Evaluating Access to Drinking Water in Northern Ghana

2013 Group Report

Glass Half Full Consultants

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1. The Republic of Ghana

Ghana, a West African country located in the Gulf of Guinea, has a population of about 24 million (CIA 2012). The total area of Ghana is 238,535 km^2 (92,098 mi^2). The top three largest cities in Ghana are Accra, Kumasi, and Tamale, contributing to 20% of the total population in the country. The word Ghana, derived from the ancient Ghana Empire, means "Warrior King" (Jackson 2001). Only a few degrees north of the Equator, Ghana has a warm climate throughout the year (Figure 1).

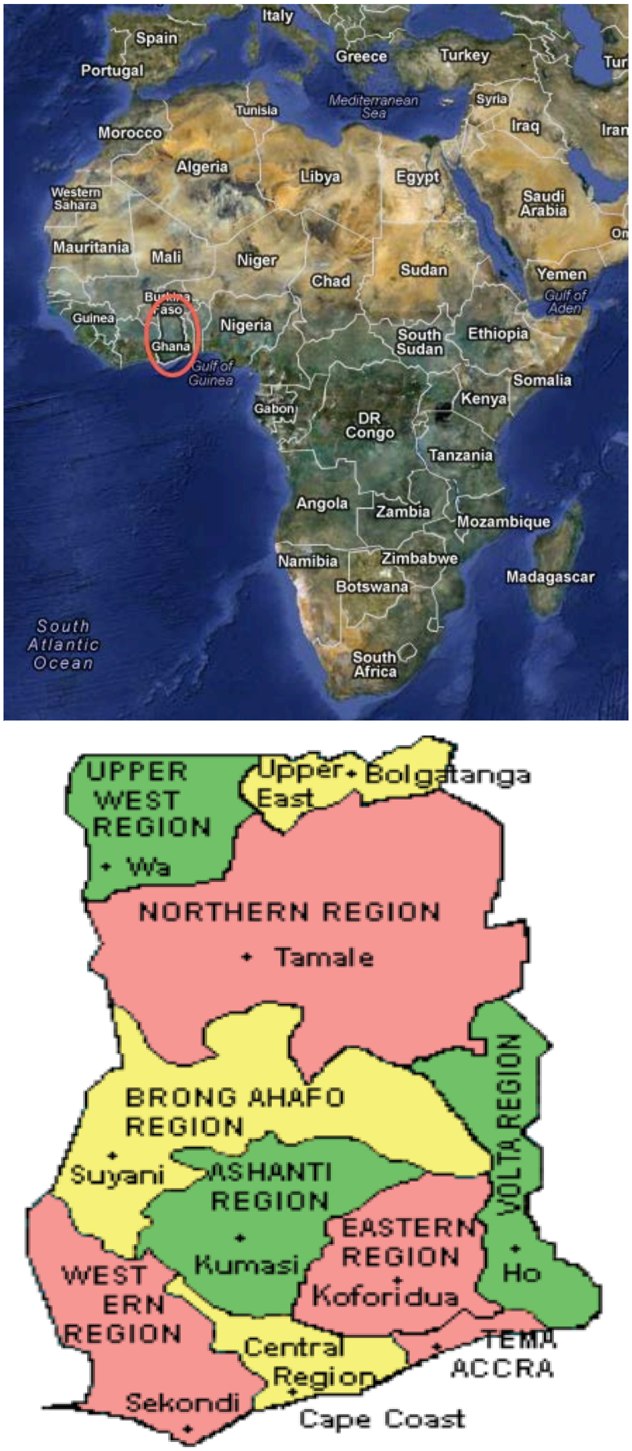

Figure 1: Map of Africa and Map of Ghana (Credit: Google Map, GhanaWeb

Since its independence in 1957, Ghana has been a parliamentary democracy, followed by alternating military and civilian governments. Military government gave way to the Fourth Republic after presidential and parliamentary elections in late 1992. Ghana is a Lower-Middle Income Economy and 27% of its population was living on less than $1.25 per day by 2011 (World Bank 2011). The native and largest ethnic group is Akan, as of 2012, 45.3% of the population is Akan (CIA 2012). English is the official language, and Akan is the largest native language. However, there are some 60-70 other local languages spoken by different tribal and ethnic groups throughout the country.

Ghana is a member of the United Nations, the Commonwealth of Nations, the South Atlantic Peace and Cooperation Zone, La Francophonie, the African Union, and the Economic Community of West Africa States (World Bank 2011).

Drinking Water in Ghana

Ghana is currently officially "on track" for reaching water Millennium Development Goal for improved water by 2015 (UNICEF/WHO), but nonetheless has significant populations especially in the northern part of the country with unmet needs for safe drinking water (Murcott 2012).

Over 50% of the population in Northern Ghana lack access to safe drinking water, and use unimproved water, i.e. surface water, as drinking water sources (Figure 2). An improved source includes a public standpipe or outdoor tap, a protected well, a protected spring, or rainwater (WHO/UNICEF 41). However, these sources don't completely prevent water borne diseases. Children have high mortality rates and serious health issues due to the lack of safe water access. There is a substantial need for not only "improved" but also "safe" water management and water treatment options in Northern Ghana.

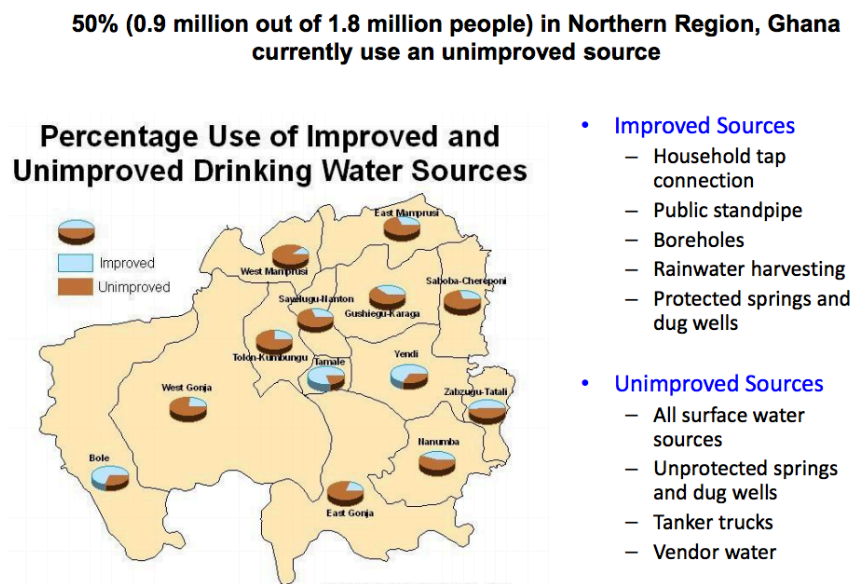

Figure 2: Northern Ghana Drinking Water Sources (Credit: VanCalcar, 2006)

Household Water Treatment and Safe Storage (HWTS) as a complement to intermittent piped water supplies

Microbial and/or chemical contaminates can infiltrate into piped distribution systems, especially where water is supplied intermittently, such as in Ghana. The low water pressure, creating an intermittent distribution system, will allow the ingress of contaminated water into the system through breaks, cracks, joints and pinholes (WHO 2012). The situation is highly likely to occur in Ghana due to its aged piping network. Water flowing out of the tap is potentially contaminated and requires additional treatment for drinking. Therefore, an added barrier of protection against contamination is desired for drinking water treatment in developing countries like Ghana. HWTS products can provide that additional barrier of protection.

Maintaining a disinfectant residual throughout the distribution system can provide some protection of recontamination; but it can also mask the detection of contamination through the use of conventional fecal indicator bacteria such as E. coli, particularly by resistant organisms (WHO 2012). A viable control measure can be utilizing household water treatment products, one example of which is porous ceramic or composite filters. These filters rely on physical straining through a porous surface to remove microbes by size exclusion. Some filters are coated with colloidal silver, which is bactericidal and kills contaminated microbes during the filtration process.

In Ghana where piped water suffers from recontamination, HWTS product creates an additional barrier of protection, and therefore serves as a first line of treatment and protection for those using unimproved water supplies and an additional barrier of protection for those with intermittent piped water supplies.

Pure Home Water (PHW)

Pure Home Water (PHW) is a registered nonprofit organization in Tamale, Ghana. Since its inception in 2005, PHW has been providing household water treatment techniques in Northern Ghana. The organization has two goals: 1) provide safe drinking water, sanitation, hygiene (WASH) in Ghana, especially to those most in need in Northern Ghana; 2) become locally and financially self-sustaining. To meet these goals, PHW has developed a ceramic water filter called AfriClay Classic Filter. This filter has been effective at pathogen removal and treating household drinking water. Having reached out 100,000 people through dissemination of the AfriClay Classic Filter, the organization has achieved some success with meeting its first goal, however, it has struggled, unsuccessfully so far, to at least break even on expenses to meet its second goal.

