and effluent of the HydrAid BSFs was conducted by having the villagers to pour a small amount of water (< 2 L) into the BSFs. The influent was the water stored in clay vessels outside the villagers homes, originally collected from the nearby dugout, Kpanvo Dam.

5.3.3 Analytical Evaluation Methods

Both, the LPD BSFs and the HydrAid BSFs were evaluated for flow rate, turbidity removal, and total coliform/*E. coli* removal. Turbidity was measured using the HACH 2100 P Turbidimeter for the HydrAid BSFs and Days 1 through 11 for the LPD BSFs. Turbidity measurements for the LPD BSFs during Days 13 through 46 was conducted by using a turbidity tube (DelAgua), which measures turbidity in the unit of TU. The detection limit of the turbidity tube is 5 TU. The TU units were converted to NTU units through the linear relation $y = 0.74\ x$, where y is the turbidity value in TU and x is the turbidity value in NTU.

Microbial testing was conducted by the 3M Petrifilm and Membrane Filtration Method for the evaluation of the HydrAid BSFs. The LPD BSFs were tested with the 3M Petrifilm until Day 11, and was tested for by the H_2S Bacteria Presence/Absence test after Day 12.

For the 3M Petrifilm method, 1 ml of the sample or diluted sampler are put on a Petrifilm (3M), by lifting the top film, adding the sample, and then rolling the top film down. The Petrifilms are incubated at 35 ^{o}C for 24 ± 2 hours. Then the colonies are counted for *E. coli* (blue colonies with gas) and total coliform (blue and red colonies with gas). Coliform density is reported as the number of colony forming units (CFU) per 100 ml of sample. Samples that produce more than 250 colonies are reported as "too numerous to count" (TNTC). The detection limit of the 3M Petrifilm is 1 CFU/ 1 ml of sample. Therefore, Petrifilms that show no colony forming units on the plate indicated < 100 CFU/100 ml.

The Membrane Filtration method (11th Edition of Standard Methods) was conducted by using the Milipore portable membrane filtration assembly unit, a 47 µm pore space paper, and the M-ColiBlue24 broth. 100 ml of the sample or diluted sample was filtered by creating a vacuum below the filter. Once the sample was completely filtered, the filter was placed on a petri dish that contained an absorbent pad with M-ColiBlue24 broth. The petri dish was then incubated upside down (to prevent condensate from dripping on the filtering paper) for 24 hours at 35 ^{o}C. Finally, the colonies was counted for *E. coli* (red colonies) and total coliform (both red and blue colonies).

5.4 Results

5.4.1 Local Plastic Design BSFs

The average flow rates and turbidity values from the dugout and the effluents of the four LPD BSFs are shown in Table 5. The flow rate of the four LPD BSFs showed a wide variance of approximately 15 L/hr - 38 L/hr with two outliers (Figure 29). The flow rates did not decline during the 46-day period of operation and measurements. The LPD BSFs have intentionally not been cleaned during this period.

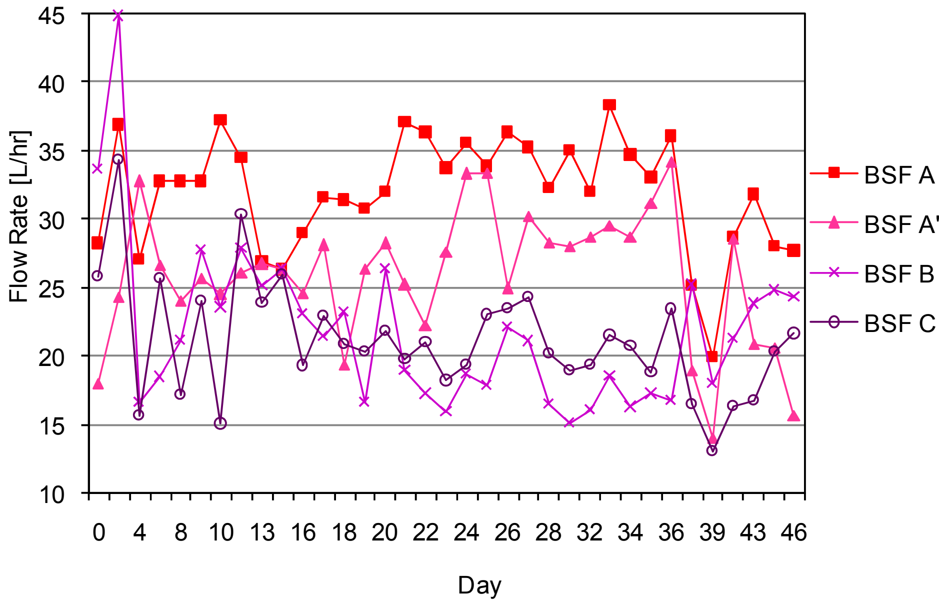

Figure 29 Flow rate of modified/unmodified LPD BSFs

The modified LPD BSFs (BSF B and C) have a slower flow rate (Table 5). This is because the additional basins with sand had slower flow rates than the basic BSF unit. Moreover, since the additional basin had a slower flow rate, it was not possible to measure the flow rates at the same maximum head as the unmodified LDP BSFs.

Table 5 Average Flow Rate and Turbidity of the Dugout and LPD BSFs

Dugout and BSFs	Average flow rate [L/hr] (standard deviation)	Average turbidity [NTU] (standard deviation) After Day 13
Ghanasco Dam		306 (97)
A (without modification)	32.0 (4.1)	22 (17)
A' (without modification)	25.9 (4.9)	20 (14)
B (additional 5 cm sand layer)	21.8 (6.0)	15 (6.8)
C (additional 10 cm sand layer)	21.1 (4.3)	14 (1.4)

The turbidity percent removal is shown in Figure 30. Here, we can see that the turbidity removal of the BSFs increase drastically after Day 13. The turbidity of the dugout varied widely from 175 NTU to 540 NTU. However, as shown in Table 5, the turbidity was overall very high with an average of 306 NTU. The water filtered through the BSFs has shown turbidities substantially lower than the raw water from the dugout, with average turbidity values of 22, 20, 15, 14 NTU for BSF A, A’, B, and C, respectively (after Day 13). Overall, the turbidity removal of the modified and unmodified LPD BSFs was significant during the period of Day 13 to Day 45, with an average of 92-95 %.

The turbidity percentage removal of the unmodified LPD BSFs (BSF A and A') declined after Day 27. The turbidity percent removal of the modified BSFs remained high during this period.

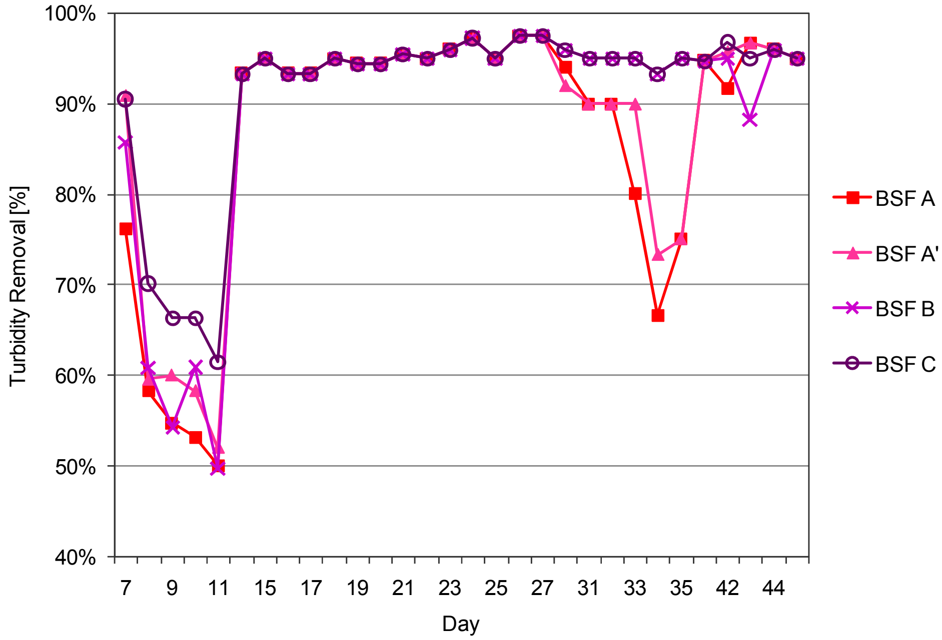

Figure 30 Turbidity percent removal of the LPD BSFs

Raw water from the dugout and the effluent of the LPD BSFs were tested for total coliform and *E. coli*. *E. coli* colonies were only detected for one sample (100 CFU/100 ml) out of the total 5 samples from the dugout. *E. coli* colonies were detected in only two samples (100 CFU/100 ml and 400 CFU/100 ml) out of 20 samples of the effluent of the LPD BSFs.

Total coliform removal results were only obtained during Days 7 through 11. The $\log_{10}$ removal of total coliform for Days 7 through 11 were calculated as ($\log_{10}$[influent] – $\log_{10}$[effluent]), and are shown in Figure 31. The average removal percentage for the four LPD BSFs was 86 % for Day 11, with an average effluent concentration of 430 cfu/100 ml. The removal percentage for BSF A, A', B, and C on Day 11 was 90 %, 83 %, 80 %, and 90 %, respectively. The effluent concentration of total coliform for BSF A, A', B, and C on Day 11 was 300 CFU/100 ml, 500 CFU/100 ml, 600 CFU/100 ml, and 300 CFU/100 ml, respectively. The average of total coliform colonies in the influent (water from dugout) during this period was 12,000 cfu/100 ml.

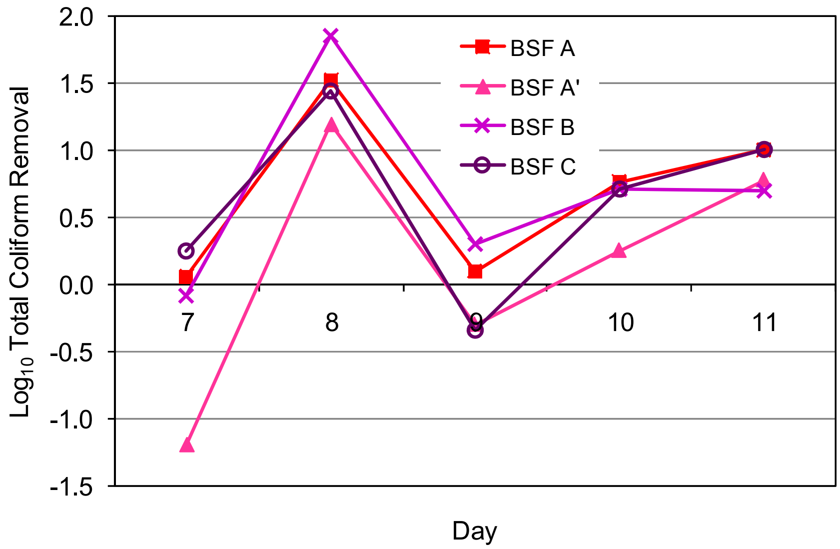

Figure 31 Log$_{10}$ removal of total coliform for day 7 through day 11

The results from H_2S Bacteria Presence/Absence tests are shown in Table 6. The results indicate that the water from the dugout had microbial contamination, and the water from the BSFs did not have the hydrogen sulfide bacteria in some cases. Therefore, while the results do not show quantitative results, we can see the trend that the BSFs were removing bacteria to some extent.

Table 6 Hydrogen Sulfide Bacteria Presence/Absence Test Results

Day	38	43	46
Dugout	Present	Present	Present
A (without modification)		Present	Absent
A' (without modification)	Absent	Absent	Present
B (additional 5 cm sand layer)		Absent	Absent
C (additional 10 cm sand layer)		Present	Absent

5.4.2 HydrAid™ BSFs

The average flow rate for the HydrAid BSFs was 17 L/hr. The flow rates were not measured at maximum head. Most of villagers have stated that they clean their filter once in every 3 days.

The average turbidity of Kpanvo Dam was 85 NTU, from three data points of 36 NTU, 85 NTU, and 135 NTU. However, due to effects of sedimentation while the villagers store their water in a clay vessel outside their house, the average influent turbidity was a much lower value of 32 NTU. The turbidity values of the influent and effluent to the HydrAid BSFs are shown in Figure 32. The average turbidity of the effluent was 2.9 NTU. The average removal percentage was 87%.

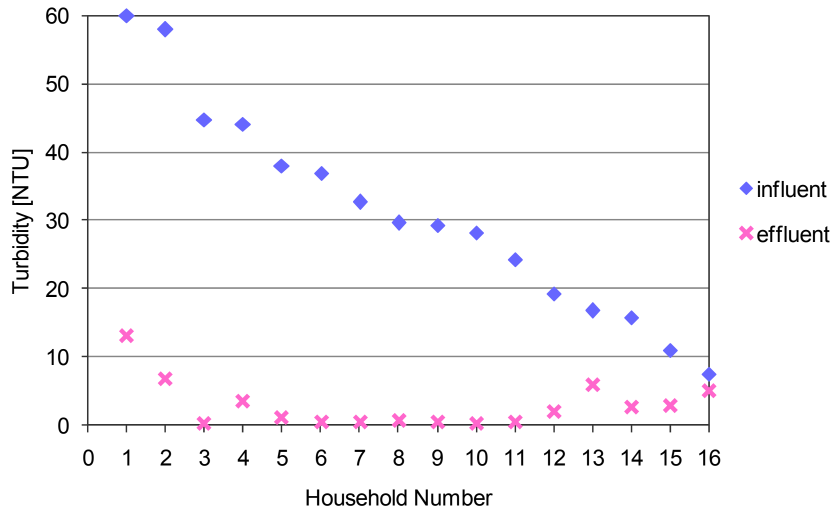

Figure 32 Turbidity Values of Influent/Effluent of the HydrAid BSFs

The total coliform colonies counted in $\log_{10}$ units for the influent and effluent is shown in Figure 33. The total coliform percent removal calculated is shown in Figure 34. The overall average removal was 95 % (1.9 $\log_{10}$ units). The average influent and effluent was 31,000 cfu/100 ml and 710 cfu/100 ml, respectively.

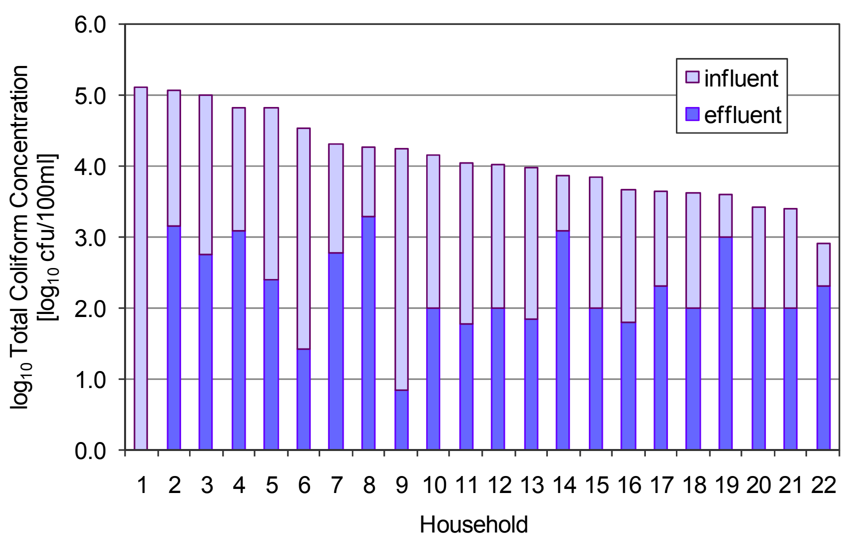

Figure 33 Total coliform concentration of influent/effluent of HydrAid BSFs

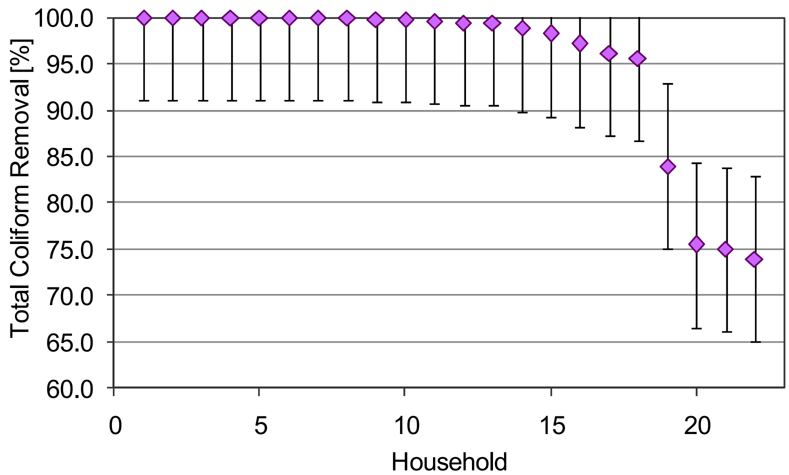

Figure 34 Removal percentage of total coliform of HydrAid BSFs

For the seven samples from the dugout, *E. coli* was only detected in one sample and the value was 10,000 cfu/100 ml. *E. coli* was detected in nine samples out of the 22 samples, collected from both the inlet and outlet of the HydrAid BSFs. The average *E. coli* concentration of these nine samples is 960 cfu/100 ml. Out of these nine samples, no *E. coli* colonies were detected from the outlet of the HydrAid BSF. By calculating the 0 count/plate results in the 3M Petrifilm method as 100 cfu/100 ml, the average percent reduction of *E. coli* within these nine samples was 55%.

5.5 Discussion

5.5.1 Locally constructed BSFs

Since the flow rates of the unmodified and modified BSFs did not decline, the filter did not clog after 46 days of operation. Although BSF A shows an average flow rate slightly above the maximum limit, the other BSFs are well within the normal range. The modified BSFs had slower flow rates due to the additional basin.

The variation in the turbidity of the water from the dugout may be due to the time and location of where the water was taken from. The water was more turbid when taken closer to bank or closer to the bottom. Other effects may be the wind conditions and the usage of the sampling site by others stirring up the sediment. It is also known that the turbidities from the dugout may differ as the dry season proceeds (Murcott, Johnson, Foran, Yazdani & Doyle, 2007). While the turbidity measurements taken by Murcott et al. showed a higher average turbidity value during the rainy season, they have also heard local users say that the water becomes more turbid as the water level in the dugout declines as the dry season proceeds. These measurements were taken under the conditions of advancing dry season.

The turbidity removal increased drastically for all four BSFs after Day 13. This indicates that the filters had ripened at this period. The time for filter ripening was consistent with previous literature stating that it takes 1-3 weeks for filter ripening. All four BSFs showed effective turbidity reduction with averages of 92-95 % after Day 13.

The decline in turbidity removal of the standard BSFs after Day 27 may be due to presumed difference in operation, such as adding water multiple times a day, or it also can be an indication that the unmodified LPD BSFs were in need of cleaning. According to the Peace Corps volunteer that was conducting the operations and measurements during the period after Day 13, the filters were occasionally operated more than one time a day. This is due to guard's drinking water from the BSFs. While it is unknown, to what extent the operation varied, or if the four BSFs were operated with the same variation, the modified BSFs (BSF B and C) did not show the same trend as the standard BSFs. The modified LPD BSFs showed the same turbidity removal as the period of Day 13 through Day 26. Although there is a possibility that the modified BSFs were treated differently by the guards, the difference in the results between the modified and standard BSFs could possibly be an indication that the modified BSFs have longer filter life (less frequent need of cleaning), or an indication that the modified BSFs withstand greater operational variation.

Quantitative results were not obtained for total coliform/*E. coli* removal after the ripening period. However, the total coliform removal was effective on Day 11 with removal percentages of 80 % - 90 %, and an average effluent concentration of 430 cfu/100 ml.

The Hydrogen Sulfide Bacteria Presence/Absence test shows the trend that the water from the dugout had microbial contamination, while the effluent from the BSFs were absent of Hydrogen Sulfide Bacteria in some cases. In order to prove the true efficacy of the locally constructed BSFs, further microbial testing is required.

5.5.2 HydrAid BSFs

The measured flow rates of the HydrAid BSFs were slower than the design flow rate of 47 L/hr. However, this is understandable since the flow rates were not measured at maximum head. Ngai et al. (2006) sets the minimum design flow rate of the *Kanchan* filter as 5 L/hr, and recommends cleaning or inspection of the filter if the flow rate is slower than the minimum design flow rate. While most villagers of the household that were visited in Kpanvo had expressed that they clean their BSFs once in every 3 days, every HydrAid BSF that was measured had flow rates higher than 5 L/hr. Therefore, clogging does not seem to be problematic under the operating conditions.

The HydrAid BSFs have shown effective turbidity removal with an average of 87 % reduction. However, it must be noted that the influent turbidity (average 32 NTU) was not extremely high. In order to truly asses the capability of treating highly turbid water, further field or laboratory experiments with highly turbid influent is recommended.

The HydrAid BSFs have also shown effective reduction of total coliform colonies with an overall average of 95 % reduction. However, the average effluent concentration of 710 cfu/100ml is higher than recommended levels set by WHO (2006).

The *E. coli* results are not as straightforward as the total coliform results since *E. coli* was not detected in a substantial proportion of the samples. In the influent samples that *E. coli* was detected, the average concentration was 960 cfu/100 ml. This was reduced to an average of <100 cfu/100 ml through the HydrAid treatment (55 % reduction). Although the percent reduction is not high, *E. coli* was reduced to an undetectable limit.

5.6 Conclusions

The locally constructed BSFs showed effective turbidity removal with an average of 92-95 % reduction. Modified BSFs showed effective turbidity removal until the end of operation, while the standard BSFs turbidity removal declined after Day 27. This could be indications that the modified BSFs have longer filter life (less frequent need of cleaning), or that the modified BSFs withstand greater operational variation. Quantitative microbial results were not obtained after the filter ripening. The HydrAid BSFs also showed effective turbidity removal of an average of 87 % reduction. The average total coliform removal was 95 %. However, the influent turbidity was relatively low. Therefore, further testing with higher turbidity influent would be required to truly assess the HydrAid BSFs' efficacy of treating highly turbid water.

6.0 Combined *Kosim* Filter and Aquatabs Treatment System in Northern Region, Ghana

Andrew Swanton

6.1 Abstract

The *Kosim* filter is a ceramic water filter that is currently used in Northern Ghana. Based on prior MIT research in Northern Ghana, this technology is effective at removing 92% of turbidity, 99.4% of total coliforms, and 99.7% of *E. Coli* from unimproved water sources. However, the product water is still microbially contaminated. The purpose of this thesis is to explore the effectiveness of combining two household water treatment technologies, the *Kosim* filter and Aquatabs, in order to achieve a more effective and complete water treatment system. Aquatabs are sodium dichlorisocyanurate chlorine tablets that are used on the household scale. They are particularly effective at killing pathogenic bacteria; however, they have predominantly been applied in emergency relief situations and have never, apart from one research study conducted by the Center for Disease Control, previously been applied in Ghana.

In this study, 59 rural households (24 in a lower-class community and 35 in a lower middle-class community) in possession of *Kosim* filters were visited as part of a three week pilot study. During the initial visit, households were surveyed about the use and perception of their *Kosim* filters, they were trained in the use and given a one week supply of Aquatabs, and their *Kosim* filtered water (without Aquatabs) was tested. After one week, the same households were re-visited. A similar survey was conducted about the use and perception of the combined *Kosim* filter and Aquatabs system, and the filtered and chlorine disinfected water was tested.

The addition of Aquatabs to the *Kosim* filtered water significantly reduced the microbial contamination; however, it did not completely remove pathogenic bacteria. The average total coliform concentration in the drinking water was reduced by 50% compared to the filtered-only water, and the percentage of households with no total coliform concentration increased from 44% to 64%. Furthermore, the percentage of households with no *E. Coli* in their drinking water increased from 88% to 98%. In terms of user acceptability, all of the survey respondents indicated that the Aquatabs "improved the taste of the water" as they associated it with municipally treated or bottled water, suggesting that the chlorine taste is acceptable to these potential consumers.

Keywords: ceramic filtration, Aquatabs, user acceptance, water quality, Northern Ghana

6.2 Introduction

There are a number of different low cost, household water treatment technologies in Northern Ghana (e.g. cloth filters, alum, candle filters, biosand filters, life straw filters). For rural communities, these household treatment options are often more practical than community scale options. One such treatment technology is the *Kosim* filter, which is a ceramic water filter that is gaining wide distribution in Northern Region, Ghana through the efforts of the NGO Pure Home Water. While this treatment option eliminates a large amount of bacteria in water sources, it does not provide 100% efficiency. Another technology is a chlorine product called Aquatabs, which has never previously been distributed in this region. The goal of this research is to determine if a combined treatment system of the *Kosim* filter and Aquatabs will result in a higher level of treatment and at the same time one that is well-liked and adopted by the users.

6.2.1 The *Kosim* filter

The *Kosim* filter is a locally made, ceramic water filter impregnated with colloidal silver. It is in the shape of a flower pot, with a volume of 8.5 L. The treatment mechanisms in the *Kosim* filter are size exclusion and chemical reaction, which remove –among other contaminants—suspended particles and bacteria. Size exclusion is controlled by the composition of the filters, which are of 50% clay and 50% sawdust. Clay is sieved to a diameter between 0.42 mm and 0.73 mm (Dies, 2003). The clay is mixed with water and then added to the sawdust particles, which have a diameter below 85 µm. Once the mixture is well-mixed, the clay is molded into a flower-pot shape with a hydraulic press, it is allowed to dry for a few days to prevent cracking, and is fired in a kiln at 887ºC (Lantagne, 2001). During the firing process, the sawdust is burned off, which leaves pores in the ceramic. Various different analytic methods have determined the pore size to be between 0.6 µm and 40 µm (Lantagne, 2001; Van Halem, 2006). Given that bacteria have a size between 0.3 µm and 100 µm (MEI, 1991), a large portion of bacteria are filtered by physical size exclusion. However, many microbes pass through the filter. To prevent this passage, *Kosim* filters are painted with two milliliters of a 3.2% strength colloidal silver solution. The silver reacts with the structural groups and proteins in the bacterial cell, produces structural changes in the bacterial cell membranes, and interacts with nucleic acids, all of which act to remove bacteria from the product water (Russell & Hugo, 1994).

Figure 35 The *Kosim* filter.

Kosim filters are tested for flow rate before distribution. If they do not have an initial flow of 1-2.5 L/hr, then they are discarded (Jackson & Murcott, 2007). However, laboratory tests of Ghanian-made *Kosim* filters have shown flow rates to be between 0.48 L/hr and 4.29 L/hr (Van Halem, 2006; Mattelet, 2006). Furthermore, the flow decreases with time from 1.84 L/hr in the first hour to 0.83 L/hr and 0.52 L/hr in the second and third hours. Use also affects flow rate. One study determined that the flow rate reduced by 50% of over a one-year period (ICAITI, 1984). One reason for this is inappropriate cleaning. As instructed, filters should be thoroughly scrubbed with brushes to the point where microlayers of clay are removed. When two dirty filters from Nicaragua were properly cleaned, the flow rates were regenerated from 0.40 to 2.1 L/hr and 0.28 to 2.0 L/hr (Lantagne, 2001; Lantagne, 2001a).

In terms of performance, *Kosim* filters have been effective at removing turbidity, total coliforms and *E. Coli*. Turbidity values in Ghana have been reduced from 100's of TUs to single-digit turbidity values, while total coliforms and *E. Coli* concentrations have been reduced by 85% to 99.7% or log reduction values of 0.82 to 2.44 (Johnson, Peletz, & Murcott, 2008). Specifically, field studies have shown total coliform reductions from 23,000 CFU/100mL to 170 CFU/100mL and *E. Coli* reductions from 690 CFU/100mL to 2.5 CFU/100mL. In terms of impact, *Kosim* filters have been shown to greatly reduce the prevalence of diarrhea. In Northern Region, Ghana, the *Kosim* filter reduces the risk of diarrhea by 42% in children under five (Peletz, 2006) and cross-sectional studies have shown that rural (traditional) households that use the *Kosim* filter are 69% less likely to have diarrhea when compared to households without filters (Johnson, 2007).

Kosim filters are locally manufactured by Cermica Tamakloe Ltd., which is located in Accra, Ghana. Two non-governments organizations, Enterprise Works and Pure Home Water, have been the primary distributers of filters. Enterprise Works sold 10,000 filters between 2006 and 2007, and Pure Home Water has distributed 10,000 in the Northern sector of Ghana and Burkina Faso since Ceramica Tamakloe Ltd. began manufacturing in 2004. Furthermore, Cermica Tamakloe Ltd. has also made direct sales in greater Accra. The total number of *Kosim* filters distributed to date in Ghana is 22,500.

6.2.2 Aquatabs

Aquatabs are household chlorine tablets, produced for everyday use and emergency relief situations. The primary chemical component of Aquatabs is sodium dichlorisocyanurate (NaDCC or $C_3HC_{l2}N_3O_3Na$) (Medentech, 2006). When NaDCC is brought into contact with water, a measured dose of hypochlorous acid (HOCL) is released, resulting in the introduction of free available chlorine (FAC). The HOCL ruptures bacteria cell walls and interacts with proteins, DNA, RNA, fatty acid groups, cholesterol, or enzymes of the cell, which ultimately inactivates the bacteria. Other chemical constituents of Aquatabs are adipic acid and sodium carbonate, which are added to maintain a constant pH of 6.2 in the water source, in order to provide optimal conditions for the HOCL to disinfect (Bakhir, 2003).

They are made in a variety of sizes in tablet or granular form, both of which self-dissolve when introduced into water. They are certified with a certificate of good manufacturing practice, which ensures that each product is produced in the same fashion. The primary purpose of Aquatabs is to kill pathogenic microorganisms, which result in waterborne disease.

Figure 36 Strip of ten 67 mg Aquatabs

Dosing with Aquatabs depends on the quality of the water source. For dirty/fecally contaminated water sources, it is recommended that the dose be doubled compared to the dose necessary for clear water sources (Medentech, 2006). The tablets used in this report are 67 mg NaDCC tablets, which are recommended for 20 L of clear water or 8-10 L of dirty water. The reason for this decrease in treatable water is due to the fact that bacteria tend to adhere to particles in water sources, which act as shields for disinfection. Therefore, more chlorine is needed to effectively treat dirty water. Recommended FAC levels are between 0.5 mg/L and 2.0 mg/L 30 minutes after dosing, according to the World Health

Organization and the Center for Disease Control, respectively (WHO, 2006; CDC, 2008). Furthermore, the free available chlorine should not drop below 0.2 mg/L 24 hours after dosing (CDC, 2008).

Studies have shown Aquatabs to be both acceptable to the user and effective at treatment. Among participants of a pilot study in Honduras, Aquatabs were the first choice among water purification options (Medentech, 2006). Furthermore, studies in Tanzania, Brazil, and Bangladesh have shown that 70-78% of study participants preferred Aquatabs to hypochlorite for reasons of taste, ease of use, etc. (Medentech, 2006; Medentech, 2006a). In terms of treatment, total coliform concentrations in water sources were reduced from counts on the order of 1,000's of CFU/100mL to as low as <1 CFU/100mL in Kenya, South Africa, Zimbabwe, Tanzania, France, Brazil, Honduras, and other countries, as a result of using Aquatabs (Medentech, 2006). Lastly, in terms of health, Aquatabs have been shown to reduce diarrheal prevalence by as much as 65.7% among users, with 85.7% reductions in severe cases (Molla, Hossain, Emondson, & Shipin, 2006).

A pilot study was conducted concerning the use of Aquatabs by the Center for Disease Control in 2006 in Northern Region, Ghana. The study surveyed 240 households over a period of three months. Over the course of the study, the percentage of households with no indication of *E. Coli* increased from 4.2% to 92% among households using Aquatabs (Blanton, 2006). 10 million Aquatabs were shipped to Ghana in September, 2007 to assist flood victims, but were not cleared through regulatory authorities until approximately December, 2007 (Losleben, 2008). The status of their distribution is unknown at this time.

6.3 Materials and methods

It is thought that by first filtering water through the *Kosim* filter and then dosing the filtered water with Aquatabs, higher quality treatment will be achieved. In order to test this hypothesis, the user acceptability and effectiveness of this combined system was tested within households in Northern Region, Ghana over a three week period during January, 2008. Due to time restrictions, 59 households already possessing *Kosim* filters were selected. 24 of the households were in Kalariga, a lower-class, rural community 2 miles southeast of downtown Tamale. The other 35 of the households were in Kakpagyili, a lower middle-class, rural community 2 miles south of downtown Tamale. Both of these communities primarily collect water from dugouts, which are highly contaminated surface water sources (also referred to as dams). The turbidity is on the order of 100's to 1000's TU, the total coliform concentrations are on the order of 10,000's CFU/100mL, and the *E. Coli* concentrations are on the order of 100's CFU/100mL for the Kalariga and Kakpagyili dugouts, which are fairly typical of many similar dugout sites used for domestic water supply, including drinking water throughout Northern Ghana.

6.3.1 Research plan for field testing

Each household was visited twice over three weeks, a baseline visit and a follow-up visit. During the baseline visit, the households were surveyed about the use of their *Kosim* filters. This was done to ensure that each household possessed a functional filter. Filtered water samples from each household were tested for turbidity in the field and were taken in Whirlpak® sampling bags to later test for the presence of microbial indicators in a sterile laboratory. Afterwards, the respondents were educated about Aquatabs, during which they were given a one-week supply and a 20 L jerry can for free. 20 L jerry cans are locally produced, safe storage containers. They were given explicitly to be used as dedicated safe drinking water containers (not water collection vessels) for the purpose of dosing with Aquatabs. To use the combined system, the households were told to fill the jerry cans with filtered water from the *Kosim* filter, dose with one 67 mg Aquatab, and wait at least 30 minutes for appropriate disinfection before consumption. Finally, the households were informed that a follow-up visit would be conducted in approximately seven days. During the follow-up visit, the households were surveyed about the use of the combined *Kosim* filter and Aquatabs system. The households were also asked how much they would be willing to pay for

Aquatabs. Similar to the baseline, filtered plus Aquatab water samples were tested for turbidity and taken in Whirlpak® sampling bags for microbial testing in the laboratory. The FAC was also tested for in the household on the follow-up visit.

This research plan was chosen because it allowed for households to use the combined system prior to the follow-up visit and it had the virtue of getting direct feedback from users of the *Kosim* alone and the *Kosim* and Aquatabs system. It was not an ideal study design in the sense that direct household-to-household comparisons between filtered only and filtered and chlorine disinfected water were not possible. This is due to the fact that the filtered water being tested during the baseline visit is not the same as the filtered water that is dosed with chlorine during the follow-up visit. Nevertheless, this study design determines the general effectiveness of the combined system, while still allowing for user acceptability insights.

6.3.2 Water Quality Testing Materials

The turbidity of the water samples was tested in the field with a turbidity tube. A turbidity tube is a two-part tube that pushes together to form one elongated tube. While testing with this tool is not as precise as using a turbidimeter, the turbidity tube provided a measurement of sufficient accuracy for the purpose of this research. The lowest value of turbidity provided by the turbidity tube is <5 TU. Also in the field, the FAC was tested during the follow-up visit with a Hach Digital Titrator Model #16900. The free chlorine powder pillows used in this research are for chlorine residuals between 0-3.00 mg/L, with precision to two decimal places.

To test the presence of microbial indicators, water samples were taken from households in Whirl-Pak® sampling bags. The samples were kept cool with portable coolers, until they were tested in the lab. The samples were diluted if necessary and placed on 3M Petrifilm™ plates. Afterwards, the plates were incubated in a Millipore Portable Field Incubator at 35^{o} C for 24 hours (+/-2 hrs). The total coliform and *E. Coli* concentrations were then counted and recorded.

6.3.3 Laboratory testing

Because dosing in this combined system is dependent on the availability of filtered water, the flow rate through *Kosim* filters was also tested. In order to achieve a comprehensive understanding of flow rate with respect to use and water quality, a combination of new and old filters were tested with various water samples.

While in Ghana, three new filters and one one-year old filter were assembled in the laboratory. Of the three new filters, two were used to test turbid and microbially contaminated dugout water and the third was used to test water with no turbidity, but with microbial contamination. The old filter was used to test turbid and microbially contaminated dugout water. All four filters were scrubbed thoroughly and rinsed prior to the addition of water. After cleaning, the filters were all filled to the top of the ceramic pot and the water level was marked on the outside of the plastic storage receptacles at various points during filtration. After all of the water was filtered, the volume of water between markings was measured at the different time intervals. For the three new *Kosim* filters, the same water sources were used to filter an additional 11-12 L of water (20 L total) in order to test the efficiency of the combined system with Aquatabs under laboratory conditions.

Lastly, once back in Massachusetts, three new *Kosim* filters were used to test local tap water, which has no turbidity or microbial contamination, with the same method described previously.

6.4 Results and discussion

6.4.1 User acceptability

Households readily accepted the use of the combined *Kosim* filter and Aquatabs system. All 59 households said "yes" when asked if the Aquatabs "improved the taste of the water." Furthermore, every household said that they would recommend Aquatabs to others, that they were easy to use, and that they didn't experience any problems with the Aquatabs. Despite these unanimously positive survey results, a number of households alluded to particular ailments associated with the use of Aquatabs. Specifically, three individual households attributed stomach aches, not feeling well, and the development of hernias and more concentrated urine to the use of Aquatabs.

The fact that the same households that answered "no" when asked if they "have had any problem using the Aquatabs" also indicated specific problems associated with the use of the product, indicates that there may be survey bias in the results. The most likely explanation is that the respondents were giving the answers that they thought wanted to be heard by the surveyor. This is likely a result of interpersonal differences between the respondents and the interviewer, due to demographics

Concerning cost, the willingness to pay differed drastically between the two communities. In Kalariga (the lower-class community), only 6 of the 24 survey respondents were willing to pay the full GHC 3 for 100 Aquatabs (approximately equal to US $3). In Kakpagyili (the lower middle-class community), 33 of the 35 households were willing to pay the same price[23]. These results indicate that while the combined system may not be financially sustainable among all people in Northern Region, Ghana, there is a potential market among particular demographics.

One relevant baseline survey result is that 80% of households fill their filters 2-3 times per week. This is relevant because if the *Kosim* filter volume is 8.5 L and the filter is filled 2-3 times per week, then households will likely only be able to dose with Aquatabs approximately once per week. Furthermore, only 7 of the 59 respondents indicated that they ever drink unfiltered water. However, considering the frequency with which the filters are filled, the volume of the filters, and the average household size in rural communities (12-14 persons per household (Peletz, 2006; Blanton, 2006), only 0.3 L of treated water would be available per person per day. With the tropical climate in Ghana, one would assume that people drink more than 0.3 L of water per day. Therefore, the response to this question may not be accurate.

Lastly, the breakage rates among the two communities varied. In Kalariga, community members had their filters for one year prior to this study and 5 of the 24 filters (21%) had experienced breakages of some sort (cracks in two storage receptacles, one lid, and one ceramic filter, and one broken tap). In Kakpagyili, community members had only had their filters for three months and none of the filters incurred breakages.

6.4.2 Field effectiveness

There are four distinct stages in the *Kosim* filter and Aquatabs treatment system. The first is the origin of the water at the dugouts. The second is the storage of the water in pre-treatment, storage vessels (roughly 2-5 per household), which is standard practice in Ghanaian households lacking a piped water supply. In

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[23] It should be noted that due to a prior study undertaken in January, 2007, people in Kalariga had received their 24 *Kosim* filters for free whereas people in Kakpagyili were in the process, at the time of this study, in paying for their *Kosim* filters on credit. This may have introduced another source of bias with the survey questions/responses.

these vessels, particles in the water sources settle, which reduces the turbidity and consequently the bacteria that have adhered to the particles. In Northern Region, Ghana, studies have shown turbidity values to decrease by as much as 76% in one day in these vessels (Losleben, 2008).

The stored water is then added to the *Kosim* filter. The filtered water from the *Kosim* filter is emptied into the 20 L jerry cans, where it is dosed with one 67 mg Aquatab once that volume is attained. One water sample was taken from the Kalariga dugout[24] and from each of the Kakpagyili dugouts. Furthermore, three random samples were taken from the pre-treatment, storage vessels among the households surveyed (one of these households used alum on the source water). The filtered-only and filtered and chlorine disinfected water was tested from each of the 59 household participants. The averaged water quality data from these four stages is presented below. The bars depict values of the three water quality parameters (turbidity, TC, EC). The "%Red, LRV" boxes indicate the percent reductions and log removal from stage-to-stage, rather than from dugout-to-stage. "Turb." refers to turbidity.