Table 1: PHW's AfriClay Classic Filter Performance

Flow Rate	Bacteria Removal	Turbidity Reduction
2-7 L/hour	99%	80%

2. The Effects of an Intermittent Piped Water Network and Storage Practices On Household Water Quality in Tamale, Ghana

Global Water Supply

According to the latest reports from World Health Organization (WHO)/UNICEF, in 2010 more than 780 million people worldwide lacked access to improved drinking water (UNICEF, WHO 2012). The WHO defines "improved" drinking water sources as any sources that are "by nature of its construction or through active intervention, is protected from outside contamination, in particular from contamination with fecal matter."[1] Through their "Water Ladder" framework, the WHO/UNICEF lists a piped water connection, either in the home or a public area at the top of the ladder in terms of an improved water source.

However, this definition does not necessarily mean that people with access to "improved" water sources are drinking safe water (i.e., water that is free of waterborne pathogens or other disease-causing contaminants). In fact, many studies have shown unsafe levels of bacteriological contamination in household drinking water, even when that water is supplied from an "improved" source (Wright, Gundry, et al. 2004). This contamination can be caused by any number of problems, from source water contamination, to unsanitary taps, to problems within the piped system, and problems with household storage.

Two Causes of Water Contamination

This research will focuses on two specific causes of water contamination – intermittent piped water networks and unsafe household storage.

Intermittent Piped Water Networks

An intermittent piped water network is one where water does not flow continuously to customer homes or public taps. Instead, water flows only intermittently, anywhere from several hours a day to only once a week or even once a month in extreme cases. Intermittent water supplies are found all over the developing world. It is estimated that one third of urban water supplies in Africa operate intermittently (Lee and Schwab 2005). Intermittent water supplies are caused primarily by lack of sufficient water to serve all customers and keep the piped networks fully pressurized at all times. If water is scarce, in order to deliver water at adequate pressure in one neighborhood, water may need to be routed away from other neighborhoods. Intermittency can be caused by scarcity of source water, scarcity of treatment capacity, intermittency of electricity to run water pumps, high leakage rates, high population growth, or some combination of these conditions.

Intermittent piped water networks can lead to contamination of otherwise safe water supplies due to back-pressure conditions in the system. Back-pressure conditions are present when the water in the piped network is at a lower pressure than surrounding (potentially contaminated) water, such as rainwater, sewage spills, latrine drainage, etc. This contaminated water is able to infiltrate the piped network through small leaks and cracks due to the outside water pressure being greater than the water pressure within the pipe. Because of this risk, many American state

[1] http://www.wssinfo.org/definitions-methods/ accessed on April 2, 2013

regulatory agencies require a minimum pressure to be maintained in the distribution system. The Water Distribution Systems Handbook developed by the American Water Works Association (AWWA) recommends a minimum pressure of 20 psi be maintained to prevent contamination (Mays 2000).

Household Water Storage

When water is supplied intermittently, users must use some kind of storage to have water available at all times. Water storage can exacerbate the problem of intermittent supplies as users drain the system to store as much water as possible, rather than using enough for their immediate needs. Water storage can also lead to water contamination through unsafe storage practices (Lee and Schwab 2005). Water can become contaminated in storage by keeping the storage vessel uncovered, dipping unwashed hands into the storage containers, or due to contamination within the vessels themselves.

Research Objectives

The goal of this research is to illustrate the connection between the intermittent piped water supply in Tamale, Ghana and poor water quality in households connected to the piped water system. In order to accomplish this goal, three objectives have been defined, as follows:

1. Water quality must be tracked through the entire distribution system, from the treatment plant, into the distribution system and in households, showing where the quality of the water diminishes and to what degree.

2. Household water storage will be investigated as a possible cause for diminished water quality.

3. The system will be modeled using a hydraulic model to show possible routes of contamination and quantitatively show the need for household storage.

Discussion of Key Results

GWCL Water Quality Data

GWCL records show that water quality at the treatment plant outflow meets or exceeds international requirements, such as WHO guidelines of 0 cfu/100 mL for *E. coli*, as well as national Ghanaian standards (Ghana Standards Board (GSB) 2008). Water quality in the distribution system is also adequate according to GWCL’s monthly data summary reports, although somewhat degraded compared to the samples taken at the treatment plant. This trend is particularly clear in the case of chlorine residual data. According to the GWCL dataset, chlorine residual decreased on average from 1.34 mg/L at the treatment plant, to 0.28 mg/L in the distribution system, a 78% reduction. The figure below shows the percent reduction in average chlorine residual between the treatment plant samples and the distribution system samples.

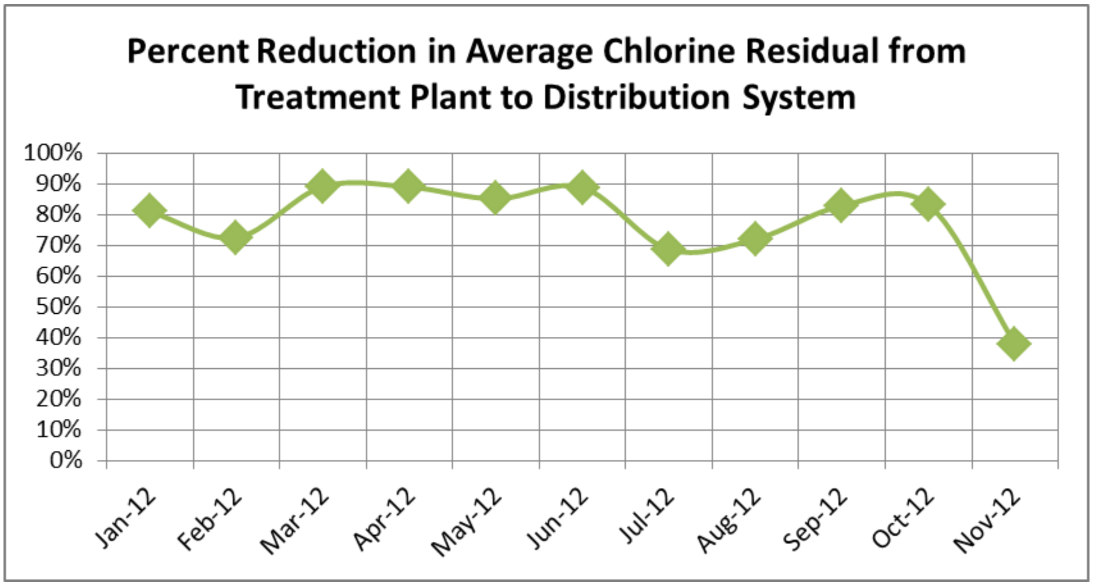

Figure 3: Percent Reduction in Average Chlorine Residual from Treatment Plant to Distribution System

Low or nonexistent chlorine residuals do not necessarily indicate that water is bacteriologically contaminated. However, water with some detectable chlorine residual is desirable in the distribution system to guard against re-contamination (US EPA 2006). Chlorine decay is expected within the system, due to water age, presence of organic particles in the pipes, biofilms on pipe walls, etc. Chlorine decay can be modeled using a first order decay expression but the decay constant will differ for each water system. The US EPA recommends conducting simulated distribution system testing to determine the decay rate of the bulk water, as well as conducting testing using portions of piping to account for decay at the pipe walls (US EPA 2006). This type of testing was not performed for the Tamale system, and therefore the chlorine decay characteristics for the system are unknown. Without knowledge of the decay characteristics it is not possible to determine whether the chlorine decay seen between the treatment plant outlet and the distribution system is due primarily to water age or to increased chlorine demand due to contamination.

All samples taken at the treatment plant and the distribution system by GWCL were negative for *E. coli*. The US EPA requires systems to maintain chlorine residuals of at least 0.2 mg/L in the distribution system in order to prevent bacteriological contamination (U.S. Environmental Protection Agency 1989). With an average chlorine residual well above 0.2 in the treatment plant samples, the water will be assumed to be coliform free at the plant outflow. In the distribution system, the average chlorine residual was 0.28 mg/L with 5 months out of 11 resulting in a mean chlorine residual below 0.2 mg/L. Every month's minimum residual was below 0.2 mg/L. Therefore, while there is no direct indication that the water is contaminated, it cannot be assumed that the water in the distribution system is free of bacteria as would be indicated by the total coliform test. Furthermore, GWCL staff indicated there are continuing issues with leakages in the system and several users reported recent leakages in their neighborhoods during the surveys.

Household Surveys

Household Storage Practices

The impact of safe storage on water quality has been repeatedly confirmed through studies and interventions (Mintz, Reiff and Tauxe 1995). In 2009 the CDC and USAID published a fact sheet summarizing recommendations for safe water storage (CDC, USAID 2009). The three key recommendations for safe storage containers were as follows:

1) The container should have a small opening with a lid to discourage users from placing items in the container (such as hands, ladles, etc.), which may be contaminated.