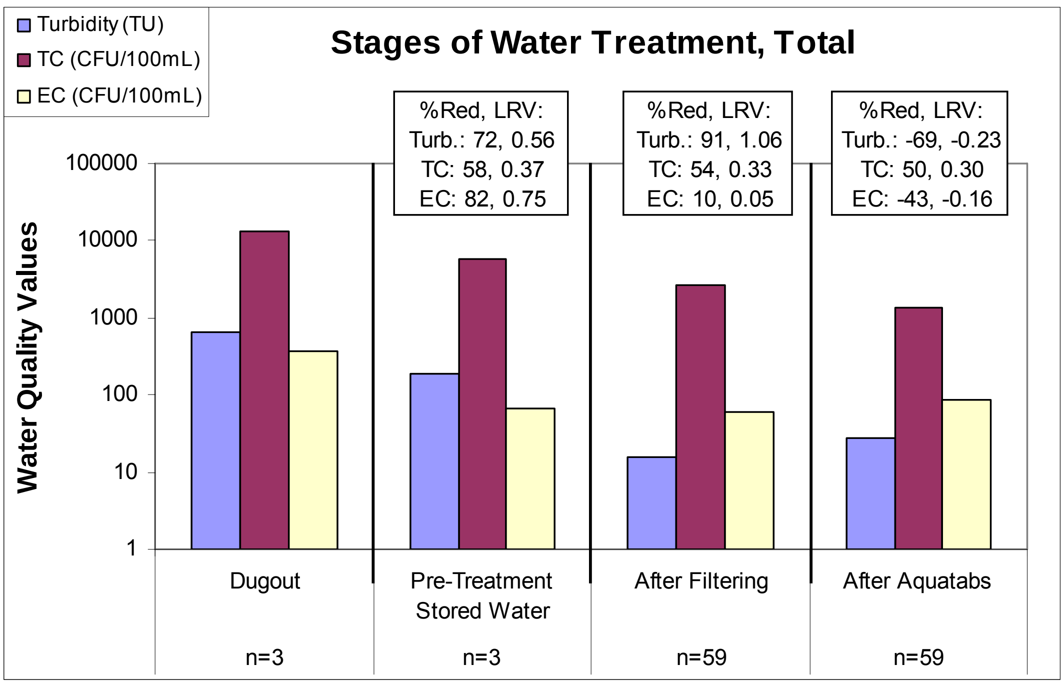

Figure 37: Average water quality data at various stages of treatment.

The turbidity decreased from the dugout to the pre-treatment, storage vessels by 72%, which is similar to the percent reduction seen in just one day from Losleben's dugout settling research in 2008 (Losleben, 2008). However, this is in part due to the fact that one of the three pre-treatment, storage samples was cleansed with alum and so had no turbidity in the sample. Omitting that result, the turbidity percent reduction from source to pretreatment is 59%. The majority of the remaining turbidity is removed during filtration, as expected. However, the average turbidity increased from the filtered-only samples to the filtered and chlorine disinfected samples. Among filtered only samples, 5 of the 59 households had a turbidity value greater than 5 TU, while among the filtered and chlorine disinfected samples, 10 of the 59

[24] The Kalariga dugout dries out at a certain point into the dry season, at which time the community members travel to the Ghanasco Dam, which is approximately 1 mile from Kalariga.

households had a turbidity value greater than 5 TU. One explanation for this would be if the filters were cracked or somehow dysfunctional. However, none of the households with turbidity during the baseline were the same as the households with turbidity during the follow-up, which disproves the hypothesis that the variation was due to dysfunctional filters. Another potential explanation could be that this study was performed during the middle of the dry season—a time when dugouts are drying up and hence potentially concentrating the turbidity. A final explanation is that this turbidity increase is due to natural variation as opposed to a result of using the Aquatabs.

The *E. Coli* results show significant reductions. Figure 37 indicates that the average *E. Coli* concentration increases as a result of chlorination. However, the average concentration is not truly indicative of the actual effectiveness. This is due to the presence of an outlier in the data set. Among the filtered only samples, seven indicated the presence of *E. Coli*. These seven samples had concentrations within a 50-200 CFU/100mL range. Among the filtered and chlorine disinfected samples, only one sample indicated the presence of *E. Coli*. However, this one sample had a concentration of 2,200 CFU/100mL, resulting in an average *E. Coli* concentration of 86 CFU/100mL among all households (compared with a 60 CFU/100mL concentration among filtered-only samples). A truer indication of the effectiveness of the combined system is that the percentage of households that did not indicate the presence of *E. Coli* increased from 88% at baseline to 98% at post-intervention.

The average total coliform concentration decreased among each of the four stages of treatment. From dugout to pre-treatment, the average total coliform concentration decreased by 58%. While this is partially due to the use of alum in one of the pre-treatment, storage samples, the gravity settling of particles also likely aided in this reduction. The average total coliform concentration was further reduced by 54% after passing through the *Kosim* filter, resulting in average concentration of 2,635 CFU/100mL in filtered-only samples. After chlorine disinfection, the total coliform concentration reduced by another 50%.

While this is a marked reduction, the average total coliform concentration from filtered and chlorine disinfected water samples was still 1,328 CFU/100mL. Similar to the *E. Coli* results, this high concentration is most likely due to the presence of outliers in the data set. One filtered and chlorine disinfected water sample in Kalariga had a total coliform concentration of 42,000 CFU/100mL, which is 127% larger than the most contaminated filtered-only sample taken. Moreover, this sample was taken from Kalariga, where the next highest total coliform concentration among filtered and chlorine disinfected samples was 47 times lower (900 CFU/100mL). If this outlier were omitted from the data set, the average total coliform concentration from all households would be reduced to 627 CFU/100mL, resulting in a 76% reduction from filtered-only to filtered and chlorine disinfected water samples.

Given that outliers likely affected the results, the total coliform data may be better understood by observing the percentage of households with reduced concentrations (46%) versus the percentage of households with increased concentrations (17%) as a result of using Aquatabs. This means that 37% of household water samples remained the same. The reason that 17% of households had increased concentrations is likely a result of natural variation. The filters will not consistently produce water of the same quality every time. Therefore, by comparing filtered only water with different filtered water (that has been chlorinated); one is not obtaining a true indication of the improvement of the Aquatabs only.

Table 7: Decreasing/Increasing TC Contamination Trends among Communities Before and After Using Aquatabs

Community	TC Count Decreased	TC Count Increased	TC Count Remained the Same

Kalariga	15/24=63%	3/24=13%	6/24=25%
Kakpagyili	12/35=34%	7/35=20%	16/35=46%
Both	27/59=46%	10/59=17%	22/59=37%

The last water quality parameter tested in this study was the FAC residual. FAC results from the Center for Disease Control study in Northern Region, Ghana were reported as the percentage of households with a residual greater than 0.1 mg/L at the time of the visit (Blanton, 2006). In that study, 50-85% of the samples were above the 0.1 mg/L benchmark. Additionally, over 90% of the households in that study had access to piped water, which was presumably already dosed with FAC. In this study, 64% of households had a chlorine residual above 0.1 mg/L.

Furthermore, there was a correlation between the FAC and the microbial contamination of the water samples. The "n=x/y" values on the x-axes indicate the number of samples with either a reduced or increased TC concentration (x) out of the total number of samples with that specific FAC range (y). The percentages from the two graphs do not sum to 100% because many of the household's TC concentrations remained the same from baseline to follow-up.

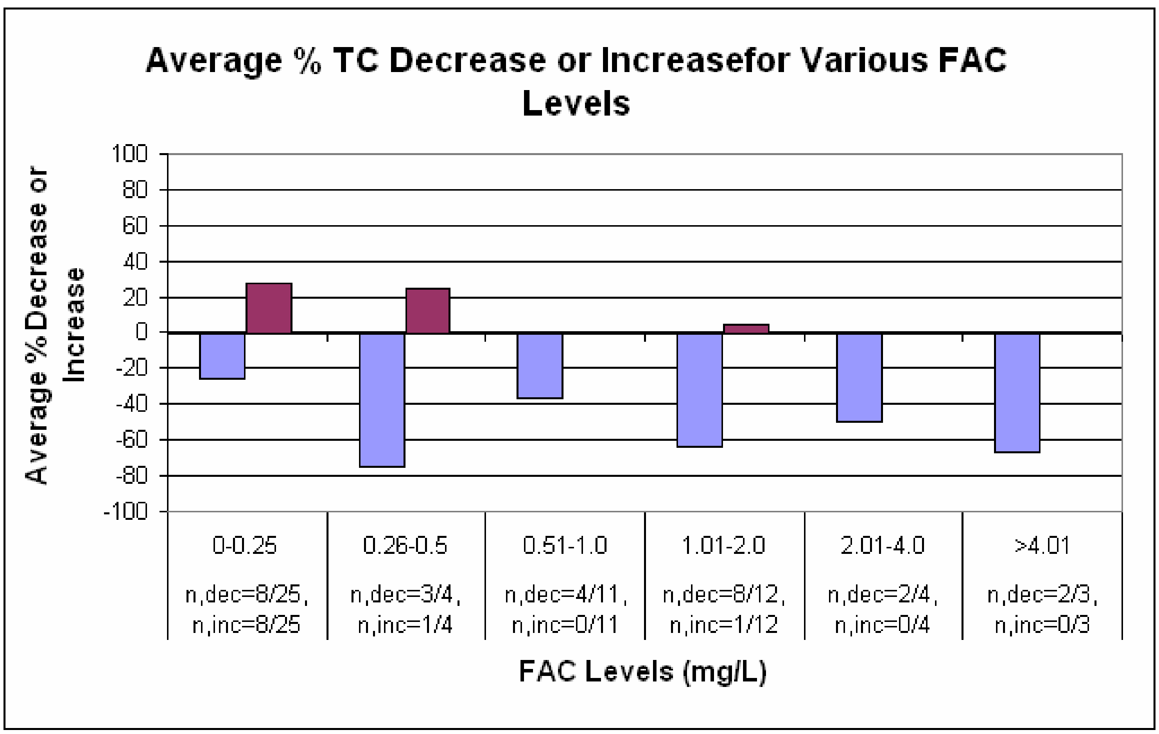

Figure 38: Percent of households that had reduced and increased TC concentrations at post-intervention for different FAC ranges.

There is a general trend in Figure 38 that increased chlorine residual leads to more household reductions in total coliforms. When the FAC levels are between 0 and 0.25 mg/L, 32% of the households have reduced total coliform values and 32% of the households have increased total coliform values (36% remained the same). However, when there are FAC levels between 1.01 mg/L and 2.0 mg/L, 67% of the households have reduced total coliform values and 8% of the households have increased total coliform values (25% remained the same). This direct correlation between FAC levels and % reductions—and indirect correlation between FAC levels and % increases—in total coliform concentrations is fairly consistent over the various FAC ranges presented.

There are similar correlations between the FAC levels and the *E. Coli* concentrations, as well. The only household of the 59 surveyed that indicated the presence of *E. Coli*, had a FAC level of 0 mg/L. Additionally, this household had dosed their water the same day of the survey, which likely means that the filtered-only water was highly contaminated and that all of the chlorine released from the Aquatab was consumed in killing a fraction of the bacteria present in the water sample. Also, of the seven households that indicated the presence of *E. Coli* in their filtered-only water samples and did not indicate the presence of *E. Coli* in their filtered and chlorine disinfected samples, four of the post-intervention samples had a FAC level greater than or equal to 0.5 mg/L. The three remaining samples all had a free available chlorine level of 0 mg/L. For these three samples, only one was asked the last time that they dosed their water. This household had dosed their water five days prior to the visit, which explains why their FAC level was so low. It is highly possible that the remaining two households that had EC present in the filtered-only samples and no EC present in the filtered and chlorine disinfected samples and also had a FAC level of 0 mg/L, only had a 0 mg/L FAC level because of the time elapsed from dosing.

6.4.3 Laboratory effectiveness

Three water samples with varying water quality were tested with new *Kosim* filters and Aquatabs. None of the samples indicated the presence of *E. Coli*. The first water sample had a turbidity of 200 TU and a total coliform concentration of 100,000 CFU/100mL, both of which were removed beyond detection after filtering (and remained below detection after chlorination). The second water source had a turbidity of 300 TU and a total coliform concentration of 2,150 CFU/100mL. After filtration, the turbidity was reduced below detection, but the total coliform concentration increased to 7,300 CFU/100mL. One explanation for this is that the storage container used for testing may have been previously contaminated. However, after dosing this clear, contaminated water with Aquatabs, the total coliform concentration was reduced below detection. The last water sample had no turbidity and the total coliform concentration reduced in each treatment stage. Initially the total coliform concentration was 3,000 CFU/100mL. After filtration the total coliform concentration was reduced to 1,700 CFU/100mL and after chlorine disinfection the total coliform concentration was further reduced to 400 CFU/100mL.

Finally, the FAC values for the samples were 0.97 mg/L, 1.15 mg/L and 0.69 mg/L for the three water samples, respectively. All three samples were within the Center for Disease Control recommendations of a minimum FAC value of 0.5 mg/L 30 minutes after dosing and a maximum value of 5.0 mg/L.

6.4.4 Flow rate

From the flow rate tests performed in this research, microbial contamination and prolonged use both impede the flow rate through *Kosim* filters, while turbidity does not affect flow rate.

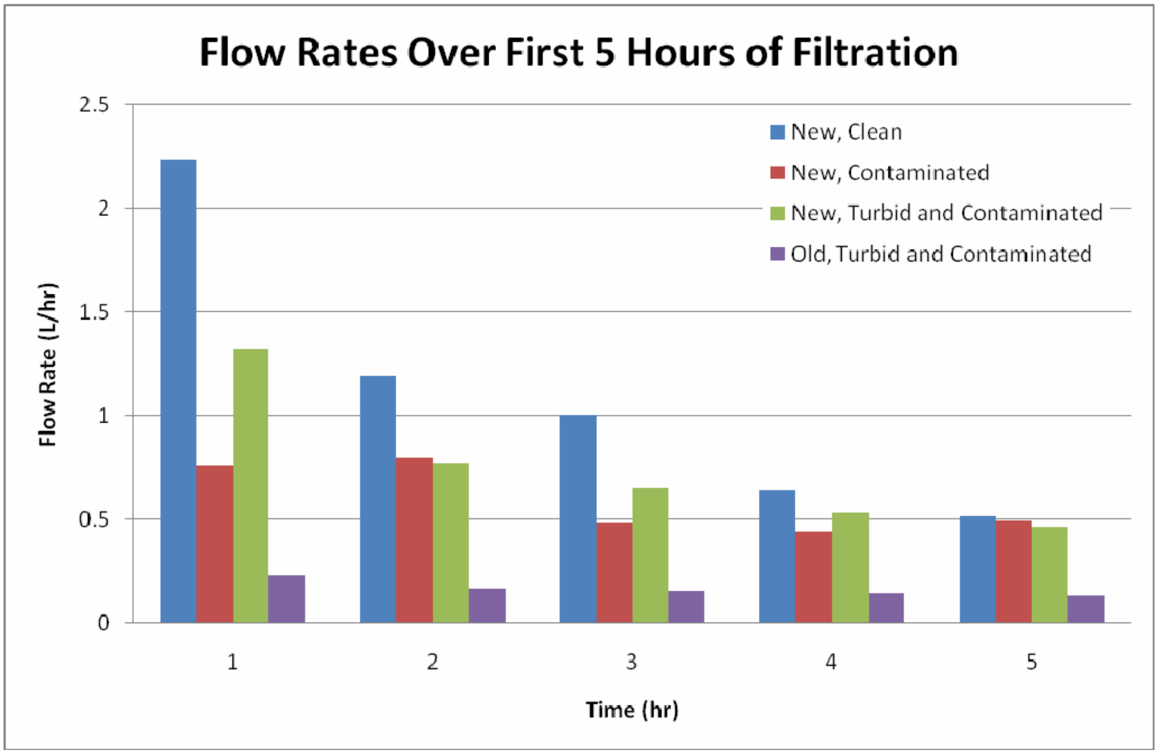

Figure 39: Flow rates over the first 5 hours of filtration time for different water sources and filters of varying age.

The fastest flow occurred through three new filters (averaged in Figure 5) with water free of turbidity and microbial contamination. Among these filters, the average time required to entirely filter a full pot was 32 hours. The next fastest flow rates were seen in two new filters (averaged in Figure 5) with turbid and microbially contaminated water. In fact, with a new filter and water with similar microbial contamination (to the two new filters with turbid and microbially contaminated water) but with no turbidity, the flow rate decreased. The most likely explanation for this decrease is that the filters used were compositionally different. For all of the flow rate tests performed in Figure 39, different filters were used. As discussed previously, the clay and sawdust used in *Kosim* filter production is sieved to a particular range. Therefore, some pots may be composed of particles on the smaller end of that range, while other pots composed of larger particles. Moreover, clay composition likely differs from batch to batch. Consequently, the pore size of each individual filter would be different. This is most likely the reason that the clear, contaminated water had a slower flow rate than the turbid, contaminated water. Among the three microbially contaminated water samples, the average time to entirely filter a full ceramic pot was 44 hours. This data suggests that turbidity does not impede flow, but the presence of microbial indicators does. It also shows the need for the manufacturer to adopt stricter quality control measures.

Figure 39 also shows the affect of use on flow rate. A one year old filter was tested with turbid and microbially contaminated water, resulting in a flow rate drastically less than the flow rates in new filters. This filter required 151 hours to filter 7 L of water (1.2 L remained in the pot at the end of the test). It should be noted that this filter was taken from a household that specifically complained about the speed of filtration. Therefore, the reason for this reduced flow may be that the filter was compositionally different.

6.5 Conclusions

The combined *Kosim* filter and Aquatabs treatment system is an effective household water treatment system and is relevant for implementation in Northern Ghana, particularly to lower class and lower middle-class communities. The addition of Aquatabs removed 50% of total coliforms from the *Kosim* filtered water and the percentage of households with no total coliforms increased from 44% to 64% as a result of using Aquatabs. Furthermore, households unanimously approved of both the taste and treatment level of Aquatab dosed water. In conclusion, as part of the combined *Kosim* filter and Aquatab treatment system, Aquatabs should be marketed towards lower-class and lower middle-class, rural households in Northern Region, Ghana.

<u>Key Points</u>

- Average TC concentration was reduced by 50% from baseline (filtered-only) to post-intervention (filtered+Aquatabs) from all 59 households
- 46% of households experienced reduced TC concentrations in Aquatabs treated water, while 37% remained the same as post filtered-only water (most of those households had no contamination in either sample) and 17% increased
- Percent of households that did not indicate the presence of TC (<100 CFU/100mL) increased from 44% to 64% from baseline to post-intervention
- EC present in only 2% (1/59) of post-intervention water samples, compared with 12% (7/59) of filtered-only water samples
- 62% (10/16) of households had a FAC level greater than 0.2 mg/L 24 hours after dosing, at time of post-intervention visit
- 64% of households had a FAC level greater than 0.1 mg/L at time of post-intervention visit (0.1 mg/L FAC was the benchmark used for randomized chlorine testing in the CDC study in the neighboring village of Bipelar in Northern Region, Ghana in 2007)
- Among households with a FAC residual in treated water between 0 and 0.25 mg/L, 32% of households had reduced TC concentrations, while 32% had increased TC concentrations
- However, among households with a FAC residual in treated water between 1.01 and 2.00 mg/L, 67% of households had reduced TC concentrations, while 8% had increased TC concentrations
- All survey respondents indicated that Aquatabs "improved the taste of the water" and that they "would recommend Aquatabs to others"
- 33/35 (94%) of lower middle-class survey respondents were willing to pay the full GHC 3 for 100 Aquatabs, while 6/24 (25%) of lower-class survey respondents were willing to pay same price (100 Aquatabs is sufficient for 1 year of treatment with the combined system)

As a result of the positive Aquatab perception results seen in this study, a possible combined alum and Aquatabs treatment system should be considered. Some of the advantages of this system compared with a *Kosim* filter and Aquatabs system is that it would be cheaper and would provide more water. Comparative prices for treating 23.5 L of water per week (the amount of water yielded by the combined *Kosim* and Aquatabs system) are shown in Table 2.

Table 8: Cost Comparison among Different Treatment Technologies Evaluated at Net Present Value (NPV)

	Cost (GHC)[25]				
Treatment System	**Capital Cost**	**Weekly Cost**	**Cost After 1 Year**	**Cost After 5 Years**	**Cost After 11+ Years**
Alum+Aquatabs		0.09	4.50	17.50	28.00
Kosim+Aquatabs	17.50	0.04	19.20	24.00	28.00
Kosim only	17.50		17.50	17.50	17.50

Concerning the flow rate through the *Kosim* filter, more research still needs to be done. This research shows that use greatly diminishes flow rate. The initial flow rate of a one year old filter was 0.23 L/hr (compared with 0.76-1.71 L/hr in new filters with water of similar quality). Therefore, more research should be done concerning the relationship between use and flow rate. Additionally, more research needs to be done comparing water quality (specifically turbidity and microbial contamination) with flow rate through the *same* filter. This would show which water quality parameter(s) affects flow.