2) The container should have a spigot or other small opening to dispense water without the use of hands or bowls, which may be contaminated.

3) The container should be of a size appropriate for the household water treatment method in use, with instructions for the treatment and cleaning method attached to the container.

None of the containers observed had instructions for treatment and cleaning attached to them and very few households practiced additional household water treatment. Therefore, only the first two recommendations will be evaluated.

Of the storage containers observed during the household surveys, only jerry cans, poly tanks, and steel tanks met the first two criteria listed above. Although the poly tanks and steel tanks had large enough openings for hands to be inserted the tanks themselves were large enough to discourage anyone climbing on top of them to make use of those openings. All other types of storage observed had large openings and no spigot for dispensing water. Figure 4 shows the distribution of the different types of storage containers. Note that this data simply counts whether or not a type of container was present and does not specify how many containers of each type or the volume of water stored by each type of container. Containers that meet the recommended criteria are classified as “Safe” in the figure, while containers that do not meet the recommended criteria are classified as “Unsafe” in the figure.

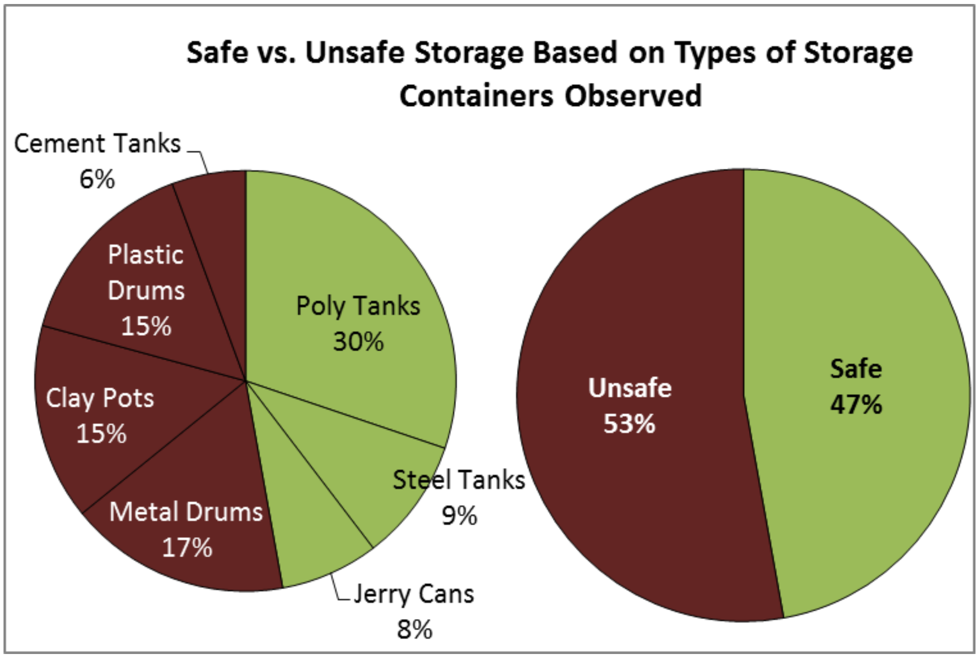

Figure 4: Safe vs. Unsafe Storage Based on Types of Storage Containers Observed

Continuity of Water Supply

Survey answers to the question "How often is water flowing from the piped supply?" varied significantly from person to person and neighborhood to neighborhood based on user perceptions of the water supply. Separating out each neighborhood's answers allows a clearer view of the variability within each neighborhood, rather than the city as a whole, as shown in the following figure.

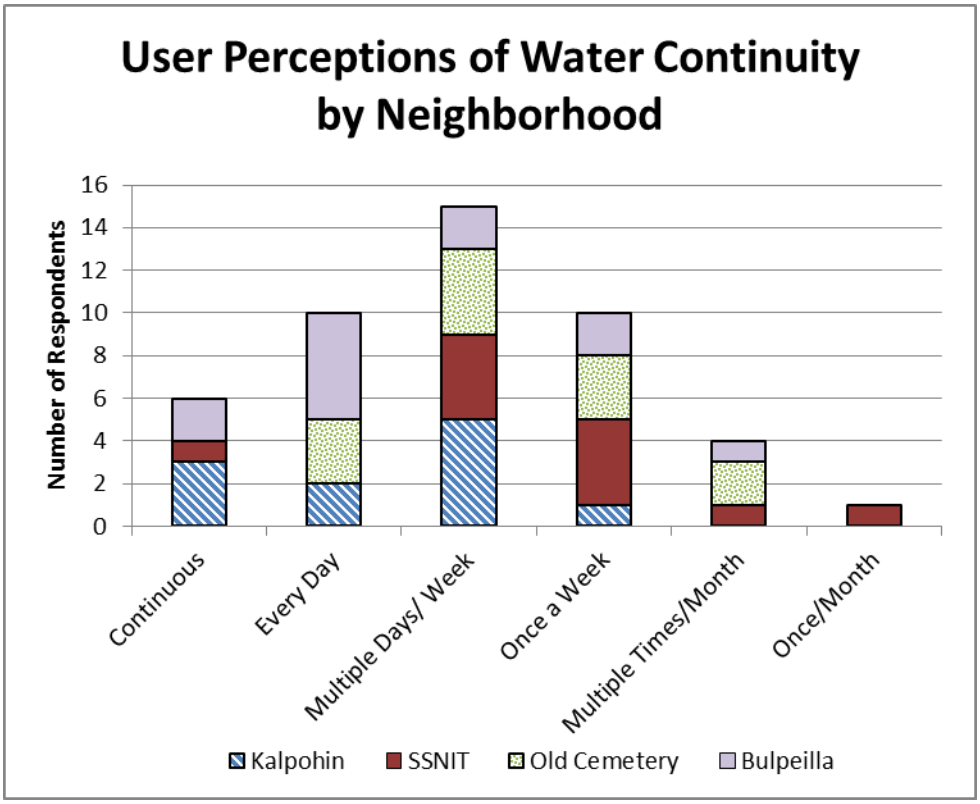

Figure 5: User Perceptions of Water Continuity by Neighborhood

As shown in Figure 5, users in each neighborhood gave a range of answers. Bulpeila and Old Cemetery generally showed a higher perception of the continuity of the water, with most respondents answering that water was running continuously or multiple days per week. SSNIT residents had the poorest perception of their water continuity, with most reporting that water was running less frequently than every day. Kalpohin residents reported that water continuity was very high, with most reporting that the water was running continuously or at least on multiple days per week. For the Bulpeila, Old Cemetery, and SSNIT data sets, responses mimic a roughly normal distribution, with a central peak around the most common response for each neighborhood. Although this is a very small dataset, this pattern implies that the most common answer is likely the most accurate, with variances from the modal value reflecting differences in user perceptions among a population. The fact that the Kalpohin data does not show this pattern, combined with the overall vagueness of the answers, implies that the Kalpohin dataset is the least reliable of the four on this particular topic.

Household Water Quality Data

The samples taken from household water storage resulted in an average chlorine residual of 0.097 mg/L. This represents a 67% reduction from the average chlorine residual found in the distribution system samples taken by GWCL. One mechanism for this decay is water age. In the interviews, most respondents reported that their piped water supply was running multiple times per week, meaning average water age in the storage vessels was likely 3-4 days.

In addition to water age, chlorine residual can decrease due to recontamination of water during collection or storage. As shown previously, 73% of the household samples tested positive for total coliforms and 33% tested positive for *E. coli*. There is no data from GWCL on total coliforms in the distribution system, so the presence of these bacteria does not definitively show that water quality has decreased in the households rather than the system itself. The presence of *E. coli* in the stored water samples however indicates that water quality has degraded between the distribution system samples and household storage since all distribution system samples were negative for *E. coli* and 33% of household storage samples tested positive for *E. coli*.

System Performance Modeling

Geographic information systems (GIS) shapefiles were obtained from GWCL for the piped network of three DMAs: A1 (SSNIT), C5 (Bulpeila), and C7 (Old Cemetery). The GIS data was converted to .inp format suitable for use in EPANET and imported into EPANET. It was not possible to obtain flow and pressure data for these DMAs by the deadline for this thesis. Without flow and pressure data, the model could not be calibrated to actual system conditions. Without a calibrated model, it was not possible to simulate different scenarios that could cause intermittency in the system (power outages, water losses, etc

Despite being unable to calibrate the model, the flow and pressure data that has been made available to the author can provide a more quantitative assessment of the intermittency in the system. The following figures show flow and pressure at the entrance to the SSNIT flats neighborhood (DMA #A1) and the Old Cemetery neighborhood (DMA #C7). This data was recorded at 15 minute intervals over the course of 4 days in early May. Pressure is shown in pounds per square inch (psi) and flow is shown in gallons per minute (gpm).

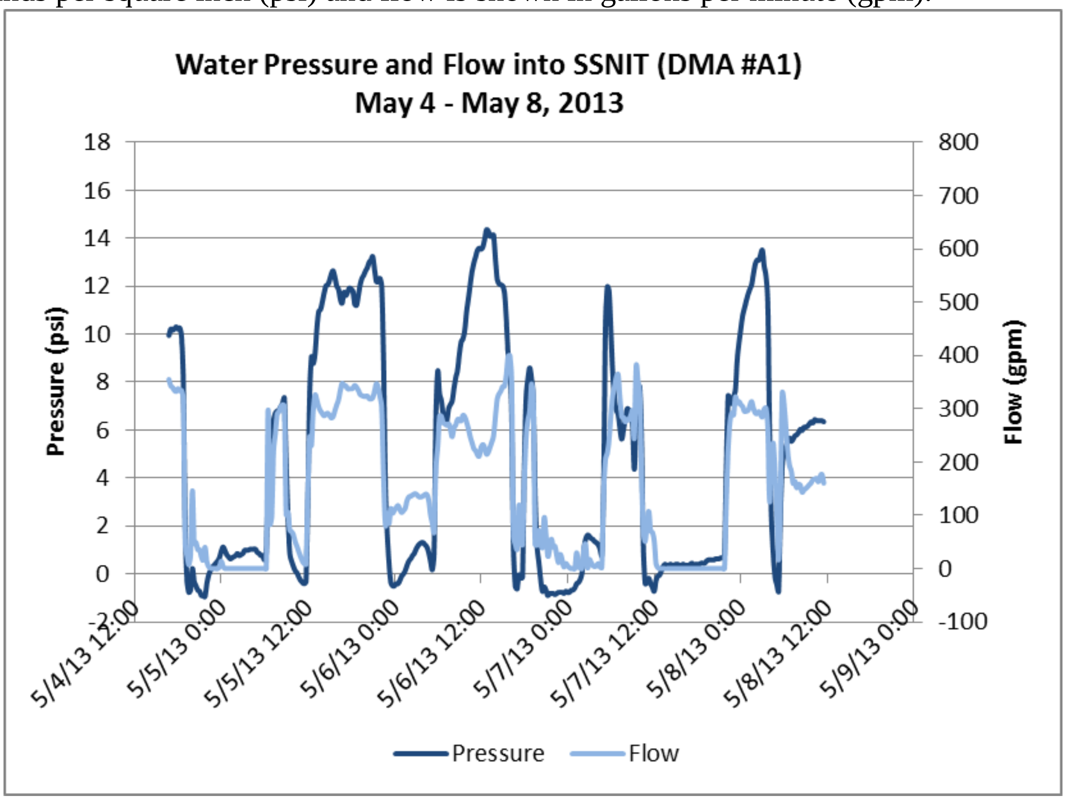

Figure 6: Water Pressure and Flow Data for SSNIT

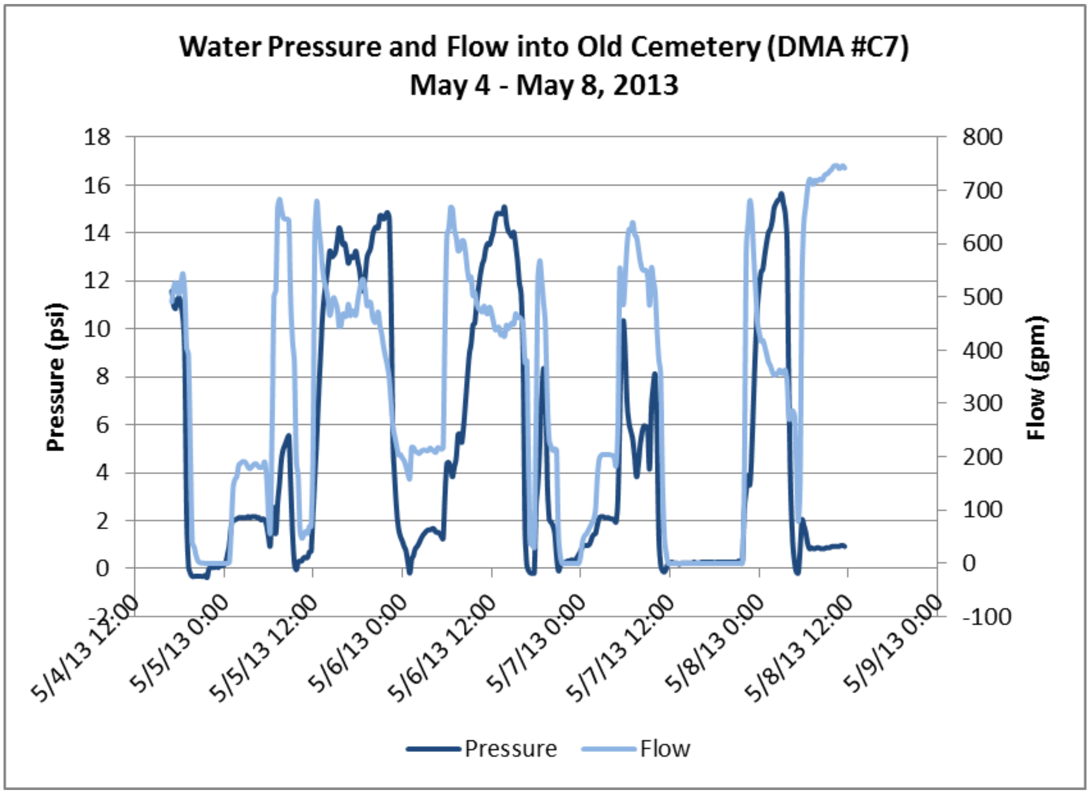

Figure 7: Water Pressure and Flow Data for Old Cemetery

In both neighborhoods, flow and pressure vary cyclically over the course of the four days, with positive flow and pressure during daytime hours, and low flow or negative pressure during nighttime hours. Overall, both neighborhoods show intermittent flow and pressure, but SSNIT has significantly worse performance in terms of pressure variation. Water pressure in SSNIT drops to negative values for 18% of the time monitored, while in Old Cemetery pressure is negative for only 6% of the time monitored. Total flow into SSNIT is much less than that into Old Cemetery, but without knowing the population of each neighborhood, it is impossible to say whether one neighborhood is better served with water per capita than another. Neither neighborhood ever reaches the minimum pressure prescribed by the US EPA of 20 psi.

Conclusions

Objective 1: Water Quality Degradation in the Distribution System

Two water quality parameters were used to track water quality in the distribution system: free chlorine residual and *E. coli*. Comparing results from the Dalun-Nawuni WTP and the distribution system show a clear degradation in water quality, as evidenced by diminishing free chlorine. On average, free chlorine residual values decreased by 78% between the Dalun-Nawuni WTP outlet and the sample sites in the distribution system. Further work is needed to determine if this degradation is due primarily to aging of the water in the distribution system or contamination through back-pressure situations. No *E. coli* was detected in either the treatment plant outlet samples or the distribution systems samples so there is no evidence of bacteriological contamination based on this dataset. However, it is unknown where samples were collected in the distribution system, so it is possible that these samples do not represent the most vulnerable areas of the system.

Objective 2: Water Quality in Household Storage Containers

Free chlorine residual, total coliform, and *E. coli* were tested in household storage containers in four different neighborhoods in Tamale. Free chlorine residual levels were found to be below 0.2 mg/L in 92% of samples tested, the level considered "safe" by the USEPA and WHO. Without further observations of storage behavior, it is not possible to know how much of this chlorine decay is due to water age vs. contamination by the users. However, evidence of contamination was seen in the bacteriological results, with 83% of samples having detectable levels of total coliform, and 33% of samples having detectable levels of *E. coli*. It is possible that the water already contained bacteria prior to collection, but observations of unsanitary storage practices during the household surveys strongly imply that the water is being contaminated by users after collection. These practices included storing water in open containers, dipping hands in containers, and using containers that appeared dirty.

Objective 3: Modeling the Distribution System

Currently, there are no commercial models available suitable for modeling an intermittent distribution system. However, there are several models in development by researchers. In addition, it is possible to approximate an intermittent system using a combination of conventional modeling tools such as EPANET and SWMM. This approach requires inputs of: GIS data of the network, customer demand information, and flow and pressure data for calibration. While GIS data and flow and pressure data were provided by GWCL, the final pieces of information were sent in May 2013, too late to attempt to calibrate and run a model within the academic year. However, the data can provide an excellent starting point for future research using a hydraulic model.