[25] 1 GHC = 1.025 US Dollar on May 19, 2008.

7.0 Efficacy of Gravity-Fed Chlorination System for Community-Scale Water Disinfection in Northern Ghana

Cash Fitzpatrick

7.1 Abstract

Although chlorine is one of the lowest cost ways of providing disinfection to drinking water supplies, currently billions of people lack water that has had this simple treatment. Arch Chemical's Pulsar 1 unit is an innovation in chlorine dosing in so far that it is a gravity-fed system which does not require electricity while providing relatively accurate dosing. The purpose of this study is to investigate the technical feasibility of the Pulsar 1 unit using high-test hypochlorite (HTH) as a viable chlorination option for community-scale drinking water disinfection in Northern Region, Ghana.

This study is also meant to provide a comparison to the possible household treatment of the *Kosim* filter used with Aquatabs, which has been simultaneously evaluated by another MIT researcher. The *Kosim* filter is a pot-shaped Potters for Peace-type ceramic water available in Northern Ghana.

A pilot study done in Mali in 2005 by EAU Lambda showed the Pulsar's potential to correctly dose a piped water supply with a flow rate of approximately 42 gpm (9.6 m^3/hr). The present pilot study has evaluated the Pulsar system in Ghana and Cambridge, MA at flow rates of 18 gpm (4.1 m^3/hr) and 9 gpm (2.0 m^3/hr), respectively. This was determined to be difficult because the Pulsar was designed for swimming pool applications and thus chlorinated at levels higher than appropriate drinking water standards (less than 2.0 mg/L of free residual chlorine after 30 minutes according to the CDC) at reduced flow rates. As a result, several modifications were made to lower the chlorine concentrations from the Pulsar system into the appropriate range.

Both the Pulsar 1 and Aquatabs systems were found to be technically feasible. The main two advantages of using the Pulsar system over Aquatabs are the vastly reduced operational costs (in \$/m^3) of disinfection treatment (about 48 times cheaper) and its ability to reach an entire community (compared to just a single household). However, these benefits are gained as a tradeoff for increased system complexity and higher capital costs. Overall there is no "single best option", which means site-specific circumstances should dictate the appropriate technology.

Keywords: chlorination disinfection, Pulsar 1, Aquatabs, HTH, Kosim filter, community-scale chlorine treatment, gravity fed water treatment, Ghana

7.2 Introduction

According to the Center for Disease Control (CDC), the concentration limits for free chlorine residual for disinfection of drinking water is 0.2 to 2.0 mg/L after 30 minutes of contact time(1). In order to stay within this range, a chlorine doser with strict dosage control must be used. One unit which shows potential for success is Arch Chemical's Pulsar 1. Although originally designed for swimming pools, it could potentially also be used to meet drinking water criteria. Some of its advantages include being entirely gravity-fed (and thus requiring no electricity) and reliable chlorine dosing. The overall goal of this thesis is to investigate the technical feasibility of available chlorine disinfection options for drinking water on both the household and community-scales in the Northern Region of Ghana.

7.2.1 Chlorine disinfection

Water disinfection destroys harmful microorganism pathogens including bacteria, viruses, and protozoa. While certain pathogens can be eliminated through sedimentation and natural die-off by storage in open tanks, this is often unacceptable because of the resulting growth of algae and other sources of contamination. In order to measure disinfection efficacy, the term Ct is used. "C" is the free chlorine residual (in mg/L) and "t" is time (in minutes); the two terms are multiplied together to obtain a value. Ct charts exist for each microorganism at a specific pH and temperature (WHO, 2004).

When chlorine is added in water, the two main disinfectant species formed are hypochlorous acid (HOCl) and hypochlorite ion (OCL^-). Together, they are called "free available" chlorine. Of the two, hypochlorous acid is the more effective disinfectant but can be dissociated at high pH values. The following two equations show the relationships between solutions of calcium hypochlorite.

$$Ca(OCl)_2 + 2H_2O \rightarrow Ca^{2+} + 2HOCL + 2OH^{--}$$

$$HOCL \rightarrow H^+ + OCL^{--}$$

The chlorine dose needs to be sufficient to provide a desired free residual beyond the water's demand. The demand is related to the impurities in the water and can vary considerably. The relationship between the two is linear and can be estimated by the following equation (Cairncross & Feachem, 1983).

$$\text{Chlorine Demand (mg/L)} = \text{Dose (mg/L)} - \text{Residual (mg/L)}$$

One thing to note is that even clean water is likely to have a chlorine demand of 2 mg/L (Cairncross & Feachem, 1983). In addition, chlorine residual should generally be in the range of 0.3 – 0.5 mg/L with a contact time of 30 minutes (WHO, 1997). At higher concentrations taste problems may occur, and a lower concentration does not provide adequate protection.

Some important influent parameters are necessary in order for chlorine to be an appropriate technology. The first is turbidity. As turbidity measurements begin to rise above 5 NTU, the turbidity can begin to interfere with disinfection or give rise to a significant chlorine demand. If chlorination is attempted with turbid water, not only will suspected carcinogenic disinfection by-products such as trihalomethanes and haloacetic acids form (M20, 2006), but it will require more chlorine to be as effective. The other important parameter is pH, especially if pH gets too high. By the time the pH has reached a value of 8, nearly 80% of the effective disinfection mechanism has been lost because much of the calcium hypochlorite has dissociated into the less-effective form, hypochlorite (Meyer, 2004).

7.2.2 Pulsar 1 System

The Pulsar 1 runs as a parallel system, which means for a given water line the unit will "tap into" or divert away a portion of the flow for itself for treatment. The quantity of diverted flow is proportionally based on the flow through the water line; as the main water line flow increases so does the diverted flow to the Pulsar. Once the diverted water enters the Pulsar, it is directed to a chamber where it contacts solid chlorine tablets (called high-test hypochlorite or HTH). A concentrated aqueous chlorine solution is then formed which drips down to the base of the unit where it is pulled out of the Pulsar and re-injected back into the main line. Figure 40 shows this internal progression throughout the Pulsar system.

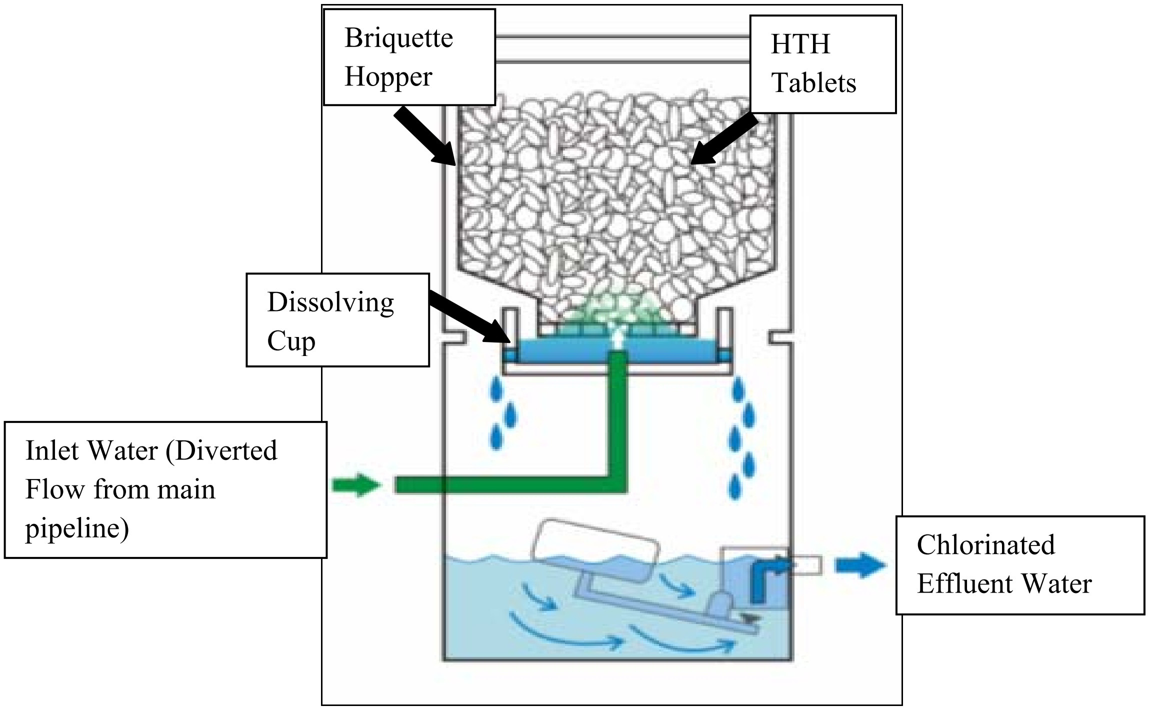

Figure 40: Pulsar 1 Internal Flow Diagram (Blanchette 2006)

The Pulsar 1 system is classified as a "wave" technology because the influent water is directed into the *dissolving cup*, where the water level rises similar to a wave and contacts the solid HTH tablets located inside the *briquette hopper*. The *ball valve* and *emergency shutoff valve* (not shown) control the flow rate into the Pulsar at a given water pressure by either regulating the inlet flow or closing the valve if the solution height in the base becomes too high. Once the concentrated chlorine solution is created, a vacuum force created by a *venturi* pulls the chlorine solution out of the Pulsar unit and back into the main line. As the inlet flow decreases, so does the water level in the dissolving cup and the outlet flow.

7.3 Materials and Methods

7.3.1 Water quality measurements

Field measurements were made throughout January in Tamale, Ghana and then later on at an MIT lab in Cambridge, MA. The field site in Ghana was an elevated storage tank (the top was 16.4 feet above ground) with a 350 gallon capacity. It was connected by pipe and filled once a week by the municipality of Tamale. It twice became necessary to hire a private vendor to bring a water delivery truck which would pump into the tank when either the piped water didn't flow or the tank ran dry during research. The water quality of both sources were comparable; both had turbidity less than 5 NTU, no free & total chlorine residuals, a pH of about 6, and a chlorine demand of 2-3 mg/L. Once the water was stored in the tank, the entire system (including the Pulsar 1) operated completely by gravity.

Turbidity and pH data was initially taken to ascertain the source water quality. This task was completed with a turbidity tube and Hach pH test strips, respectively. The chlorine measurements were taken with a Hach DPD Pocket Colorimeter II, DPD Titration, and Hach Chlorine Foil Singles (test strips). The Colorimeter was preferred because of its ease and high reliability, and the other two methods were used primarily for quality control purposes.

7.3.1.1 Pulsar 1 evaluation in Ghana

Once the site had been chosen and the unit installed, experimental test runs to properly chlorinate the water began. While the Pulsar 1 unit has many advantages, it is designed to chlorinate swimming pools which already have high chlorine demands and to keep chlorine residual concentrations higher than appropriate drinking water standards. Although it may be possible to offset these factors with a large enough water supply, the available water system in Tamale was a small tank with low chlorine demand water. Thus the Pulsar unit would naturally overdose with chlorine concentrations much greater than drinking water standards, which necessitated a way to decrease the values. One of the main objectives of the pilot study was to determine whether it is possible to achieve these reductions in free chlorine residual concentrations by modifying the Pulsar unit.

The easiest and most logical way of decreasing the concentrations was to reduce the amount of water contact with the chlorine in the dissolving cup. This was achieved by using a raised grid which contained 1/4" spikes, which essentially required the water height in the cup to be higher to achieve the same chlorine output. Arch Chemicals had conducted some tests with the new spiked grids and determined that for the appropriate Pulsar flow rates (0.4 – 0.6 gpm), the chlorine residual concentrations would be 800-900 mg/L, respectively (Blanchette, 2007).

The next two modifications were made in conjunction with each other to provide additional lowering of concentrations. The first part was to add a dilution nozzle assembly inside of the Pulsar 1 unit which diverted a portion of the incoming water away from chlorine contact which lowered the water level in the dissolving cup and diluted the output concentrations. Lowering the flow rate through the dissolving cup can also lead to scaling blockage through drying of the aqueous chlorine, so the second adaptation was to modify the emergency shutoff valve to allow more inlet flow. While this may seem counterintuitive because more flow into the Pulsar 1 would result in higher effluent chlorine concentrations, this alteration was made knowing a significant portion of the flow would be diverted away from the dissolving cup through the dilution nozzle.

When even these three modifications could not achieve low enough concentrations, the final adjustment was to partially close the inlet & outlet valves to the Pulsar 1. Its effect would be to reduce the amount of water coming both in and out of the Pulsar, which would reduce the overall concentration. As will be discussed later, this final tactic would turn out to be unsuccessful.

In order to test these modifications, determining the water system's flow rate was necessary to predict output concentrations. Since the container was a cylinder, this was accomplished with the following equation where the radius and the change in height & time were all known or directly measured.

$$Flowrate = Q = \left(\frac{\pi \times [radius]^2 \times [height]}{time} \right)$$

7.3.1.2 Further Pulsar 1 evaluation in Cambridge, MA

The further modifications made in Cambridge, MA were based on the successful aspects from the Ghana trip, and in most ways simply took them further. Specifically, the emergency shutoff valve and dilution nozzle assembly parts were enlarged. As before, the purpose of these additions was to simultaneously increase the flow rate (larger shutoff valve) into the Pulsar 1 while diverting more water (larger dilution capacity) from the dissolving cup.

7.4 Results

7.4.1 Pulsar 1 results obtained in Ghana

Three trials were conducted to determine flow rate, and an average flow rate of 18.1 gpm (with a range of 17.6 to 18.5 gpm) was recorded. Next, to conserve limited supply water in Ghana, a test was performed to determine the ability of the Pulsar 1 system to stabilize on an effluent chlorine concentration. Prior to this test, it was believed to require at least a few minutes. The results, however, showed the Pulsar 1 system in Ghana could equilibrate effluent concentrations in approximately 30 seconds. Although this result was reconfirmed by other runs at differing values, almost all of the data was taken after at least 60 seconds of runtime to be conservative. Still, the water savings and resulting allowance of more available water from this action alone were considerable. Following that, a set of results evaluated the capability and ranges of the dilution nozzle. When the nozzle was fully open and allowed full dilution, the free chlorine residual concentrations were in the range of 6.6 mg/L to 16.8 mg/L. The final modification made to the system was successful in meeting the 2.0 mg/L maximum concentration for free chlorine residual as defined by the CDC, but unfortunately it was achieved in such a way that created scaling blockage. As a result, additional lab research was conducted at MIT in Cambridge, MA.

7.4.2 Additional results from Cambridge, MA lab

As previously mentioned, the modifications made at the MIT lab in Cambridge, MA were based on the successful aspects from the Ghana trip and included enlarging the emergency shutoff valve and dilution nozzle assembly parts. The net effect was increased dilution potential when compared with the Ghana system. Figure 41 shows the results of the Cambridge, MA Pulsar 1 system with the ¼" spiked grid installed and the dilution valve fully on to achieve maximum dilution.

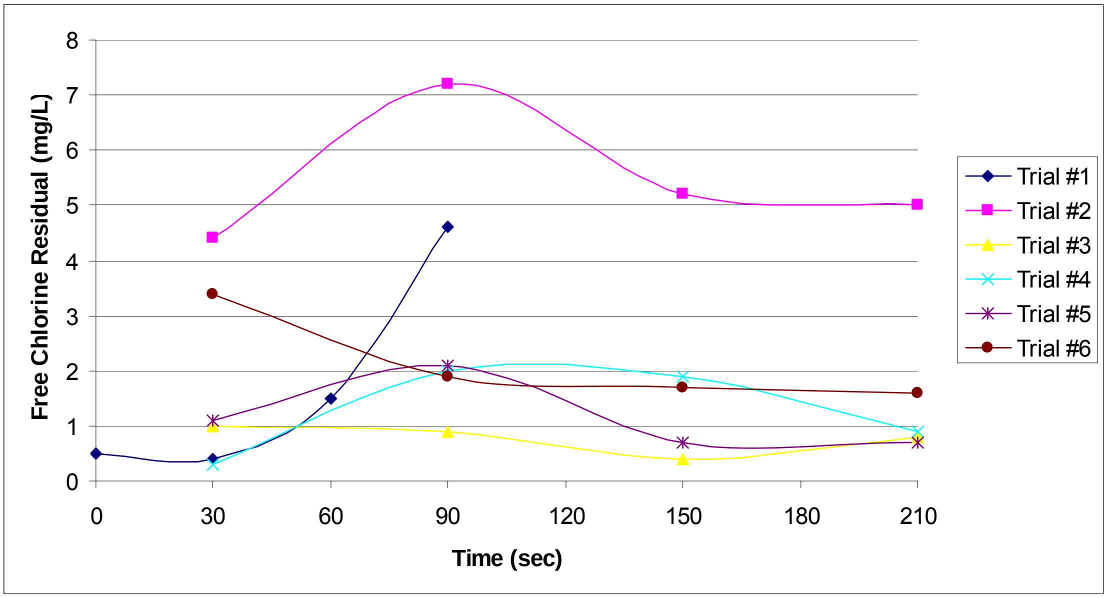

Figure 41: Chlorine Residual Concentrations Over Time With "Newer" Pulsar Modifications in Cambridge, MA

The results show that the new dilution nozzle and emergency shutoff parts were mostly successful in lowering free chlorine residual concentrations to below 2.0 mg/L. The values are actually even more encouraging because all the higher values occurred in the first few trials, which suggests the Pulsar 1 system may experience slightly elevated levels during startup which but level out over time.

7.5 Discussion

7.5.1 Community-scale potentials

The results demonstrate the potential of the Pulsar 1 system to operate at lower flow rates. While previous work showed the unit's ability to function at approximately 42 gpm, this study provides data from Ghana and Cambridge, MA which shows promise of success at lower flow rates of 18 gpm and even 9 gpm, respectively. As previously discussed in Section 0 the minimum water parameters necessary are turbidity <5 NTU and a pH <8 to ensure the chlorine disinfection mechanisms are uninterrupted. For many water sources, especially those originating from surface waters, this is only achievable in conjunction with other treatment processes. As with other community water projects, there are some indicators and metrics which can be used to evaluate the likelihood of success. Arch has identified the following three relevant parameters (Meyer, 2004).

- Locals accepting responsibility to pay their own water bills;
- Organization of a local water committee to oversee collection;
- Local involvement in construction and operation & maintenance.

Water quality problems should also not be addressed in isolation from sanitation and hygiene improvements. Water quality is often interrelated with sanitation efforts since poor sewerage practices can lead to large amounts of fecal sludge released into the environment (Vodounhessi, 2006). Unfortunately conventional sewerage collection and wastewater treatment is often not affordable to many households without massive outside subsidies (government, donor, etc) (Whittington, Lauria, Wright, Choe, Hughes, & Swarna, 1993).

Proper education is also an important factor of success. One Ghanaian study found a link between maternal education and childhood diarrhea rates (Gyimah, 2003). By analyzing the 1998 Ghana demographic data, the paper shows the probability of childhood diarrhea is almost 30% lower (47% versus 76%) for a household with a "highly educated" versus "low educated" mother. The author explains the results by suggesting that educated women are more regularly exposed to the importance of hygiene and nutrition in school, and as a result are more aware of disease causation and likely to engage in good sanitary practices.

7.5.2 Operational challenges

The lessons learned while on-site in Ghana combined with the insights gained from the application of other chlorine dosing technologies suggests there are several challenges which must be overcome for the Pulsar 1 system to be successful. Below is a list of possible hurdles:

- *Necessary training required to install and maintain Pulsar 1 system*

Compared to other household water treatment options (such as the *Kosim* filter with Aquatabs), the Pulsar unit is difficult to install. It requires plumbing materials and knowledge, as well as general familiarity with water flow characteristics. For instance, it would be difficult to explain its operation without using terms like pressure head, venturi, and suction flow. Such complexity could be prohibitive in certain situations (both rural and urban) which demand simplicity such as those experienced by the author during January 2008 in Ghana.

- *Availability of dry HTH chlorine*

The Pulsar 1 unit requires HTH tablets to run. One characteristic which makes distributed access easier is that local production of HTH is unnecessary and likely impractical. Therefore, a site which cannot expect dependable delivery is not well-suited. HTH also has a recommended shelf life of 1-2 years (Meyer, 2004). Proper storage might therefore make it possible to keep a future stock but it must be understood that the available chlorine percentage will slowly degrade over time and the HTH must be stored within the appropriate conditions.