Recommended Improvements to Household Storage

Although safe storage practices alone will not totally eliminate the risk of contamination in household water supplies, there is clearly great potential for improving the design of household storage vessels and hygienic behavior in Tamale. Through their household water treatment and safe storage (HWTS) network the WHO has worked to publish literature advocating safe water storage in developing countries[2]. Publications from the network include fact sheets, research papers, and examples of national action plans. Local NGOs in Tamale could make use of these resources and work in collaboration with GWCL to educate customers about safe storage practices and distribute safe storage containers.

One NGO in particular, Pure Home Water (PHW) is already working in the Tamale area to produce and distribute ceramic water filters and safe storage containers to residents, especially targeting those without a piped water connection. (For more information on PHW, refer to Cheng 2013). It is recommended that this group consider adding safe storage education and sale of safe storage containers to their scope of work. While some users interviewed were aware of the importance of safe storage practices, many were not and were surprised to learn during the course of the interview that it was possible for their piped water supply to become contaminated.

[2] http://www.who.int/household_water/network/en/

Recommended Improvements to the Distribution System

There are two major approaches that are considered to improve intermittent supply systems. One approach is to reduce intermittency by increasing supply and reducing non-revenue water. The other approach is to assume the system will stay intermittent and take measures to prevent contamination in the system (Cabrera-Bejar and Tzatchkov 2009). It is recommended that both approaches be carried out. In the long term several steps should be taken to reduce the intermittency of the distribution system. Reducing intermittency will help improve water quality in the system by reducing low pressure episodes that could lead to contamination. Reducing intermittency will also decrease the need for users to store water in their homes and decrease the risk of contamination through home storage.

There are several major, interrelated causes for intermittency in the Tamale system. According to conversations with GWCL staff, one of the most urgent problems is that of non-revenue water in the system. Large percentages of the water supply are lost each month through physical losses (leaks) as well as commercial losses (water that is not paid for). If non-revenue water could be reduced, there would be more water available for the system and the network could become more continuous (although it would still likely be intermittent). With the 2008 expansion of the Dalun-Nawuni treatment plant, its maximum capacity is now 44 MLD. Given the population estimate of 371,351 people (Ghana Statistical Services 2012) this plant would be able to supply 118 liters per person per day if every household was connected to the system and there was minimal non-revenue water. The UN recommends that each person have access to 20-50 liters per day for cooking, cleaning and drinking so 118 liters per person would be more than adequate[3]. In order to accomplish this, more resources need to be allocated towards fixing leaks and tracking down illegal connections. Improving maintenance on the system and reducing non-revenue water will also help prevent contamination in the short term. In addition, efforts need to be made to improve the reliability of the treatment plant. GWCL employees say that power outages at the plant are a common cause of interruption and residents report instances of prolonged water outages due to maintenance issues.

[3] http://www.unwater.org/statistics_san.html

3. Finite Element Modeling of Flow Through Ceramic Pot Filters

The ceramic filters produced at PHW have evolved over the years from a flower-pot shape, to a paraboloid, to the current hemispheric filter design. As the filter design changes, quality control measures must be reassessed. The flow rate of a filter is a crucial quality control measure that can provide information about the efficacy of the filter in removing bacteria and reducing turbidity. Acceptable flow rate values must be greater than 1 liter per hour in order to fulfill a family's daily needs, but must be low enough that the water passing through has sufficient contact time with the colloidal silver coating the filter in order to maximize pathogen removal (The Ceramics Manufacturing Working Group, 2011). The CDC Best Practice Recommendations suggest that the maximum flow rate should be 0.35 liters per hour per liter capacity of filter element; however, other research suggests that maximum acceptable flow rates may vary more widely than this.

The current PHW standards, which accept filters with flow rates in the range of 3-10 L/hour, while indicative of inconsistencies in the manufacturing process, may not be indicative of inadequate bacteria removal. It is therefore necessary to perform additional assessments of the PHW filters themselves in order to assess the impacts of the materials and processes specific to the PHW factory.

While prior theses (e.g. Miller, 2010) have developed analytical models for flow through a ceramic pot filter, missing from the prior attempts to model clay pot filters is a model that will allow for easy sensitivity testing to changes in hydraulic conductivity and other parameters. Such a model would need to be sufficiently refined so that any approximations made in the model do not propagate through to the model results. A more refined model would also allow for closer examination of the flow through the ceramic filter and a more robust comparison among filter shapes.

As the quality control process continues to be refined, the following questions have been raised: 1) Can the cause of the flow rate variability in PHW filters be isolated and the flow rate range refined? 2) Is there a filter shape that may produce a lower variability in flow rate, where the flow rate through that filter is less sensitive to inconsistencies in manufacturing? And 3) Is there a filter shape that produces an optimal flow rate? This study seeks to address the three questions listed above by developing a model of water flow through each filter shape and simulating flow through the filters for a range of hydraulic conductivities in order to examine the sensitivity of each filter shape to changes in hydraulic conductivity, and also to assess the efficiency of each filter based on the flow rate computed for a given hydraulic conductivity. Because the PHW factory is currently manufacturing hemispheric filters, while the global norm is the flower pot shape, this study will focus on the comparison between these two shapes. Kelly (2013) provides a description of the methodology and results for the assessment of the paraboloid shape as well.

Laboratory Flow-Rate Testing

Flow-rate tests were conducted on the hemispheric filter and flowerpot filter in the laboratory at MIT. The hemispheric filter tested was manufactured at the Pure Home Water factory in Ghana, while the flowerpot filter was manufactured in Cambodia. These tests were conducted while maintaining a constant water level in the filter. Measured water volumes collected after 10 minutes were recorded for all filter shapes at four different water heights.

Modeling Filter Flow

As discussed in the introduction, one of the primary goals of this project is to develop a model of flow through each of the filter shapes in order to better understand how the geometry of each filter impacts its flow rate. This study developed a model using FEFLOW, short for Finite Element Flow, which is a groundwater modeling software produced by DHI-WASY that can be used for finite-element modeling of flow through porous media (DHI-WASY, 2012). The FEFLOW user manual (DHI-WASY, 2012) provides a complete description of the various capabilities of FEFLOW beyond those discussed in the following sections. The corresponding thesis (Kelly, 2013) details the procedure for the development of each filter flow model in FEFLOW. A summary is provided below.

In order to develop a model for flow through the filter using FEFLOW, we define the region of flow as the filter itself. Three-dimensional flow through the entire filter can be determined by modeling flow through one half of a filter cross section in only two dimensions. Figures 8 and 9 illustrate cross-sections of the flowerpot and hemispheric filters.

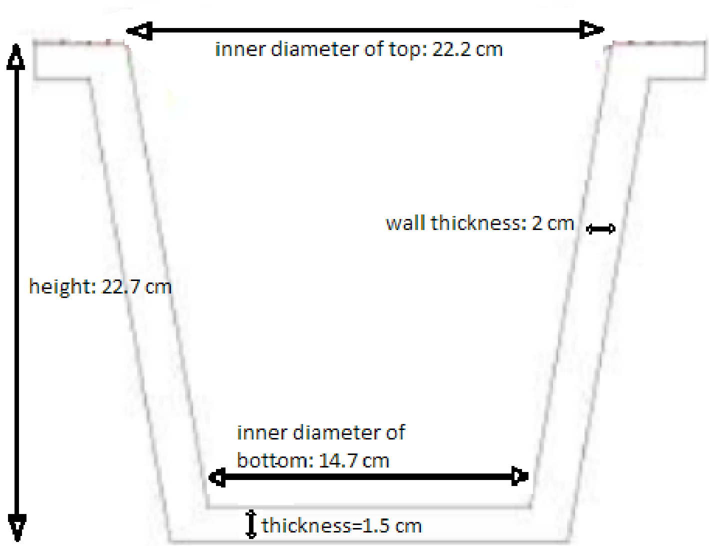

Figure 8: Cross section of flowerpot filter

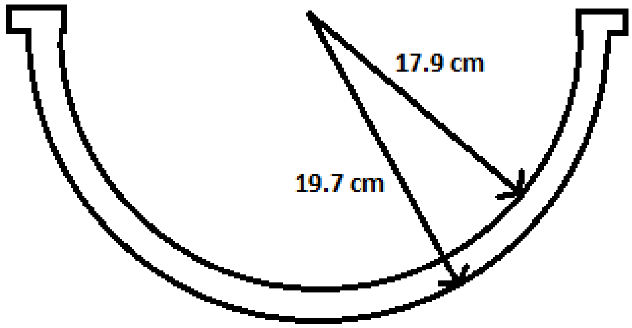

Figure 9: Cross section of hemispheric filter

The FEFLOW model was run for a hydraulic conductivity of 0.234 cm/hr (the value obtained by Miller, 2010), and for values of 0.42 and 0.83 cm/hr in order to conduct a sensitivity analysis. The porosity was set at 0.45 (based on Miller, 2010). Finally, constant head boundary conditions are set. The derivations of these boundary conditions are provided in the thesis corresponding to this project (Kelly, 2013). After running a steady-state simulation in FEFLOW of flow through the flowerpot filter with a constant water level, FEFLOW computes the flow rate Q out of a selected boundary, and the associated change in filter water height can be derived (Kelly, 2013). Simulations were then run at varying heights over a series of discrete time steps.

Laboratory & Model Results

Lab test Results

Tables 2-1 and 2-2 summarize the measured flow rate for each filter shape at each designated water height.

Table 2-1: Flowerpot lab test results

Water height [cm]	Amount collected after 10 minutes [mL]	Flow rate [L/hr]
23.0	600	3.60
20.0	400	2.64
15.0	240	1.44
10.0	125	0.75
5.0	55	0.33

Table 2-2: Hemisphere lab test results

Water height [cm]	Amount collected	Flow rate [L/hr]

	after 10 minutes [mL]	
18.5	985	5.91
14.5	550	3.30
10.5	275	1.65
6.5	130	0.78

Numerical Modeling Results

Figures 10 and 11 show the Darcy flux, *q*, in the filter cross-section for each filter shape, for a conductivity of 10 cm/day. It is clear from comparing the Darcy flux distribution in each filter that the hemispheric filter has a larger flux over more of its exterior surface area.

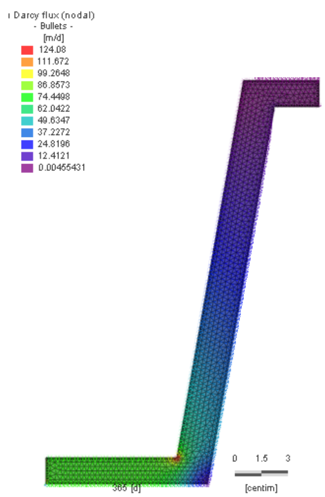

Figure 10: Darcy flux in full flowerpot filter

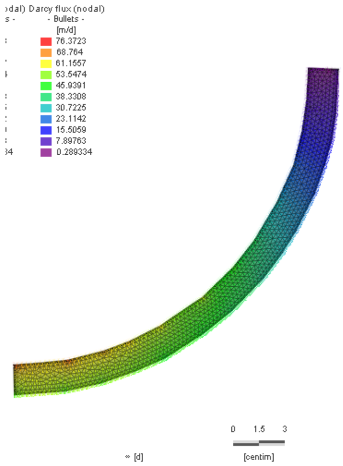

Figure 11: Darcy flux in full hemispheric filter.

Flow Rate Variation with Water Height

For each shape, the modeled flow rate results are graphed with respect to water height, for all modeled values of hydraulic conductivity. These graphs are shown in Figures 12, 13 and 14 .

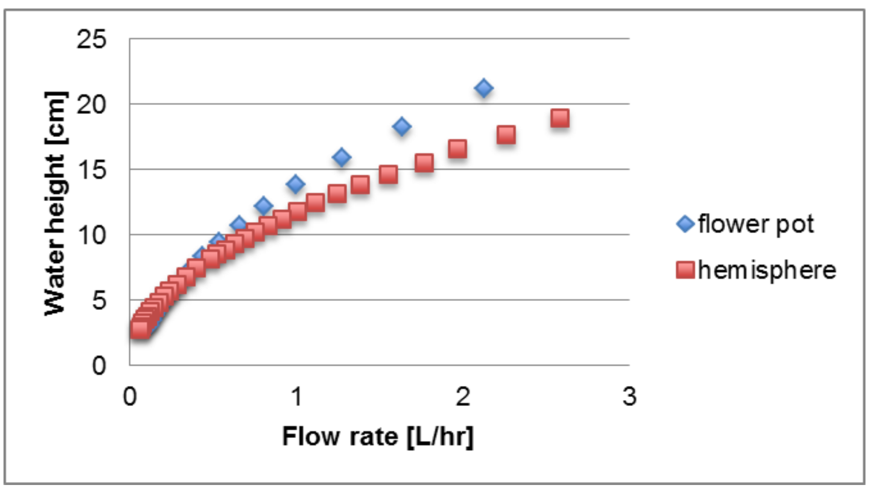

Figure 12: Modeled flow rate versus water height for flowerpot and hemispheric filters, K = 0.234 cm/hr.

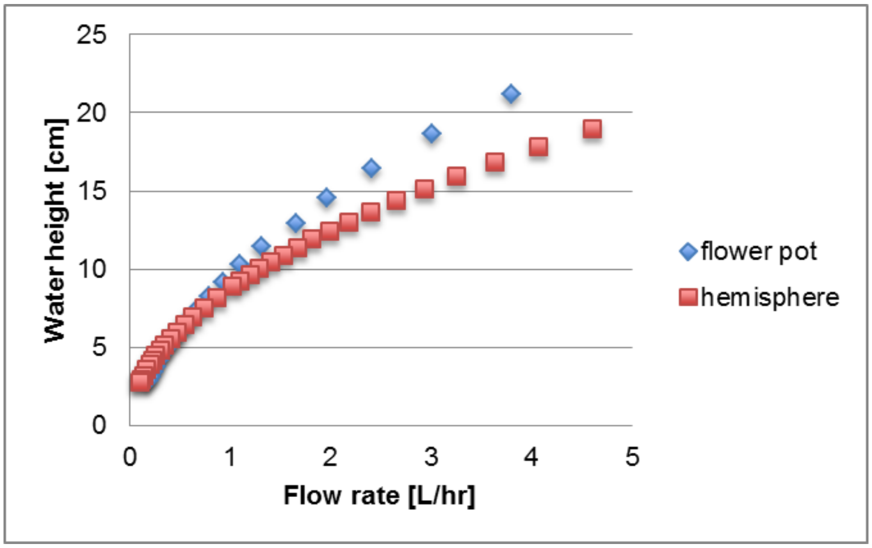

Figure 13: Modeled flow rate versus water height for flowerpot and hemispheric filters, K = 0.42 cm/hr.

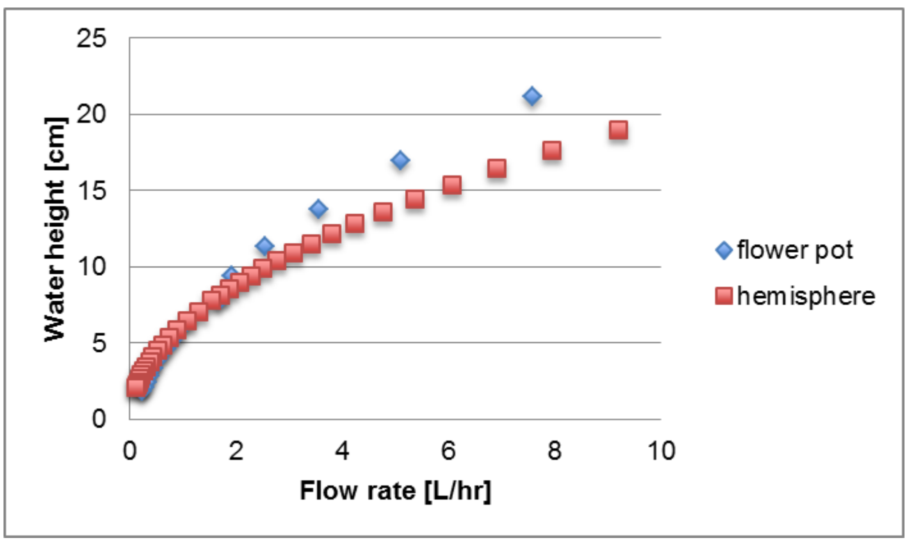

Figure 14: Modeled flow rate versus water height for flowerpot and hemispheric filters, K = 0.83 cm/hr.

Parameter Sensitivity Testing

In order to test the sensitivity of the flow models to changes in hydraulic conductivity and examine the variation of this sensitivity among filter shapes, each model was run with three different values of hydraulic conductivity. Kelly (2013) provides the full details of the results of this sensitivity testing. For each filter, there is a strong correlation between the flow rate Q at a given height h and the filter hydraulic conductivity K. Figures 15 and 16 illustrate the change in flow rate with height as K varies.