- *Water quality data requirements*

The system requires regular, systematic, and dependable water quality data collection and maintenance over time for a minimum of 3 key parameters (turbidity & pH of influent water, and free chlorine residual of effluent). Once the system has been configured and is unaltered, the output chlorine concentrations will likely remain fairly constant until the water quality (i.e. chlorine demand) changes. In some cases this could be predictable, as is the case for the first rain of the year. For other unpredictable situations, it might be difficult to anticipate chlorine residual changes. To ensure continued water quality, a program which monitors free chlorine residual, pH, and turbidity (at a minimal) should be created.

- *Difficulty of predicting chlorine output residual concentrations*

Inevitably the incoming water quality will change, either predictably or unpredictably. Assuming proper training, it is easy to know the appropriate type of alteration, but very difficult to know *how much* of a change to make. At this time, there is no data, equation, or methodology which lays out how to precisely set the system controls to achieve desired free chlorine residuals. Thus, proper operation and maintenance of the Pulsar 1 system would require a certain level of technical capacity. This capacity could be available in Northern Ghana, but it would require specific training and follow up.

7.5.3 Maintenance challenges

While the Pulsar unit is fairly sturdy, it does contain many parts which could possibly break. The operations manual lists 29 parts total, with the only routine maintenance issue resulting from calcium carbonate buildup (Arch Chemicals, 2003a). Recommended service includes a simple washing of the tablet grid with a dilute acid solution or scraping with a putty knife. Over the course of the research, two internal fittings were delivered broken for the unit in Cambridge, MA, and the Ghana unit suffered a cracked outer shell while in shipment. Thankfully the latter damage was only aesthetic; otherwise the on-site Ghana research might have been severely limited. The inner fittings required replacement, which could have resulted in a prolonged shutdown if it occurred in a rural area of Northern Ghana.

7.5.4 Potential hazards with handling and use of calcium hypochlorite

An issue of concern is the effect of weather on the Pulsar and HTH. The Material Safety Data Sheet (MSDS) for HTH calcium hypochlorite lists the maximum recommended storage temperature to be 125 degrees Fahrenheit (~52 degrees Celsius) (Arch Chemicals, 2001). Parts of Ghana can experience weather of this magnitude, which could result in rapid decomposition of the HTH. Above this temperature the product can combust, and as such both the Pulsar unit and the HTH briquettes should be kept out of the sun at all times. No such problems were experienced in the course of this research because the temperature never rose above ~105 degrees Fahrenheit in the month of January 2008. Moreover, the product should not come into contact with certain other materials (see the MSDS in for further information).

7.5.5 Sensitivity to input parameters

As discussed before, the Pulsar unit is sensitive to its input parameters. Should turbidity rise above 5 NTU or the pH above 8, chlorine disinfection efficacy will drop off precipitously. The author's work was conducted in the middle of the dry season and thus experienced no rain during the three weeks of field research. Further studies need to be done to observe the effects of the natural water variation across both the dry and rainy seasons.

The most important system parameter is likely the flow rate. Even with all other water quality parameters remaining constant, the flow rate will drastically alter the operation of the Pulsar 1. For instance, as the flow rate increases, the height of water in the dissolving cup will rise, leading to more contact with the HTH and thus a higher chlorine concentration output. Unfortunately this increased chlorine dosage is not necessarily the proper amount to keep the overall chlorine output in equilibrium. Thus each separate flow rate has to be tested with one or more of the modifications listed in Section 0 in order to remain within the correct free chlorine residual target range.

7.5.6 Study Limitations

Though the research built upon much of the past work, certain limitations were experienced. For instance, influent water quality remained consistent over the course of the study. Since the source is a water treatment plant with a surface water intake on the Volta River, the possibility remains that quality might only mildly fluctuate over time. However, assuming consistent influent parameters over time in other circumstances is likely to be unrealistic.

Another shortcoming of the study is that the alterations made in the Cambridge, MA lab have not been tested in Ghana. While the results look promising in the lab, unexpected complications can always occur when introduced into different real world situations.

A final limitation of the results was that the testing duration was too short to experience any serious maintenance issue or breakdown. Similar to the study done in Mali, no discernible system failure was observed. Although the Pulsar 1 operated successfully in both cases, it remains unknown what, if any, additional problems might occur over time in challenging conditions like those in Ghana.

7.5.7 Comparison to Aquatabs

Comparing these two chlorination technologies is not entirely straightforward because they are used at different scales (Aquatabs for household and Pulsar 1 for a community). Nevertheless, there are certain evaluation metrics available which allow comparisons to be made.

In order to get a better understanding of the relevant differences between these products, a multi-objective analysis table is below. Note than many of these items are subjective and reflect only the opinion of the author. Also, the values for each category are meant to be relative, not absolute. If these systems were compared to others the values could be different.

Table 9: General Sustainability Comparison of Chlorination Systems

	Kosim Filter with Aquatabs	Pulsar 1 Unit with HTH
Maximum Flow Rate	Low (1-7 L/day)	High (>100,000 L/day)
Can Serve Many People	●	● ● ●
Cost of Treatment ($/m^3)	● ●	● ● ●
System Lifetime	~2 years*	~10 years*
Low Initial Cost ($)	● ●	●
Low Running Cost ($/yr)	● ● ●	● ●
Simple O&M	● ● ●	● ●
Materials Availability	● ●	● ●

*Value Assumed by Author ● =Poor ● ● = Moderate ● ● ● =Good

This table highlights many of the tradeoffs between the critical issues when choosing one system over another. There is clearly no "single best option", which means site-specific circumstances should dictate the appropriate technology.

7.5.7.1 Cost of high-test hypochlorite (HTH) and Aquatabs

One of the most important drivers for any technology, especially in a developing country, is cost. Comparing the costs of Aquatabs for use in the *Kosim* filter and HTH for the Pulsar 1 system is relatively straightforward. The HTH retail cost was estimated by assuming a dosage treatment (3 mg/L), and then estimating the purchase cost to be \$280 for a 40 kg container (Tew, 2008). This resulted in the retail cost of HTH to be \$0.032/m^3. As a comparison, the retail cost of Aquatabs in Ghana is estimated to be \$0.03 per tablet (Eau Lambda, 2005), which results in a treatment cost of \$1.5/m^3 of water. Figure 42 shows how these two technology costs compare to other drinking water options in Ghana.

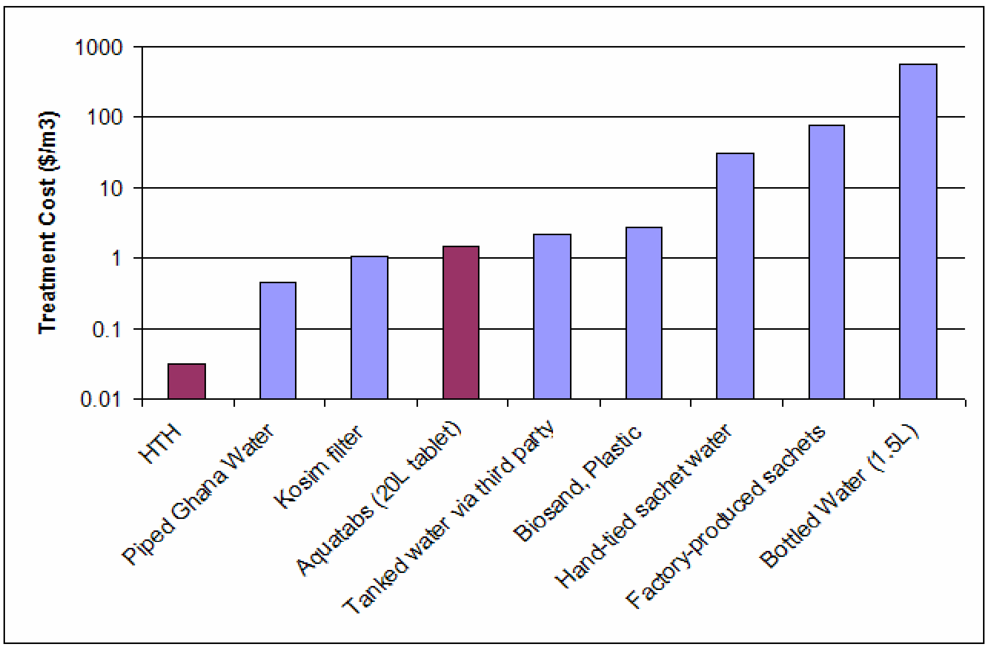

Figure 42: Cost of HTH & Aquatabs Compared to Other Drinking Water Options (Murcott 2007b)

While both chlorination methods are relatively cheap, HTH is clearly more cost effective at \$0.032/m^3 (approximately 48 times cheaper than Aquatabs). This is expected since it treats a much larger amount of water, which provides an economy of scale. The Pulsar system remains cheaper (on a net present value \$/m^3 basis) even when the analysis is expanded to include the capital cost of the unit and its potential labor costs. Figure 43 below shows the total costs of treatment.

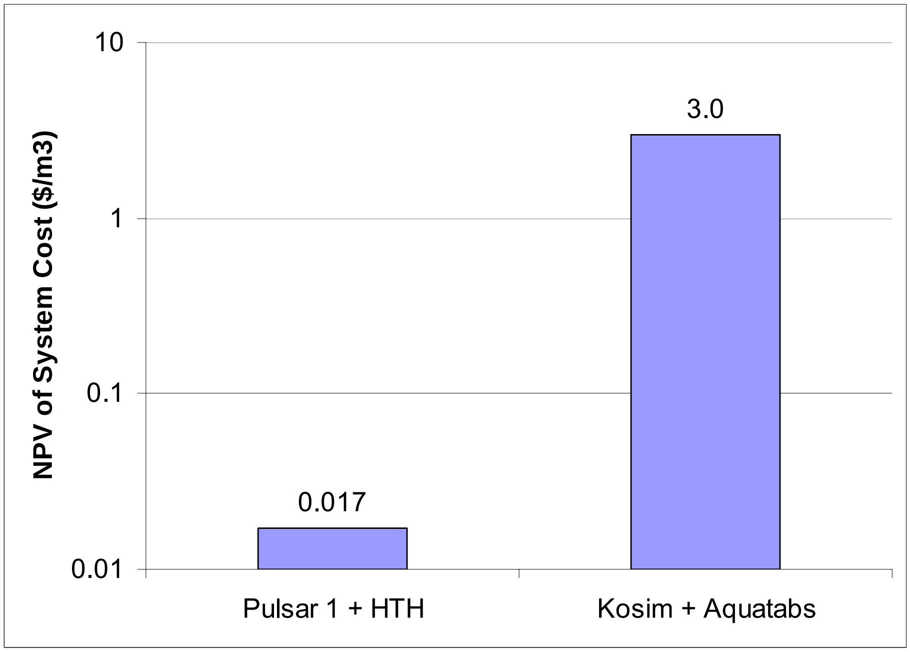

Figure 43: Net Present Value (NPV) Comparison of Pulsar 1 + HTH versus *Kosim* + Aquatabs, Normalized to Treatment Cost per Volume

The results show that total treatment costs of these systems in net present value terms are substantially different, with the Pulsar 1 + HTH option approximately 170 times cheaper than the *Kosim* + Aquatabs treatment (0.017 $\$/m^3$ versus 3.0 $\$/m^3$, respectively). Although some of the input assumptions are subjective, the overall result of the Pulsar 1 + HTH option being much cheaper is likely to remain true under any reasonable set of assumptions.

7.6 Conclusions

The Pulsar 1 system, using high-test hypochlorite as a chlorine source in conjunction with the other discussed modifications, shows potential of being a successful community-scale water disinfection system. While previous research showed the system could operate at flow rates approximating 42 gpm (Eau Lambda, 2005) this research focused on lower flow (18 and 9 gpm) scenarios. The following key findings support these conclusions:

- Field testing in Ghana (system at 18 gpm) indicated that most (3 out of 4) values had free chlorine residual concentrations in the range of 10 - 14 mg/L while running at full dilution with modified parts. By additionally altering the Pulsar's inlet flow rate, this value was successfully reduced to less than 2.0 mg/L in all cases (10 out of 10). However, this final action was determined to be inappropriate because it would likely lead to scaling blockage.
- Laboratory results in the MIT lab (system at 9 gpm) in Cambridge, MA showed most (17 out of 24) of the free chlorine residual data was equal to or less than 2.0 mg/L at a very low flow rate (9 gpm).
- The author did not observe a system breakdown during the three weeks of field testing in Ghana or during subsequent research in Cambridge, MA.

8.0 Household Water Treatment and Safe Storage Options for Northern Region Ghana: Consumer Preference and Relative Cost

Vanessa Green

8.1 *Abstract*

A range of household water treatment and safe storage (HWTS) products are available in Northern Region Ghana which have the potential to significantly improve local drinking water quality. However, to date, the region has failed to see significant HWTS product adoption and sustained use. Therefore, this consumer preference study was conducted to help stimulate product uptake by giving implementing organizations a method and tool to fit water quality interventions to the preferences and needs of different demographics of the local population. This work outlines the relative value and cost of the HWTS options available in northern Ghana, and highlights those products most likely to have the greatest impact on drinking water quality, based on product effectiveness, adoption and sustained use. The research methodology included a consumer preference survey and water quality testing in 238 households in four rural and three urban communities around Tamale, Ghana in January 2008. Turbidity testing and total coliforms (TC) and *Escherichia coli (E.coli)* removal were used to assess source water quality. The research confirmed that local purchasing decisions are dominated by a desire for products that offer a major health improvement and have a traditional durable product look, with relatively less emphasis on water taste and look, treatment time and price. The consumer choice research reveals that a traditional durable product such as Pure Home Water's *Kosim* ceramic pot filter is a good fit for communities with turbid source water; however, a portfolio HWTS approaches will be required to meet the diverse needs of the Northern Ghana population. Specifically, there is a cross-segment need for a safe storage product, as well as a low-cost chlorine disinfection option. Opportunities also exist for revenue generation through a sachet water or modern durable filter business targeted to the high-income segment of the urban market.

Keywords: water quality, health, consumer preference, adoption, sustained use, willingness to pay, HWTS, choice-based conjoint analysis

8.2 Introduction

This household drinking water treatment and safe storage (HWTS) consumer preference research was conceived as a collaborative effort between the MIT Civil and Environmental Engineering Department, MIT Sloan School of Management, Pure Home Water (PHW) and PATH's "Safe Water Project" to help address the dire drinking water conditions of low- to middle- income communities in northern Ghana. The goal of this work is to assess the relative value and cost of household water treatment and safe storage (HWTS) options in Northern Region Ghana. This analysis is used to make recommendations about which HWTS products would be likely to have the greatest impact on local drinking water quality, based on product effectiveness, adoption and sustained use.

8.2.1 Water management in Ghana

Ghana faces significant challenges in meeting the basic water and sanitation needs of its 22 million people. This challenge is magnified in Northern Ghana, particularly the rural communities, where 50% lack access to safe water (Ghana Statistical Service). Piped water is rare and intermittently supplied (personal communication, 2008), with many urban communities only receiving piped water once a week or once every other week. There has been a significant push to expand borehole drilling; however, there remains a significant opportunity for HWTS to improve the livelihoods of the estimated 900,000 people in Northern Ghana that lack access to improved water sources. Furthermore, there is an opportunity to serve urban and peri-urban communities that are faced with unreliable piped water, and thus are forced to store their water for long periods, a practice which has been shown to lead to frequent and extensive recontamination (UNICEF, 2008).

8.2.2 History of household water treatment and safe storage

Household water treatment and safe storage (HWTS) is a new approach in the toolkit of public health interventions to bring safe water to the 1+ billion people in the world that currently lack access to improved water sources. Throughout the 1990s, water quality received relatively little attention among interventions to reduce the diarrheal disease burden in the developing world. The lack of investment in water quality generally was significantly influenced by a meta-analysis by Esrey et al. (1991) that concluded that sanitation and hygiene education yielded greater reduction of diarrheal disease than water supply or water quality interventions. However, more recently, a study by Fewtrell & Colford (2004) commissioned by the World Bank found that hygiene education and water quality improvements have a greater impact on the incidence of diarrheal disease (42% and 29% respectively), than sanitation and water supply 24% and 23% respectively. Currently, there is evidence to suggest that safe water in the home can reduce diarrheal disease by 6-50%, independent of improved sanitation or hygiene (Nath et. al., 2006).

The new research has drawn international attention to the benefits of HWTS, and a number of new technologies have emerged. Household chlorination and safe storage, solar disinfection, biosand filtration, and the Potters for Peace ceramic pot filters are all core examples of existing HWTS technologies that have been developed to address this global water challenge. However, a consensus has not emerged about which treatment option is most effective. Furthermore, HWTS intervention efficacy often varies by geographic region, water source characteristics, and community type, and adoption rates and project sustainability also depend on the cultural relevance of the implementation strategy selected as well as ability to pay. Therefore, this research seeks to provide a relative assessment of the product appropriateness for the range of HWTS options seen in Ghana.

8.2.3 HWTS consumer choice context

Water projects in the developing world have suffered from poor performance due, in part, to a lack of consumer adoption of water infrastructure and/or new HWTS products. Consumer understanding is viewed as a key barrier to sustained use of improved water sources and products, and thus local consumer choice research has emerged as a critical element of successful HWTS interventions. In the case of Northern Ghana, there are several locally available HWTS product options that have the potential to significantly improve the local drinking water quality. However, to date, the region has failed to see significant HWTS product adoption and sustained use. Data collected through consumer preference studies has the potential to help stimulate product uptake, as it can be used to tailor water quality interventions and marketing efforts to local preferences and needs. In this case, the consumer choice study has been designed to assess a range of drivers of HWTS product adoption in both urban and rural communities.

8.2.4 Clean water: a right or economic good

The question of whether developing world consumers should be charged for a clean water supply and/or household water treatment products has been extensively debated. Access to a regular supply of safe water is widely viewed by the international development community as a basic human right (WHO, 2003). The rights-based approach to water management strives to empower people to use legal systems to gain access to safe water. Under the right to water model the principles of freedom from discrimination and equality can be used to rule out exclusion from access based on ability-to-pay (WHO, 2003). However, since the early 1990s, international development projects have also strived to establish sustainability by pricing products slightly above the cost of production. Through the social entrepreneurship approach NGOs and local entrepreneurs have sought to use the "double bottom line" market forces of supply and demand to sustain the project independent of donor funding.

Market-oriented sustainable development is based largely on a capitalist model that suggests that unless people are willing to pay for a product they will be unlikely to value it (Shea, 2007). However, several recent studies have challenged the validity of this paradigm by demonstrating that payment is not closely correlated with product adoption and sustained use (Kremer & Miguel, 2007; Ashraf, Berry, & Shapiro 2007). At the community level, pricing water at full supply cost has been shown to have a positive impact on equity, efficiency and sustainability in the water supply (Rogers, Silvia, & Bhatia, 2002). Proponents of full-supply pricing argue that removing water subsidies can, in fact, serve to enhance equity of access and long-term system sustainability by reducing overall demand and providing funds for expansion of supply into previously underserved communities.

8.2.5 Contingent valuation: willingness to pay assessment

The international development community has not reached agreement regarding the utility of charging impoverished developing world consumers for clean water and/or HWTS products; however, if a commercial "double-bottom line" approach is desired, an assessment of willingness to pay is critical to successful project implementation.

Historically, following a series of disappointing investments in water supply systems in the 1980s the Contingent Valuation approach emerged as the methodology of choice for assessing relative value and cost of water infrastructure projects (Whittington & MacRae 1988). By asking consumers to respond to a series of scenarios, Contingent Valuation provides additional information about the local demand for improved water systems as well as the response of consumers to new water supply options. At the household level, Contingent Valuation began to be used to assess willingness to pay for water treatment products or improved water supply alternatives. Through these efforts it has been shown that households are willing to pay anywhere from 5% to 20% of their annual income for improved water access (McPhail, 1993; Moor & Calamai)

8.2.6 Alternative tools: micro-market models & multi-feature conjoint analysis

Contingent Valuation willingness to pay assessment is inherently limited by the bias generated by asking for hypothetical preferences. Therefore, in recent years, micro-market models have been developed that offer a more robust tool for assessing willingness to pay in an actual purchasing scenario (Ashraf, 2007). However, micro-market studies are poorly suited to a multiproduct assessment as the large number of variables significantly drives up the desired sample size (Glennester, personal communication, November 2008).

Conjoint Analysis was developed as a statistically robust tool to improve product design and marketing messaging while avoiding expensive and time-consuming market tests which are inherently limited in the number of features that can be tested simultaneously. Conjoint Analysis is based on the premise that people cannot reliably express how they weight separate features of any given product, but researchers can assess the relative preference for various product features through repeated evaluations of product concepts (Orme, 2006). A Choice-based Conjoint (CBC) seeks to incorporate these trade-offs into the survey design.

> *"In contrast to answering direct questions about individual product features, conjoint survey respondents cannot simply say that all features are important – they must trade off different aspects of the product (as in real life), weighing products that have both highly desirable and less desirable qualities (Sawtooth, 2008)."*

Therefore, CBC has emerged as the methodology of choice for complex consumer preference studies as it most closely matches a real market scenario where customers simply chose the product they most prefer. Furthermore, CBC is effective for smaller studies because the number of trade-offs made by each individual allow for higher statistical significance with a smaller sample size. As the HWTS study described here sought to collected data on a number of product features across a large range of HWTS products, CBC would be an effective approach for our research scope.

Little experience had been documented to date on multi-feature Conjoint Analysis in developing world environments. Focus groups using a similar choice task methodology have been utilized to identify HWTS customer segments with some success in rural India (Austin, personal communication, November 2007); however, integrated assessments of product feature preference have typically not been utilized in development work. Through the support of Sawtooth Software, the MIT team was able to use a web-based platform for CBC survey generation and data analysis. As developed for this study, CBC proved a relatively low-cost tool to enhance consumer understanding across a number of critical elements of HWTS design.

8.3 Methodology Part I: Survey instrument design

The methodology for this research was formulated in conjunction with a team of four Masters of Business Administration students and their advisors from MIT-Sloan School of Management. From October 2007 to January 2008 the team worked to develop a consumer choice survey instrument and gain approval from

PATH, our project sponsor. During the month of January 2008, the team spent four weeks on the ground executing the survey and collecting water quality data. During this time the MIT team worked closely with four Ghanaian surveyors who helped to refine the survey methodology and conduct the field work.

8.3.1 Consumer preference survey design

The goal of the CBC element was to determine which HWTS product features are the most desirable to the target customers. To develop the CBC tool a list of potential features of HWTS products which could be tested was developed. The initial list included nine variables: water look, water taste, product look, product durability, health impact, ease of transport, treatment time, storage volume and price. First, features that could be assessed through the baseline survey such as demand for large storage volumes and ease of transport were eliminated. Next, the remaining features were prioritized by focusing on those product features critical to describing differences between source water conditions and potential treatment options for Ghana. Ultimately, features that only existed in a discrete range of combinations in Ghana were merged (i.e., water look with water taste and product look with product durability).

After selecting the desired feature set, images were developed to help depict the CBC choices. The pictorial element proved critical to the research as the task screens were required to effectively communicate the product trade-offs to the potentially illiterate Dagbani-speaking respondents. The final feature set and images used are shown below (Figure 44). Originally, the researchers planned to show twelve different task screens per interview (Figure 45). Each participant would be asked to choose between the options shown on each task screen, and by amalgamating all the data the researchers could draw conclusions about the relative importance of HWTS features. Ultimately the number of task screens was reduced to eight based on feedback from PATH as well as the enumerators concerns about respondent fatigue.

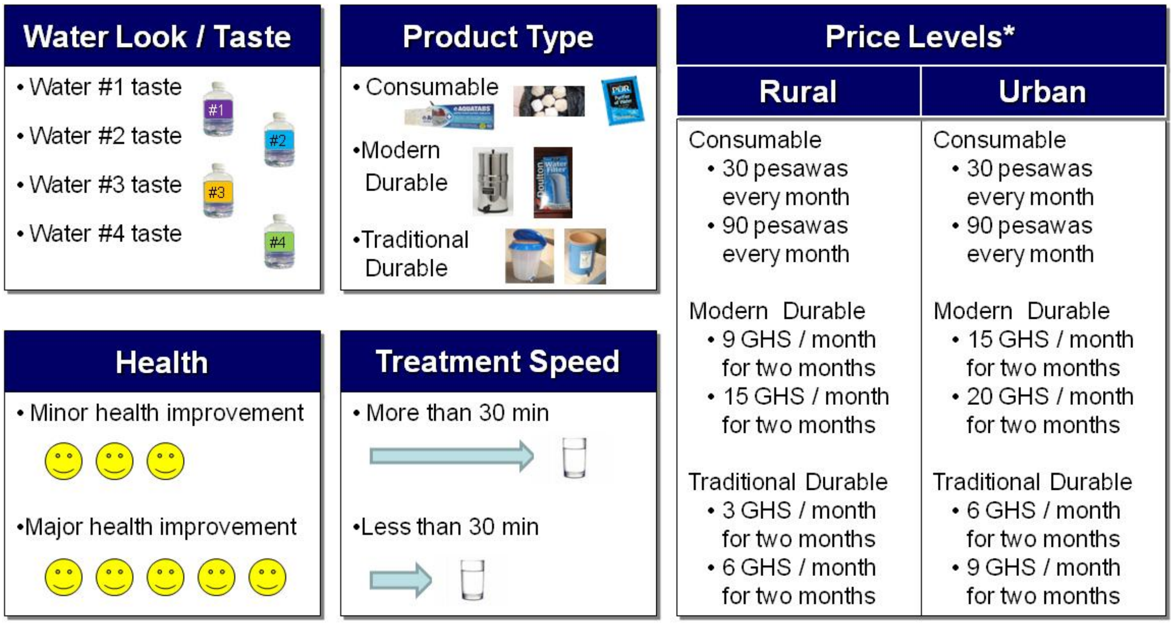

Figure 44 Selected feature set and image

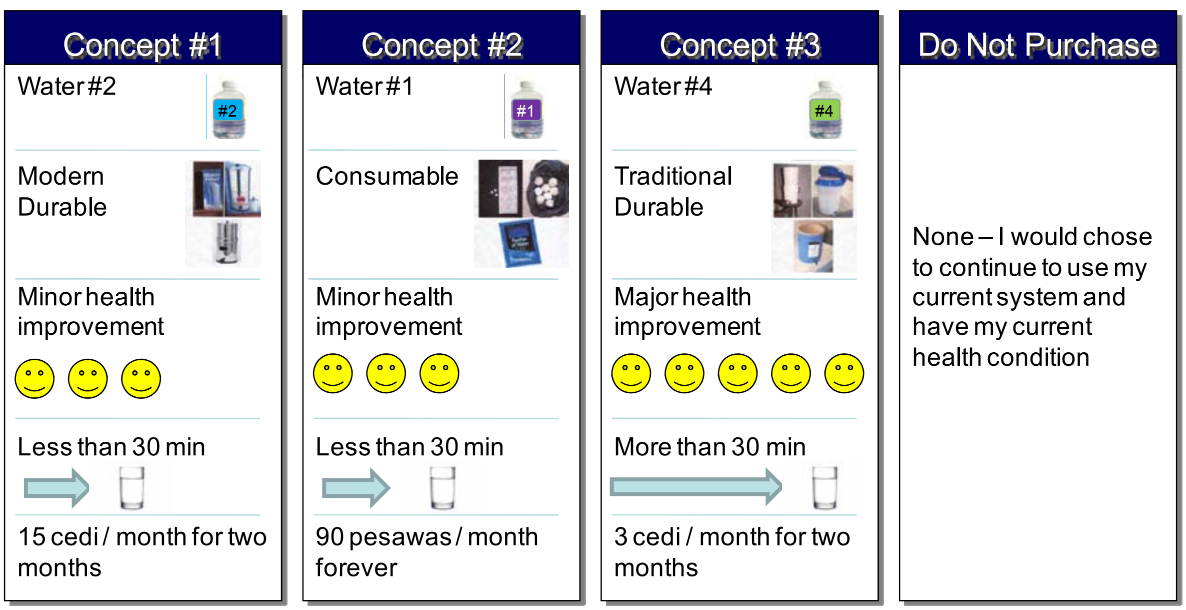

Figure 45 Example task screen - rural survey

Following the planning phase described above, the survey instruments were vetted with the local survey team and a two day pre-test was conducted in a village approximately 10 minutes by car from Tamale. To facilitate effective communication, each task screen was placed in a laminate sheet and bound together for the surveyors use. In addition, a number of props were developed.

For the water look / taste category, four bottles of water were used to demonstrate the different tastes. Water #1 was Voltic[26] bottled water. Water #2 was municipally treated water dosed with Aquatabs.[27] Water #3 was turbid water taken from the Ghanasco dugout in Tamale and boiled for 15 minutes. Water #4 was Ghanasco dugout water filtered through the *Kosim* filter to give and earthy taste and then boiled for 15 minutes to ensure safety. The water was changed every day, and the bottles themselves were replaced every 2-3 days to address contamination risk. During the survey the water was served to respondents in disposable plastic cups.

Product type was described using full size sheets showing the products.[28] The color images were placed in laminate sheets for the surveyors to refer to while describing the differences in products. In addition, the product type images shown were visually linked to those on the task screen. As product type was only one feature of the consumer choice task, the researchers did not want to overemphasize product thus, multiple examples were shown for each product type (Figure 46).

Figure 46 Conjoint props product type images

To communicate health challenges associated with waterborne disease images were used that had been prepared by a local artist for PHW. The images show some potential negative effects of poor health, such as diarrhea, tiredness, and expensive hospital visits (Figure 47). Alternatively, the healthy images show people engaged in daily activities such as farming, attending school and playing a common board game (Figure 48). The researchers were concerned that the compelling images would place an undue amount of emphasis on health; however, during a two day pre-test the survey team expressed a preference for using the images.

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[26] Voltic water is a high-end bottled water product produced in Ghana. It is produced by a Ghanaian company and is among the most expensive and widely distributed bottled water products in the region.
[27] Aquatabs is a chlorine product designed for household water treatment and sold locally in Tamale. The parent company is Medentech located in Ireland.
[28] All products shown are locally available in Ghana with the exception of PuR™

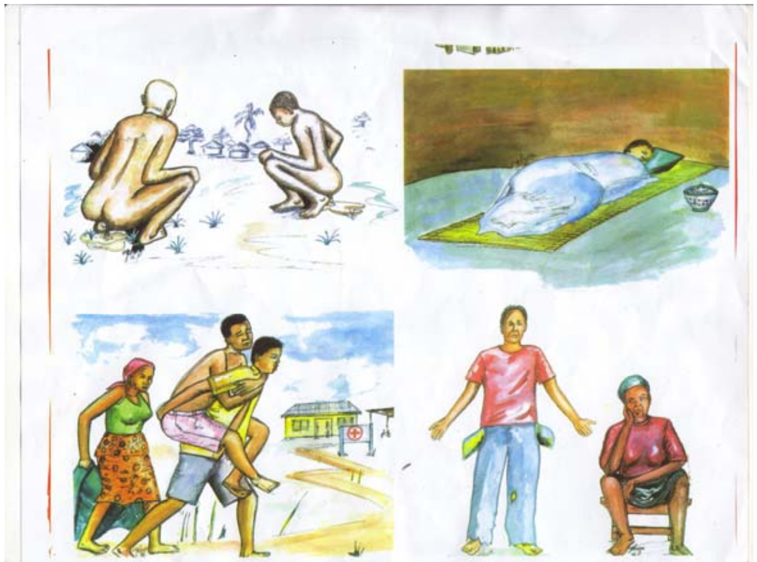

Figure 47 Conjoint props health images (impact of waterborne disease)

Figure 48 Conjoint props health images (benefits of no waterborne disease)

It was ultimately decided that no props were necessary to communicate treatment time and price, although the researchers were aware that this had the potential to introduce a bias towards those features that were described using colorful props.

8.3.2 Baseline survey design

Baseline data on all households surveyed was also collected to assess variation in behaviors and preferences between market segments. Furthermore, as the relative efficacy of different HWTS products depends on the quality of the source water, water quality testing was used to characterize the water of sample populations. The household data collected was used develop an assessment of the relative easy of use, efficacy and price of HWTS options in Northern Ghana. The product assessment framework was then used in conjunction with the conjoint data to make recommendations about which HWTS products have the greatest opportunity for adoption rates and sustained use over the long-term. The primary goal of the baseline survey was to gather the information required to develop HWTS customer profiles, and to identify target customer segments for different HWTS product options. The baseline section of the survey included four elements: 1) Household Information, 2) Purchasing Decisions, 3) Ability to Pay, and 4) Current Water Practices.

8.3.3 Water quality testing

Water testing was conducted to characterize the water quality conditions in each household surveyed. One water sample was collected from the drinking water source of each household surveyed, typically a large earthen drinking water vessel in the family's central courtyard or home. Samples were collected in sterile Whirl-Pack^{TM} bags, placed on ice and processed in the afternoon 2-4 hours after the completion of the day's surveys. Specific water quality tests conducted included turbidity and the 3M™ Petrifilm™ test for the enumeration of *E.Coli* and total coliform. Chlorine residual tests were not conducted.

8.4 Methodology Part II: field research

During the first week of January 2008, the team conducted two days of orientation and training, followed by a two day pilot test. Through the pilot test it was determined that each surveyor could conduct four to five high-quality surveys per day. In addition, a number of wording changes were made to the survey instrument. In particular, the price of the items was converted to old cedis (x10,000 GHS) because the respondents and the surveyors appeared to be much more comfortable with that currency metric which was officially in effect until June, 2007. Following the pre-test the final survey instrument and methodology was approved by both MIT COUHES and PATH HSPC. It was determined that the research project described in this thesis qualified for exempt review status as defined in the federal regulations, 45 CFR 46.101 (b) (3) (Internal communication, Elizabeth Trias, January, 10 2008). Subsequently, the MIT-PHW team along with four Ghanaian survey enumerators completed a total of 238 surveys over three weeks.

8.4.1 Household selection & community engagement

Upon arrival in Ghana on January 2, a set of seven representative communities was selected. Ultimately three urban communities and four rural villages were chosen, all of which had no exposure to PHW's products. The goal was to survey 40 households per urban community and 32 per rural community to reach a sample size of 250; however, ultimately 243 surveys were completed due to rural travel time and other local circumstances. Prior to starting work in a community, a team member visited the site to obtain permission from the village chief or community leader. Subsequently, when the team arrived, all the researchers met briefly with the community leader to obtain his approval for the work. Following these proceedings, the four survey teams radiated out in four directions, and randomly selected target households to approach.

8.4.2 Respondent recruitment

The researchers aimed to include 150 female head of household and 100 male head of household for 45 minute face-to-face interviews. We sought this gender percentage (60% female, 40% male), because we hoped to assess the differences in purchasing behaviours between female and male segments of the population. We selected a slightly lower target for male respondents because our short timelines did not allow us to control for the higher percentage of men working away from the home during the four hour window in the morning during which we conducted surveys. Interviews were typically given in the central courtyard of the household compound, which could have created some response bias as the entire family was often eager to voice their opinion. All respondents gave informed consent prior to the start of the survey.

8.4.3 Survey enumeration

All elements of the survey were conducted in the local language, Dagbani. The enumerators emphasized to the MIT team that they were very comfortable and in fact preferred completing the questionnaire in English despite asking the questions in Dagbani. Thus, prior to initiating field research, the surveys were reviewed in detail in both English and Dagbani in order to build alignment about question interpretation. Although there was a Dagbani version of the survey instrument available; in practice, each surveyor translated the questions and interpreted the responses independently. While in Ghana the written survey instrument was translated and back-translated. This task was challenging for a number of reasons. First, Dagbani is a simple spoken language, and typically not expressed in written form. English is the official national language and it dominates in professional and academic settings. Furthermore, water management is a particularly challenging topic as there are a lot of idiomatic expressions around how people express their water needs and practices.

Securing highly qualified Ghanaian survey enumerators proved critical to our project's success. The MIT researchers found that taking the time to discuss the research goals with the survey team greatly increased the quality of the data collected. This initial communication aligned the goals of the entire team, which increased our efficiency as well as the MIT team's understanding of the translation limitations. The quality survey team was particularly critical for the CBC element, as effective delivery created a number of unique challenges. Efficacy of conjoint analysis hinges on the respondent's willingness to think carefully and make trade-offs across a number of features. Therefore, successful execution requires effective communication from the surveyor as well as focus from the respondent. Before starting the survey the team found that it was helpful to carefully explain to the respondent that it was not a test, and that the goal of the research was to better understand what was important to them. The props were also helpful in communicating the choice options. Each surveyor used the props slightly differently, but in all cases the images were used to help the respondent make trade-offs (Figure 49).

Figure 49 Survey delivery and use of props

8.5 Results

This section summarizes the results collected in the field during January 2008 on an aggregate basis for urban (n=118) and rural (n=119) respondents. The data shown will include six sections: 1) demographics of the sample population; 2) water source type; 3) needs assessment including water quality, health and current water management practices; 4) ability to pay; 5) an assessment of purchasing behaviours; and 6) consumer preference.

8.5.1 Sample population demographics

By design, the sample population was predominantly female in both urban and rural areas. In addition, the sample was 90% Muslim, a slightly larger majority than the 56% seen throughout the Northern Region as a whole (ModernGhana, 2008). The majority of urban respondents lived in modern homes with tin roofs and a slight majority had received some primary or informal education, but only 31% had continued to secondary school. The majority of rural households lived in traditional mud-brick hut compounds with primarily thatched roofs, and only a small percentage had received any primary education, with only 3% continuing to secondary school. The household size and age distribution was consistent across urban and rural areas with an average of twelve and thirteen individuals per household respectively, and two children under five (Table 10).

Table 10 Demographics of Sample Population

Type	Gender (% Female)	Religion (% Muslim)	House Type (Roof)		Education		Average Household Size
			% Tin	% Thatch	Primary	Secondary	
Urban (n=118)	77%	94%	100%	5%	51%	31%	12
Rural (n=119)	70%	86%	15%	97%	19%	3%	13

The similarity in household size across urban and rural areas seen in this research differs from prior results obtained by R. Peletz, 2005 and S. Johnson 2006, which found an average urban household size of six and an average rural household size of twelve. The urban difference might be due to the fact that this survey targeted lower middle class urban households while the prior work targeted wealthier middle class households.

8.5.2 Water source: type and access

Urban and rural communities in Northern Ghana utilized a very different mix of water sources. In addition to rainwater, urban communities primarily used water from private taps, either personal or those of neighbors, while rural communities mostly collected water from surface water sources, dugouts / dams, as well as boreholes. In both community types the majority of respondents were supplementing their water supplies with rainwater collection during the rainy season (June – September).

Water collection practices also varied substantially among community types. Urban data showed that respondents collected water an average of 5 times per day in both the dry and rainy season; however, this number may not be representative as the municipal water only flowed at most two times per week, and often only a few times per month. On the days when water is available at local taps, residents collect water and transport it to large storage vessels in their homes (Figure 50). Rural households collect water an average of 6-7 times per day in the rainy and dry season respectively. As the majority of rural communities use a local dugout as their primary source of water and a typical trip to the dugout takes longer than thirty minutes, water collection alone requires over three hours per day (Figure 51). In addition, three of the four rural communities surveyed had some access to a borehole, typically located near the dugout. Interestingly, many respondents said they used water from the dugout and the borehole interchangeably, storing and transporting it in the same vessels.

Figure 50 Key Urban water management challenge: water quantity and storage

Figure 51 Key Rural water management challenge: source distance and quality

8.5.3 Needs assessment: demand for improved household water Management

Water quality metrics helped characterize the current drinking water in study populations (Table 11). All urban respondents were drinking non-turbid municipal water[29]; however, microbial contamination seen among urban respondents suggests that recontamination during handling and storage is a critical issue. In rural areas, the dominant drinking water source, dugout water, was highly turbid. However, researchers observed that the water in some households had lower turbidity than the characteristic average from the source due to settling and mixing with borehole water and/or household treatment with alum. High levels of TC and *E.coli* contamination were seen throughout rural sample households.

Table 11 Water quality metrics

Type	Turbidity[30]		Total Coliform (CFU)				E.coli	
	Ave. (TU)	Max. (TU)	% with CFU	% with 100- 1000 (CFU / 100 ml)	% with >1000 (CFU / 100ml)	Ave . (CFU/ 100ml)	% with E.Coli	Ave. (CFU/ 100 ml)
Urban (n=118)	<5	<5	59%	33%	26%	2,500	8%	47
Rural (n=119)	238	1000	89%	7%	82%	18,800	26%[31]	172

[29] Urban respondents generally used dugout water for non-drinking activities such a washing (qualitative responses)
[30] Turbidity tube limit of detection is <5 TU
[31] The percentage of rural households with *E.coli* that is reflected in this data is likely lower than the actual because 1 to 10 ml dilutions were done for 70% of rural households. In these cases, only those samples with *E.coli* concentrations of 1,000 (CFU/100ml) or greater were captured. When samples with dilutions are excluded the percentage of rural households showing *E.coli* in the water increases to 69%.