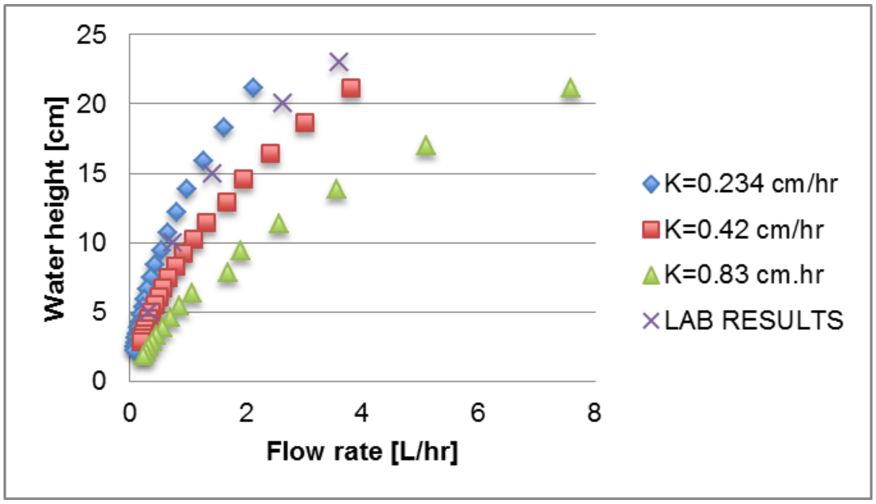

Figure 15: Flow rate versus water height in flowerpot filter, model and lab results

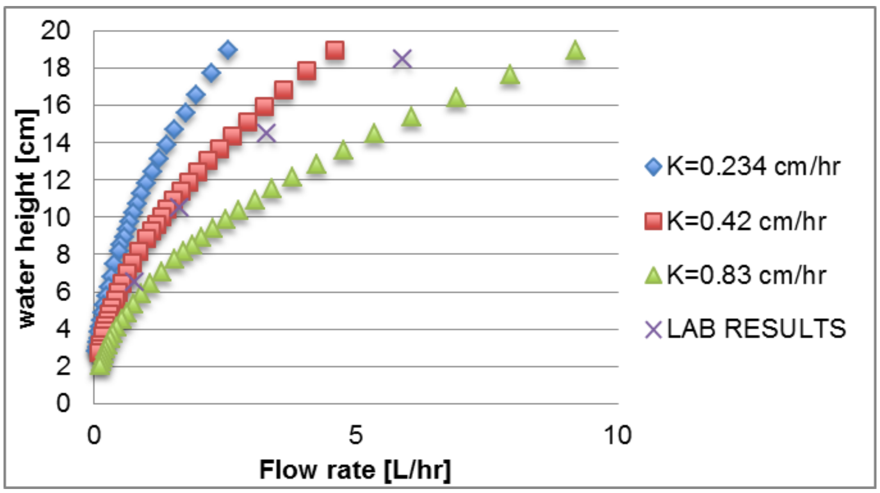

Figure 16: Flow rate versus height for hemispheric filter, modeled and lab results.

While the relationship between flow rate and height is strongly correlated with hydraulic conductivity for all filter shapes, the nature of that correlation varies. A change in K will generate changes of different magnitude in the flow through the filter depending on the shape of the filter. Figure 17 shows a plot of the derivative of flow rate, Q, with respect to K, over the range of possible water heights in the hemispheric and flower pot filters. It is evident from this graph that the flow rate through the hemispheric filter shape is almost 50% more sensitive to changes in K when full.

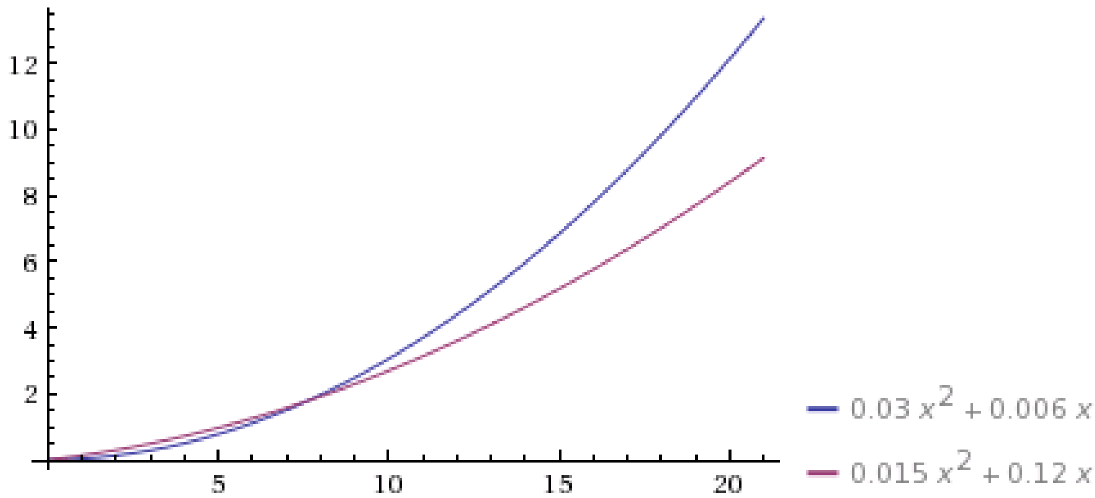

Figure 17: dQ/dK versus water height for flower pot (purple) and hemispheric (blue) filters (image courtesy of Wolfram Alpha)

Because the numerical models are based on actual dimensions of filters manufactured in the PHW factory, the results of the model can be used to estimate the hydraulic conductivity of a given filter. Once a flow rate Q is observed at a given height h, as was done for the flower pot filter above, the relationships established among Q, h, and K will allow for easy calculation of filter hydraulic conductivity. It is important to note, however, that the relationships determined in this thesis are valid *only* for the filter geometries specified.

Flow Rate Variation with Time

The results of the numerical modeling allow for an approximation of flow rate over time, based on the selected time step Δt. The results of the modeled flow rate over time for both filters are plotted in Figures 18 and 19.

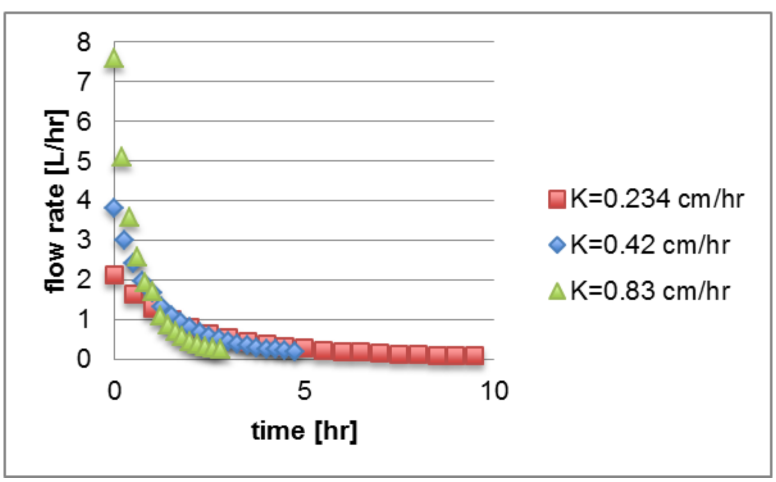

Figure 18: Modeled flow rate versus time, flowerpot filter.

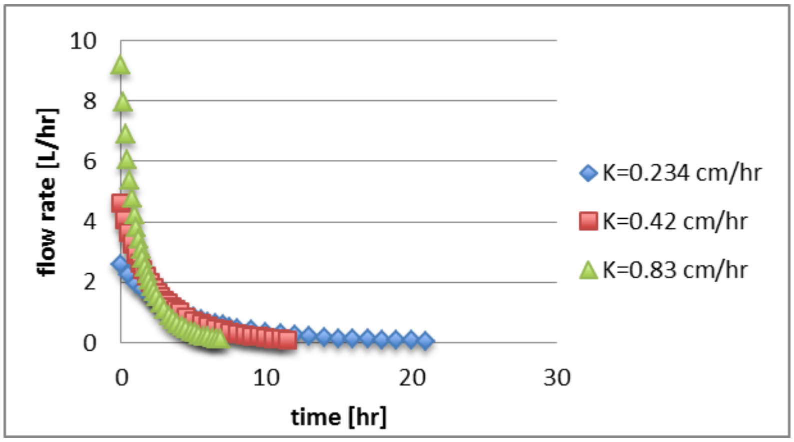

Figure 19: Modeled flow rate versus time, hemispheric filter.

Discussion of Flow Rate vs Time Results

Understanding how the flow rate through a filter varies over time is critical to assessing the performance of that filter. When factories such as the PHW factory perform flow rate tests, the flow rate is obtained simply by measuring the amount of water filtered in the first hour of flow through a saturated filter, starting when the filter is full. It is evident from the graphs above that this number is not an accurate representation of the flow rate. Figures 20 and 21 show a "zoomed in" version of the modeled flow rate over time plots for each filter shape, focused on the first three hours of flow. From these graphs, it is clear that most of the flow through the filter occurs during the first three hours of use, assuming that the filter is saturated at the starting point. From a practical standpoint, this means that if a family fills the filter and waits for it to drain completely before refilling it, they are not using the filter to its full potential.