Although health status was not assessed in detail in this study; one question relating to diarrheal incidence was included in the survey. The diarrheal data was collected by asking respondents to self-report incidence of diarrhea in the past week, and the information collected provides an additional metric to help measure need for improved water treatment and health outcomes. Overall, 25% and 32% of urban and rural households respectively reported a diarrheal incident in the past week. Children under five saw the highest rate of illness, particularly when considered on a per capita basis (Figure 52)

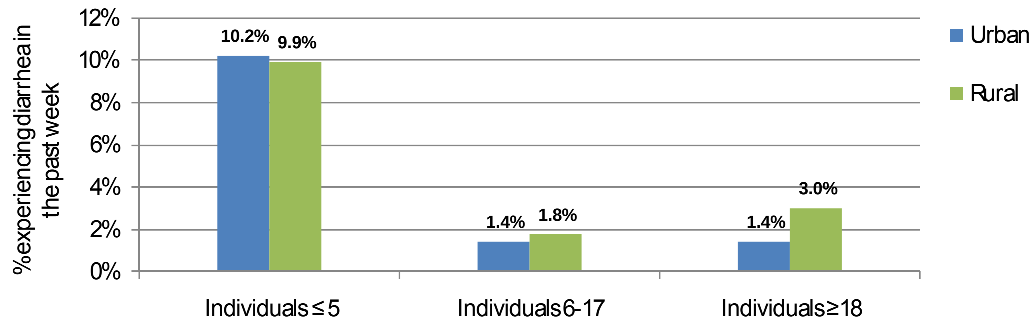

Figure 52 Diarrheal incidents in the past week

8.5.4 Water management practices

Differences in source water between urban and rural populations appear to be correlated with differences in household water management. Urban populations tend to rely primarily on the quality of the municipal water from the Ghana Water Company (96%), while the rural respondents typically use a cloth filter (93%) supplemented by settling in a storage vessel and alum treatment (Figure 53).

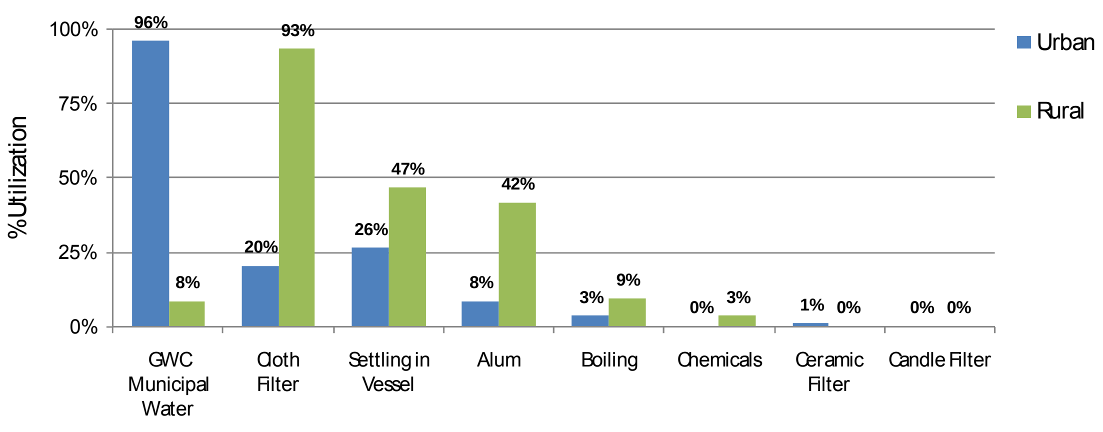

Figure 53 Current water treatment methods

Nearly all rural households engaged in some form of household water treatment; however, less than 10% actively treated microbial contamination either by boiling or with chemical disinfectants. In particular, the cloth filters provided by the Carter Center throughout the region as a part of the Guinea Worm Campaign, appear to have achieved substantial uptake[32]. In addition, alum is used seasonally when turbidity is particularly high. Of the 50 rural respondents that used alum, 90% only used this treatment method when the water was more turbid than usual.

8.5.5 Ability to pay for HWTS products

The team also collected annual household income data to improve estimations of ability to pay. However, in practice this data was very difficult to collect. Thus, many of the urban values were extrapolated from estimates of daily or weekly income while rural values were calculated based on the number of bags produced in the annual harvest. The calculations show an average annual income of GHS 1,530 (urban) and GHS 619 (rural) household.

Income data can be used to estimate the amount of disposable income available for HWTS product purchases. Assuming that household are willing to allocate a conservative 5% of daily income to water management (McPhail, 1993),[33] urban and rural communities would have GHS 0.21 and GHS 0.08 dollars per household per day respectively to spend on water treatment. However, in rural areas the majority of income is typically earned and spent during the harvest season from November to February. Thus, assuming an average of 50% of annual income is saved through the remaining eight months of the year, the average daily rural income for water management would be reduced to only GHS 0.06 per household day.

"If you are going to bring an expensive filter to this village you need to bring it at the time of year that we have just finished farming" – Golinga (rural)

Information on prevalence of common household goods was collected to supplement the income data (Figure 44). Willingness to pay for other household purchases reflects the size of investment a household would be able to make in the right HWTS product**.**

[32] Some households also had "pipe filters" which they used to treat water for Guinea Worm when away from home.
[33] Research by McPhail found that households were willing to pay 8% of income for water management activities.

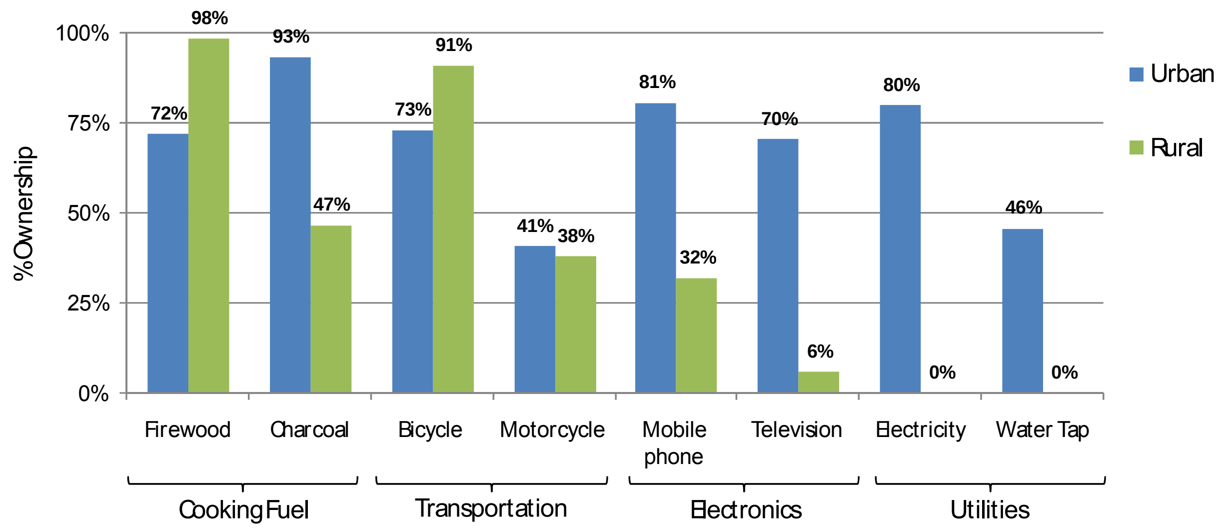

Figure 54 Ability to pay for household goods

8.5.6 Purchasing decision drivers and behaviors

Purchasing decisions questions were designed to help future HWTS marketing efforts focus investment on locations and individuals likely to have the greatest impact on stimulating product sales. Results regarding the primary purchaser, buying decision influencers and purchase location are described below.

In both sample populations the men are responsible for the majority of household purchases. Women appear to take a more active role in the purchase of large items. It is not clear from the data whether the men give them money and permission before they buy, but this was heard qualitatively from a number of respondents.

"For large purchases, like water storage vessels, my husband gives me money to buy the item." – Rural,

Data was also collected on which individuals influence buying decisions for different product types. At an aggregate level, family members had the most influence on household purchasing decisions. In addition, health workers impacted purchasing decisions about health related items. Finally, friends and community networks were seen as a strong driver of purchasing decisions. Notably, the opinions of such social networks are viewed as more important to potential HWTS customers than advice from community leaders or local officials. Although respondents rarely sited religious or community leaders as buying decision influencers, those individuals played an important role in the community's willingness to engage with the researchers (enabling the study to take place), so their social and political influence should not be underestimated.

Finally, detailed data on typical and preferred place of purchase for various types of goods including: health items, consumables, large purchases and water products. Both urban and rural residents primarily purchase items at the market. However, all respondents would like to see more local sales through either door-to-door marketing or general stores within their communities. In addition, the data shows a preference for more personalized sales models (door-to-door or roadside stand or street vendors). Such a high-touch model could be particularly effective for HWTS products that required education and follow-up for correct and sustained use.

8.5.7 Conjoint analysis results

The conjoint section of the survey is designed to help researchers assess the relative value of different features of HWTS products, with the goal of better matching HWTS product offerings to consumer preferences. We hope this will enhance product adoption and stimulate sustained use. Figure 55 below gives an overview of the relative preference for different product features, with preferred products shown to the right of the middle line for both urban and rural populations.

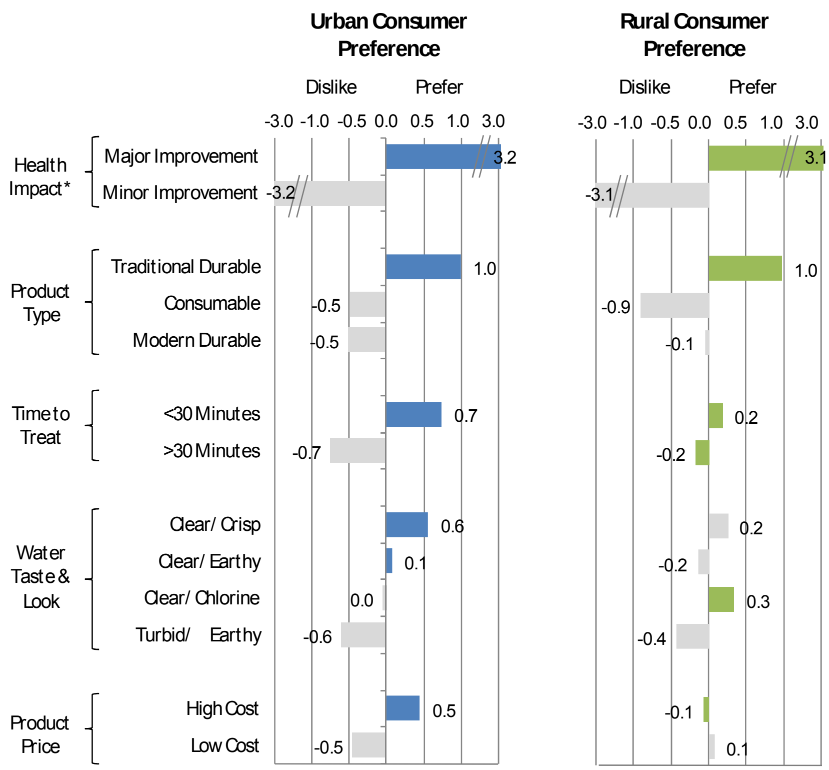

Figure 55 Product feature preference in urban and rural markets

*Note: For purposes of chart scaling health impact is discontinuous.

Urban and rural respondents showed similar preference patterns for HWTS product features; however, differences in relative importance of the product features suggests that tailoring the product type, design, educational material and marketing strategy to the preferences of different consumer segments has the potential to increase HWTS adoption.

<u>*Health Improvement:* </u>Major health improvement proved to be the most significant driver of product choice in both urban and rural markets, with a relative value of at least three times that of all other features. The researchers anticipated that health improvement would be an important driver of

purchasing behavior; however, the importance of health relative to other features highlights the need to ensure product quality and brand based on health improvement.

Product Type: The traditional durable product was preferred among both urban and rural populations. Individuals that expressed a preference for the traditional durable product typically highlighted longevity and durability as important to their choice. In addition, some respondents highlighted the attractive look of both the metallic modern durable and the plastic traditional durable. A few respondents favored consumables; however, many were reluctant to invest in a product that required repeat purchase.

Time to Treat: Time required for water treatment was largely ignored by many respondents; however, there were a few respondents that focused exclusively on selecting for short treatment times. In particular, urban respondents were more likely to see long treatment times as arduous and a barrier to use.

Water Taste and Look: Although water taste and look was a high-touch element of the survey, respondents did not show a strong preference for this feature. In a number of cases, respondents continued to ignore this feature even when reminded by the surveyor that they were choosing a water option that they had disliked in the initial tasting. In addition, the researchers were surprised to discover that there was not an aversion to the chlorine taste and in some cases respondents even preferred it because to them it made the water "taste clean." Overall, the relatively small magnitude of the taste feature reflects the limited importance placed on water taste relative to other product features.

Product Price: Product price had the least impact on overall choice, particularly in rural areas where ability to pay is low. This trend could be due to a strong desire to purchase a water treatment product or an inability to accurately assess relative prices. In urban areas, respondents tended to favor higher prices, often because of the belief that a higher price signified a higher quality, longer lasting product. The differences in price sensitivity and perceptions among sample populations highlights the importance of understanding local variations in ability to pay and price perceptions before setting a price for a commercial HWTS product.

8.6 Methodology assessment: conjoint in the developing world

The results of HWTS consumer choice research conducted in Northern Ghana using conjoint analysis demonstrates that this methodology has the potential to offer a relatively low-cost tool to enhance consumer understanding across a number of critical elements of product design. However, a number of modifications were required for effective use in the developing world.

8.6.1 Useful survey modifications

Inclusion of pictorial images proved a useful tool. The ability to engage the respondents on the pictorial images greatly enhanced the execution of the conjoint choice tasks. Here, the use of laminate sheets was a critical success factor. Binding the laminate task screens together allowed the surveyors to actively use them as props. In addition, having larger scale visuals that matched the images shown on the task screen helped some respondents better understand the tradeoffs being presented on the visually stimulating task screens. In this case, the text shown on the screens was in English; however, this was not a concern for the surveyors or respondents as Dagbani is very infrequently used as a written language. That said, as the pictorial screens were a critical element of the study, if this methodology is being considered for other cultural context it could be useful to develop translated versions.

The use of paper surveys necessitated a reduction in number of survey variations from that which would be used with an online tool. Ideally a different randomly selected set of product options would be shown to each respondent. In this case, four different surveys were produced for each population (urban and rural), and the same four sets were used throughout the research. The reduction in survey length reduced the volume of data collected; however, it did appear to enhance the quality of the results.

8.6.2 Lessons learned

Data analysis could have been expanded by utilizing the same survey instrument for both rural and urban populations. A similar conjoint tool was chosen for the two populations, but higher prices were used for the urban survey. The change was made as a result of anticipated differences in urban and rural ability to pay. However, the urban and rural populations actually had somewhat similar ability to pay, and using a single conjoint tool would have facilitated a comparative analysis of urban and rural data. The CBC approach would likely have been equally effective with smaller sample size, and a greater emphasis on in-depth translation and discussion. A number of the greatest insights gathered in the research came from patterns observed in commentary and discussion. Thus, a more detailed approach with a smaller sample could have offered greater understanding of the local preferences, politics, beliefs and traditions that govern water management behaviors. In addition, qualitative approaches based in anthropological research methodologies could be explored.

8.6.3 Comments on product feature selection

Prior to commencement of the survey the merits of including a health impact variable were extensively discussed. Inclusion facilitated assessment of the relative importance of health in HWTS purchasing decisions. Conversely, strong selection for this variable had the potential to mask preference for other features. Furthermore, as health impact of a single product cannot be easily quantified, the health variable might not have been the most effective way to describe HWTS products. To help offset the strength of the health variable a "fixed" task screen was included where the product options were matched to real products, with major health impact displayed in all three options. Despite the fixed task, the health attribute ultimately overshadowed all the other features. Thus, if the research were replicated in a different context it might be better to assume major health improvement is the most important driver of HWTS product purchase and either exclude the health attribute or set it at "major health improvement" throughout the study. In addition, the decision was made in this research to co-vary price with product type to more accurately replicate the existing market landscape. The co-variance was useful in that it ensured that the product prices matched the product type; however, it made it difficult to clearly distinguish the relative in importance of price versus product type.

8.6.4 Opportunities for further research

The initial Conjoint Analysis clearly demonstrated the potential for the conjoint tool for developing world consumer choice research. The ability of the surveyors to communicate (and the respondents to accomplish) the choice task is a critical step in proving the viability of the methodology for developing world product assessments. However, additional work is required to assess correlations between conjoint preferences and actual purchasing behaviors in communities with clear and turbid water. The test of the CBC methodology would be most effective if similar features are used to describe the most appropriate HWTS products for each segment in the micro-market study.

Additionally, although relative importance of price in purchasing decisions was assessed using this conjoint methodology, price was only one of the five variables, so the researchers were not able to develop a price to demand curve. Therefore, to learn more about willingness to pay for HWTS in Northern Ghana, two options could be considered. First, a conjoint could be developed based on one or two of the product descriptions above, that used price as the only variable. Alternatively, price variations could be incorporated into the micro-market model; however, given the large number of products being assessed, the later approach would require a large sample size to achieve statistical significance. Finally, given local purchasing patterns seen in Northern Ghana, the author would recommend that any micro-market follow-up attempted be conducted in December-February, post-harvest season, when respondents are most likely to have enough extra cash on hand to invest in a larger household purchase. Overall, the conjoint methodology proved a useful tool to assess product feature preference in Northern Ghana. As a result of this study, the researchers learned which features of a water treatment product are most important to the local communities in urban and rural Northern Region, Ghana. However, further micro-market research would be useful to assess whether the conjoint methodology was effective in capturing actual purchasing behaviors.

8.7 HWTS local product effectiveness

The researchers aimed to identify those HWTS products likely to have the greatest impact on water quality and health outcomes in our target communities in Northern Region Ghana in both the short and long term. As intervention efficacy varies by geographic region, water source characteristics, and community type, we considered the HWTS product options described in the local context of Northern Ghana. Based on the results of the survey, the range of available HWTS products were prioritized based on three screens: 1) efficacy for treatment of source water, 2) local availability 3) product price relative to consumer ability to pay (Table 12).

Table 12 Initial comparative assessment of HWTS products in Northern Region, Ghana

Type	Household Water Product		Turbidity Efficacy	Microbial Efficacy	Local Availability	Annual cost (GHC) / family*
Particle Removal	Cloth Filter		Low	Low	High	0.0
	Alum		High	Low-Moderate	High	2.2
	BioSand Filter	Local LDP	High	Moderate	Low	10
		Int. Aid	High	Moderate	Low-Moderate	22
Particle Removal & Safe Storage	Pot Filter (*Kosim*)		High	Moderate	High	10
	Candle Filter	OK	High	Moderate	Moderate	14
		Mission	High	Moderate	Low	50
		Berkefeld	High	Moderate	Moderate	136
Disinfection	SODIS (UV)		Low	Low-Moderate	Moderate	8
	HTH Chlorine		Low	High	Low	0.3
	Liquid Chlorine		Low	High	Low	2 – 5
	Aquatabs (20l)		Low	High	Low-Moderate	13
Coagulation & Disinfection	PuR (P&G)		High	High	N /A	45 - 80
Safe Storage	Locally Manufactured		N / A	N / A	Low	1.2
	CDC (SWS)		N / A	N / A	Low	2.4
Sachet Water	Hand-tied (single)		N / A	N / A	High	275
	Factory (wholesale)		N / A	N / A	High	657

Note: Annual cost per family was estimated by calculating using an anticipated average household size of 12 individuals and 2 liters of drinking water per individual per day[34].

As shown in Table 3, among the low-cost particle removal options, alum and the *Kosim* ceramic pot filter have the most potential in the short term, as they effectively remove turbidity as well as microbial contamination and are available in Northern Ghana. In addition, the OK candle filter and the two models

[34] Values used for price calculations:
1) cloth filters given by Ghana Health Service;
2) alum cost GHC 0.02 / ball which can treat an estimated 2x40 liters of water;
3) Biosand filter price of GHC 30.00 for locally manufactured LDP (Kikkawa, 2008) and 3 year filter life;
4) Biosand filter price of GHC 65.00 for International Aid product and 3 year filter life;
5) *Kosim* ceramic pot filter price of GHC 15.00, 2 filters per household, and 3 year filter life;
6) OK filter price of GHS 18.90, estimated GHS 1.62 replacement filter (6 months), and 7 year filter life (5 year warranty);
7) Mission filter price of GHS 50.00 and GHS 15.00 for replacement filters and chlorine, 2 filters per household, 5 year filter life;
8) Berkefeld filter price of GHS 42.00 and GHS 32.00 for replacement filters (6 months), 2 filters per household, 5 year filter life;
9) One plastic SODIS container (liter) purchased per person every other month for GHS 0.11;
10) Annual HTH cost estimated at 48x lower than Aquatabs;
11) Liquid chlorine minimum calculated from PSI typical cost of GHS 0.25 / bottle for 1.5 month per household;
12) Aquatabs cost based on Northern Region Ghana distributer price of .03 / 20 liter tablet;
13) PuR price of 0.05 / sachet (10 liters) which would likely be the minimum price in Ghana given a $0.035 price to NGOs;
14) Locally manufactured safe storage includes GHS 2 jerry can and GHS 1 tap, 2 containers per household, 5 year life;
15) CDC SWS safe storage estimated at GHS 6 in Ghana (price of $5 in USA), 2 containers per household, 5 year life;;
16) Hand tied sachet is priced at 0.02 / 700ml (Okioga, 2007);
17) Factory produced sachet is priced at 0.05 / 500 ml.

of biosand filter may have longer term potential as these products are also reasonably priced. However, as these filters, particularly the biosand, are large durable products and thus are difficult to transport, an appropriate distribution model and/or outreach program would need to be developed to get these products to rural communities. Moreover, the OK filter would not be able to handle high turbidity waters.

Among disinfection options, solar UV disinfection has not been shown to be highly effective given local environmental conditions in Northern Ghana (Foran, 2007), and thus chlorine emerges as the priority alternative. However, chlorine disinfection is less effective in water with turbidities greater than 30 NTU. Therefore, in rural areas where source waters are highly turbid chlorination should be used in conjunction with a particle removal option such as alum or the *Kosim* ceramic pot filter. PuR™ offers a simple solution, as it combines both particle removal and disinfection in a single sachet; however, the relatively high-cost reduces the attractiveness of this option particularly in lower income rural areas where combined treatment is most needed. In addition, as PuR™ is not currently on the market in Ghana, so local scale-up would be required to assess viability in the longer term. Safe storage is also highlighted because although such products do not provide water treatment, they are an important component of water quality management. In this case, low-cost safe storage options have the potential to enhance protection from recontamination, particularly if used in conjunction with chlorine disinfection.

8.8 Recommendations

This research highlights the set of HWTS options with the greatest product effectiveness in northern Ghana. In addition, we use consumer preference research to match priority HWTS products with customer demand, and to identify those promotional strategies that are most likely to have a long-term impact local drinking water quality by stimulating product adoption and sustained use. The results indicate that a portfolio approach is needed; however, it is our hope that local organizations seeking to implement point-of-use water treatment interventions can use these recommendations to target their efforts towards those interventions and HWTS products that are the best fit for the local consumers, and thus most likely to stimulate product adoption and sustained use.

8.8.1 New Product Development

Low-Cost Safe Storage: The data show a significant short-term need for a low-cost plastic safe storage product throughout both urban and rural communities. Strong preference for traditional durable product type and high levels of recontamination in both urban and rural areas support this recommendation. Ability to pay estimates and product cost suggest that a commercial market would exist for this product.

Household Chlorine Product: Opportunity for local manufacturing and/or promotion of a low-cost HWTS chlorine product (e.g., liquid chlorine or Aquatabs). Our surveys showed substantial numbers of people with clear, microbially contaminated drinking water, and slight preference for a chlorine taste. In urban communities, chlorine treatment prior to use could reduce recontamination risk. Due to the high turbidity of the sources waters of rural communities, household chlorine treatment scale-up in rural communities will likely require a low-cost product and clear dosing protocol, given lower ability to pay and need for a multi-step process that includes particle removal prior to disinfection.

8.8.2 Revenue Generating Opportunities

Targeted Sachet Water Business: Opportunity for sachet water vendors focused on urban traders and professionals, and brand differentiation through product look.

High-End Modern Durable: Limited market for modern durable filters among urban upper class. Sales at the general store as well as social marketing should be emphasized to stimulate demand.

Chlorine Disinfection & Safe Storage: Urban areas offer an initial target commercial market for a combined chlorine disinfection and safe storage product. Urban communities are good entry point for this product as the market is large, relatively easy to reach, and generates enough income to pay commercial prices for chlorine and safe storage containers. Significant microbial contamination observed, despite clean source water, supports the recommendation for residual protection and safe storage. Success depends on the development and communication of a clear chlorine treatment dosing protocol, specifically treating within twenty four hours of consumption to maintain residual protection. Preference for door-to-door purchasing suggests that a local sales model (vendors or local store) would likely be most effective for marketing a consumable product to these segments.

8.8.3 Bottom of the Pyramid

Alum, Chlorine Disinfection & Safe Storage: Rural communities could be served by a combined treatment system including alum, chlorine and safe storage. Opportunities for low-cost combined treatment products (e.g., alum / ceramic pot + chlorine disinfection) only exist in communities with turbid source water. Success depends on the development and communication of a clear dosing protocol at the household or community level. The low income nature of the rural agricultural population creates a potential concern about ability to pay, particularly outside of the harvest season

Target market for *Kosim* Ceramic Pot Filter (and biosand): The locally available *Kosim* ceramic pot filter is also a solid fit for rural agricultural communities. In addition, biosand filters could also be considered, but difficulty of transport could be a concern as there is a strong preference for a local sales model among rural agricultural respondents.

8.8.4 Considerations for Implementation of HWTS Interventions

Understanding local needs and clearly communicating product value in terms that are relevant for the local communities is critically important for successful implementation. In addition, education about importance of correct and sustained use should be highlighted for each community and potentially incorporated through marketing materials or product bundling (e.g., dedicated cup for water, products for cleaning, maintenance). Furthermore, where behavioral change is required, it will be important to continue to seek mechanisms of reinforcing correct use.

Local purchasing behaviors must also be considered in developing a successful implementation strategy, particularly if commercial sustainability is desired. A community level sales model is desired; however, door-to-door marketing is challenging from a commercial perspective as a substantial number of resources are required to make house calls for limited total sales. One way to address this challenge, particularly for consumable products, could be to provide inventory on a local level and restocking from a centralized distributor. Timing is also critical, particularly in rural areas where income is cyclical. If households are only able to make large purchases during the months following the harvest, then sales cycles should be seasonally calibrated. In Northern Ghana, males make the majority of the purchasing decisions, while women are responsible for water management. Thus, successful HWTS marketing will require a two-pronged approach; women must want to use the product and men must want to buy the product. Finally, social networks appear to be important at the community level; however, community leaders are not cited as particularly influential in terms of purchasing behavior

8.9 Conclusion

Although household water treatment efforts in Northern Ghana have expanded steadily towards the goal of reaching the 900,000 people in the region that lack access to an "improved" supply drinking water, a substantial number of households remain underserved. This research aims to provide a reference for organizations considering HWTS interventions in Ghana, and throughout West Africa, to aid in the assessment of the relative value and cost of HWTS product options. The consumer preference research helped identify which features of HWTS products are most important to consumers. In addition, this work offers insight on the HWTS consumer landscape including assessments of: 1) existing water management practices, 2) need for improved water treatment based on health status and water quality, 3) HWTS product feature preference (strong demand for health improvements and traditional durable products with little sensitivity to water taste and price), 4) purchasing power and ability to pay, and 5) purchasing behavior and priority distribution channels.

Today, a range of HWTS products are available in Northern Ghana that are both appropriate for the local water quality needs, and are within the economic means of households in both urban and rural areas. Therefore, an opportunity exists to extend the reach of HWTS throughout the region by focusing on distribution and/or commercial sale of a discrete set of priority products to the most appropriate consumer segment(s). In addition, by seeking to expand local availability of supporting products such as safe storage and a cheaper chlorine disinfection product, the range of locally available HWTS options can be expanded to include the full suite of HWTS options that are a good match for the household water treatment needs of every community in the region.

9.0 Conclusions

9.1 Pilot horizontal roughing filtration

<u>Summary of Key Results</u>

- During this pilot HRF study, Ghanasco Dam dry season turbidities were between 176 and 540 NTU.
- The pilot HRF system removed between 76-84% of the total influent turbidity while its average flow rate stayed within the SANDEC guidelines (54 – 270 mL/min).
- The granite gravel (G) media performed the best and met the target of reducing the turbidity to < 50 NTU by removing 84% of the influent turbidity (128 - 313 NTU) and producing an average effluent turbidity of 51 NTU.
- The average effluent value for the granite gravel (G), local gravel (D), and broken pottery (P) was 61 NTU, which nearly reached the target of < 50 NTU for SSF.
- Laboratory settling tests showed about 30% of the turbidity in the tanks settled while data from the pilot HRF showed approximately 57% of the turbidity settled.
- Settling tests showed that the particle removal mechanisms in HRF were responsible for 46% of the turbidity removal in the granite gravel (G) tube and 30% and 19% turbidity removal for the local gravel and broken pottery respectively.
- The filtrability and sequential filtration tests showed that the majority of particles left in the HRF effluent are colloidal and small supracolloidal particles that do not easily settle.

9.2 Modification of a biosand filter

<u>Summary of Key Results</u>

- Local plastic design (LPD) BSFs showed effective turbidity removal with an average of 92-95 % reduction.
- Modified LPD BSFs showed effective turbidity removal until the end of operation (46 days). Unmodified LPD BSFs turbidity removal declined after 27 days. This could be indications that the modified LPD BSFs have longer filter life (less frequent need of cleaning), or that the modified BSFs withstand greater operational variation
- Quantitative microbial results were not obtained after filter ripening (Day 13).
- The total coliform removal on Day 11 is relatively good with an average of 87 % removal and an average effluent concentration of 430 cfu/100 ml from an influent concentration of 15,000 cfu/100 ml.
- *E. coli* colonies were not detected in the majority of the influent/effluent samples of the LPD BSFs.
- The HydrAid BSFs also showed effective turbidity removal of an average of 87 % reduction. The average total coliform removal was 95 %, with an effluent concentration of 710 cfu/100 ml.

9.3 Kosim plus Aquatabs

Summary of Key Results

- Average TC concentration was reduced by 50% from baseline (filtered-only) to post-intervention (filtered+Aquatabs) from all 59 households
- 46% of households experienced reduced TC concentrations in Aquatabs treated water, while 37% remained the same as post filtered-only water (most of those households had no contamination in either sample) and 17% increased
- Percent of households that did not indicate the presence of TC (<100 CFU/100mL) increased from 44% to 64% from baseline to post-intervention
- EC present in only 2% (1/59) of post-intervention water samples, compared with 12% (7/59) of filtered-only water samples
- 62% (10/16) of households had a FAC level greater than 0.2 mg/L 24 hours after dosing, at time of post-intervention visit
- 64% of households had a FAC level greater than 0.1 mg/L at time of post-intervention visit (0.1 mg/L FAC was the benchmark used for randomized chlorine testing in the CDC study in the neighboring village of Bipelar in Northern Region, Ghana in 2007)
- Among households with a FAC residual in treated water between 0 and 0.25 mg/L, 32% of households had reduced TC concentrations, while 32% had increased TC concentrations
- However, among households with a FAC residual in treated water between 1.01 and 2.00 mg/L, 67% of households had reduced TC concentrations, while 8% had increased TC concentrations
- All survey respondents indicated that Aquatabs "improved the taste of the water" and that they "would recommend Aquatabs to others"
- 33/35 (94%) of lower middle-class survey respondents were willing to pay the full GHC 3 for 100 Aquatabs, while 6/24 (25%) of lower-class survey respondents were willing to pay same price (100 Aquatabs is sufficient for 1 year of treatment with the combined system)

9.4 Gravity-fed Chlorination

Summary of Key Results

- The Pulsar 1 system, using high-test hypochlorite as a chlorine source in conjunction with the other discussed modifications, shows potential of being a successful community-scale water disinfection system. While previous research showed the system could operate at flow rates approximating 42 gpm (Eau Lambda, 2005) this research focused on lower flow (18 and 9 gpm) scenarios.
- Field testing in Ghana (running at flow rate of 18 gpm) indicated that most (3 out of 4) values had free chlorine residual concentrations in the range of 10 - 14 mg/L while running at full dilution with modified parts. By additionally altering the Pulsar's inlet flow rate, this value was successfully reduced to appropriate drinking water standards (determined to be less than 2.0 mg/L) in all cases (10 out of 10). However, this final action was determined to be inappropriate because it would likely lead to scaling blockage.
- Laboratory results in the MIT lab (system at 9 gpm) in Cambridge, MA showed most (17 out of 24) of the free chlorine residual data was equal to or less than 2.0 mg/L at a very low flow rate (9 gpm).
- The author did not observe a system breakdown during the three weeks of field testing in Ghana or during subsequent research in Cambridge, MA.

9.5 Consumer Preference

Summary of Key Results

- The primary urban water management challenges are water quantity and safe storage, as urban taps flow infrequently and thus households store water for long periods
- The primary rural water management challenges are source distance and source water quality as the majority of rural respondents collect water from highly turbid and heavily contaminated dugouts/ dams more than 30 minutes from their homes. In addition, mixing of borehole water with dugout water reduces water quality advantages of using the borehole source.
- In addition to rainwater collection, urban communities primarily used water from private taps, either personal or those of neighbors, while rural communities mostly collected water from surface water sources, dugouts / dams, as well as boreholes.
- Assuming that household are willing to allocate a conservative 5% of daily income to water management, urban and rural communities would have GHS 0.21 and GHS 0.08 per household per day respectively to spend on water treatment and management activities
- Major health improvement proved to be the most significant driver of product choice in both urban and rural markets. In addition, the traditional durable product was preferred due to product durability and the attractive product look, treatment time, water taste and look and product price had less impact on overall product choice.

10.0 Recommendations

10.1 Pilot horizontal roughing filtration

Recommendations

The structure of community-based management and operations of centralized water systems will greatly vary. However the following guidelines are applicable to many situations when choosing a community and project site for a community-scale water system:

- Develop Local Watershed Protection Plans
  Inexpensive improvements can be made to the periphery and catchment area of the dugout to improve its water quality. For example, one could plant natural barriers to catch particulate matter in runoff before it enters the dam, improve sanitation, or dig deeper dams to conserve water by reducing the surface area exposed to evaporation.
- Dugout Water Quality Monitoring
  Long-term monitoring of not just the improved water supplies, but the surface water and other unimproved sources including all the rural dugouts in NRG will create a much clearer picture of their physical water quality, seasonal changes, and long-term trend in water quantity, quality, accessibility, and reliability and how climate change, deforestation, desertification, and changing weather patterns are impacting the poor rural populations who rely on these sources in Northern Ghana.
- Setting up a Dugout Monitoring Campaign after the Model of the Guinea Worm Eradication Accolades
  Partner with trained Guinea Worm Volunteers (GWV), universities and schools, and Peace Corps Volunteers (PCVs) to monitor dugout water quality. If provided with some basic, inexpensive lab

equipment, the monitors could train the Guinea worm volunteers and team up with students to perform simple monthly or bimonthly physical water quality tests similar to those preformed in this study such as turbidity, solids settleability, and suspension stability plus simple microbial testing. The results could be compiled, analyzed, and shared with a central office. Follow-up support must be available to communities whose results show positive microbial contamination and/or especially high turbidity to plan for and implement a source protection and/or treatment intervention.

- Rehabilitate and Upgrade Existing HRFs
  Rather than constructing more new HRFs in Ghana, it would be more cost-effective to repair the existing HRF systems, like the channel at Kunyevilla Dam, and work closely with the community to develop better operations and maintenance practices. Preliminary work should focus on community participation together with a local leaders and a technically trained person to identify challenges and solutions. Completion of a baseline health survey before implementing the project and some time after the intervention would allow conclusions to be drawn on the HRF-SSF system's impact on reducing the disease burden of diarrheal disease. This information could be used to do a cost-benefit analysis and comparison between the Disability Adjusted Life Years (DALYs) prevented by a borehole, HRF-SFF system, and coagulation-chlorination system.
- Investigate Media and Particle Properties to Enhance Colloidal Particle Removal
  Investigation of the chemical and physical properties of coarse roughing media available in NRG and colloidal particles in the dugout water could lead to improvements in the HRF design to favor biofilm formation and/or use particles charges and chemical properties to improve turbidity removal.

10.2 Modification of a biosand filter

Recommendations

- The local plastic design BSFs should be tested with further microbial testing, in order to further asses the efficacy of these BSFs.
- Longer operation periods may reveal more differences between the modified and unmodified LPD BSFs.
- For the HydrAid BSFs, operation with higher turbidity influent is recommended, since the influent that was used in this study had a relatively low turbidity.

10.3 Kosim plus Aquatabs

Recommendations

- Further research on combined *Kosim* filter and Aquatabs system is needed. Specifically, more field data and user perception results should be gathered. To improve this study, both surveys should be altered to acquire more thorough results. Lastly, research should be conducted on the sustained use of the combined system.
- More flow rate tests should be performed on the *Kosim* filter with respect to water quality and use. For water quality, the same *Kosim* filter should be used to test water of varying turbidity and microbial concentrations. For use, more old filters should be tested to assess how use affects flow.

- A combined alum and Aquatabs system should be tested for in a manner similar to this study. Improvements should be made by selling the products to the households, rather than donating them, as well as developing a more thorough survey design.

10.4 Gravity-fed chlorination

Recommendations

There are several areas which still need to be better understood before implementation of the Pulsar 1 system should be considered in Ghana or other similarly challenging developing country contexts, and further research should be conducted in Northern Ghana and at other sites to ensure similar results.

Probably the most important issue is to create a model which predicts how altering various input parameters will affect the free chlorine residual concentration. Having such a model would allow the quick prediction of necessary chlorine, treatment costs, and even future potential challenges. The specific input parameters to be considered should, at the least, include:

- System flow rate
  The research conducted by the author was only able to observe the Pulsar 1 system treating relatively low flow rates in Ghana and Cambridge (approximately 18 gpm and 9 gpm, respectively). Other previous research also realized success at a higher flow rate of 42 gpm (Eau Lambda 2005). Ideally the system would be tested over a wider range of flows.
- Influent water quality (pH, turbidity, and temperature)
  Other major water quality parameters can alter the efficacy of the chlorine disinfection process. While the conditions which require additional chlorine (a high pH or turbidity) are understood, a potential model to quantify these effects in the Pulsar system needs further study. For instance, there is currently no way to accurately predict how much more HTH it takes to disinfect water with 5 NTU and a pH of 7.5 than a similar volume with 1 NTU and pH of 6.0 for the Pulsar 1 unit.
- Relevant Pulsar 1 system modifications such as a spiked grid, dilution nozzle assembly (DNA), and an emergency shutoff valve (ESV)
  Additional research needs to be done to identify how these various modified parts interact with each other and the other influent water parameters. Although the Pulsar 1 system's success in Ghana and Cambridge, MA was a direct result of these modifications, further work needs to be done in varied locations and conditions to better understand their behavior.

10.5 Consumer preference

Recommendations

- Low-Cost Safe Storage
  Significant short-term need for a low-cost plastic safe storage product throughout both urban and rural communities.
- Household Chlorine Product
  Opportunity for local manufacturing and/or promotion of a low-cost HWTS chlorine product (e.g., liquid chlorine or Aquatabs).
- Targeted Sachet Water Business

Opportunity for sachet water vendors focused on urban traders and professionals, and brand differentiation through product look.

- High-End Modern Durable
  Limited market for modern durable filters among urban upper class. Sales at the general store as well as social marketing should be emphasized to stimulate demand.
- Chlorine Disinfection & Safe Storage
  Urban areas offer an initial target commercial market for a combined chlorine disinfection and safe storage product. Urban communities are good entry point for this product as the market is large, relatively easy to reach, and generates enough income to pay commercial prices for chlorine and safe storage containers.
- Alum, Chlorine Disinfection & Safe Storage
  Rural communities could be served by a combined treatment system including particle removal, disinfection and safe storage.
- *Kosim* Ceramic Pot Filter (and biosand)
  The locally available *Kosim* ceramic pot filter is a solid fit for rural agricultural communities. In addition, biosand filters could also be considered, but difficulty of transport could be a concern as there is a strong preference for a local sales model.

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