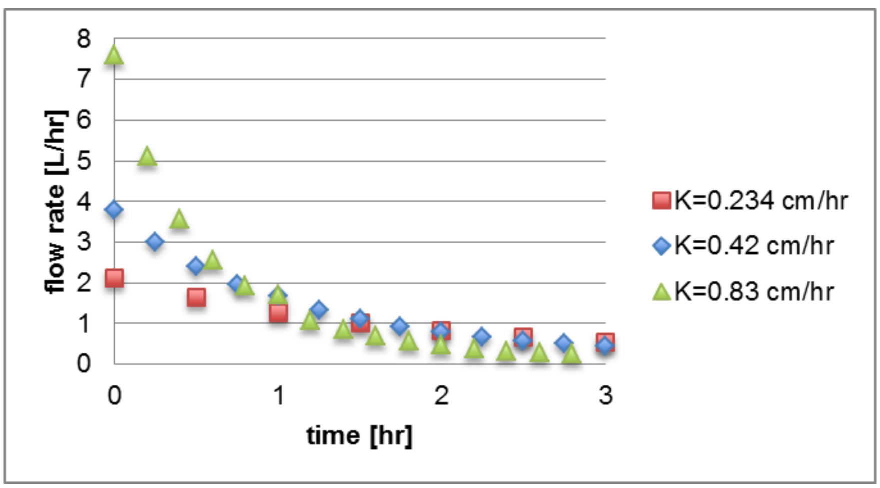

Figure 20: Modeled flow in flowerpot filter over first three hours.

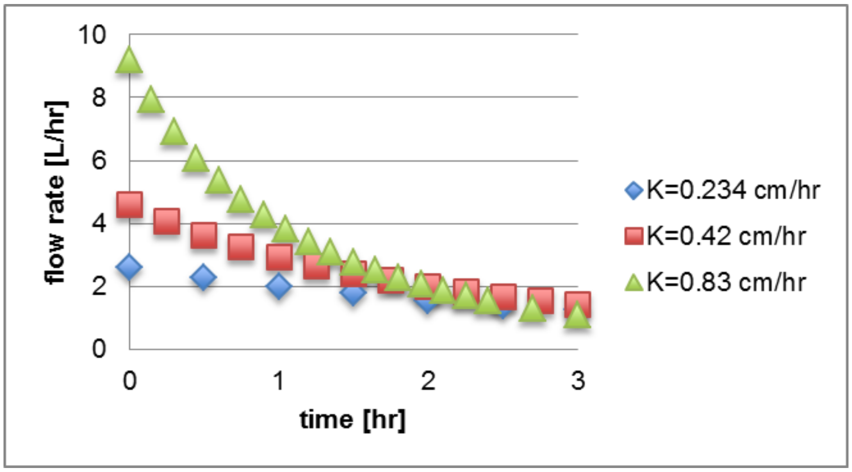

Figure 21: Modeled flow in hemispheric filter over first three hours.

It is also evident from the graphs that the flow rate during the first hour is much greater than that over any subsequent time period. The factory control tests which record the volume of water filtered during the first hour are in fact reporting the area under the above curves between t=0 and t=1. The problem with this reporting method is that it could present users with an inaccurate picture of the level of performance they can expect from their filter. A starting flow rate of 2 liters per hour does not mean that the filter will then filter 4 liters of water in 2 hours, and so this reporting method does not fully describe filter performance.

The following research goals were accomplished in this study:

1. Finite-element models were developed for flow through flowerpot-, paraboloid-, and hemispheric-shaped clay pot filters.
2. Comparison of the flow through these filter shapes revealed that the hemispheric filter provides the highest flow rate for a given hydraulic conductivity and porosity.
3. Sensitivity testing revealed that a gentler slope and greater curvature of the filter leads to higher sensitivity of flow rate to hydraulic conductivity. The flowerpot shape is therefore least sensitive to changes in hydraulic conductivity and the hemispheric shape is most highly sensitive to those changes.

Recommendations for Pure Home Water

Based on this study, several recommendations can be made to Pure Home Water regarding their current and future manufacturing and quality control processes. Firstly, after comparing the performance of the three filter shapes, it is evident that the hemispheric filter is the most efficient. Secondly, an issue of concern at the factory is that the hemispheric filters currently being produced are operating at a wider range of flow rates than the globally accepted norm. The results of this study suggest that this variability may in fact have nothing to do with manufacturing issues at the factory; rather, the hemispheric filter, due to its shape, will naturally generate a higher flow rate at a given hydraulic conductivity than the flowerpot filter. Because the flowerpot filter is the standard manufactured shape around the world for which the standard flow rate range was established, while the hemispheric filter shape is the model currently being produced at the PHW factory, it may not be reasonable to compare the quality control standards of other factories to those of PHW. However, it is still worth investigating any inconsistencies in manufacturing that might contribute to the flow rate variability.

PHW has also developed a “first drip” test that measures the travel time of a drop of water through the filter. This test measures the amount of time that it takes for the first drop of water to emerge from an unsaturated filter when full. This test on its own may not be an accurate indicator of flow rate, as it measures the travel time through an *unsaturated* filter, whereas the majority of flow through the filter is occurring when the filter is saturated. The travel time through the filter also depends on porosity and hydraulic conductivity, as well as the height of water in the filter, and the relationship between porosity and hydraulic conductivity is not known. It is therefore recommended that this test continue to be performed in conjunction with flow rate testing, as the “first drip” test alone depends upon too many unknown variables and does not present a full picture of the filter’s various properties.

Lastly, typical flow rate testing at the factory is done by measuring the volume of water produced by the filter in the first hour of saturated flow. This process can be time-consuming and, as discussed above, may be an inaccurate representation of the filter’s performance over time. Because the models presented in this thesis have been developed for a specific filter shape, the observed flow rate through a full filter corresponds to a unique hydraulic conductivity and unique relationships between flow rate and height and between flow rate and time. Therefore, in order to determine the hydraulic conductivity of the filter as well as how it will perform over time, it is only necessary to find the flow rate when the filter is full, which can be done by simply measuring flow through the filter for a given amount of time, which can be shorter than an hour, while maintaining a constant water height. It is important to ensure that the filter is saturated before beginning this test. This “instantaneous” flow rate at a given height can then be used, based on the results of the model developed in this thesis, to paint a more complete picture of the filter properties.

4. Monitoring and Evaluation of the Ceramic Hemispheric Filter in Northern Ghanaian Households

The village of Yipelgu in the Northern Region of Ghana was the recipient of a 1,000-ceramic hemispheric water filter distribution, which was supplied by Pure Home Water (PHW) and funded by UNICEF-Ghana. The distribution to female heads of households began in November 2012, and approximately 700 ceramic hemispheric filters were disseminated by January 2013 when this research was conducted. This large-scale distribution provided the first opportunity to monitor and evaluate the performance of PHW's ceramic hemispheric filter design, branded as the AfriClay filter, in the field rather than during the factory quality control operations.

The goal of this thesis was to monitor and evaluate Pure Home Water's AfriClay ceramic hemispheric filter at the household level in the village of Yipelgu. The distribution at Yipelgu was the first mass distribution of filters manufactured at Pure Home Water's factory. In order to accomplish this goal, the following objectives were to: (1) Focus on water quality data as the primary filter performance indicator; (2) Identify behavioral factors from Correct Use surveys that affect filter performance; and (3) Create a baseline and compile recommendations for future distributions/monitoring efforts.

Monitoring and evaluation was based on surveys measuring Correct Use and water quality tests. Correct Use is the first component of the "3C's", which represent Correct, Consistent, and Continuous Use. Correct Use denotes that the filter is being used properly, according to the training that each user receives before filter sale/distribution and as given in the instructional sticker on each filter and in the AfriClay filter Training Manual. Consistent Use refers to whether the technology is used every day. Continuous Use relates to whether the filter is used throughout an entire year. Continuous Use is necessary and essential to the 3C's since some users have wrongly thought that they do not need to use the HWTS technology during the rainy season when cleaner rainwater is more abundant. The implementation of the 3C's is the latest thinking regarding a successful behavioral training method to sustain safe drinking water consumption. A user practicing the 3C's can realize the full benefits of the AfriClay filter and other household water treatment and safe storage (HWTS) products.

The Correct Use survey was administered to a total of 85 beneficiary households in Yipelgu. Pertinent factors, such as filter assembly, treatment, safe storage, and maintenance, related to Correct Use were addressed in the survey. The variables included in the survey were hypothesized to inform the filter performance level. Numerous prior surveys and references were studied in order to identify the pertinent factors related to correct filter use. USAID's *Access and Behavioral Outcome Indicators for Water, Sanitation, and Hygiene* and WHO-UNICEF's *A Toolkit for Monitoring and Evaluating Household Water Treatment and Safe Storage Programmes* influenced the design of the Correct Use survey. The author selected the most appropriate indicators to include in her survey that aligned with the study's objectives. Additionally, the AfriClay filter's Training Manual was rigorously scrutinized, as well as previous Master of Engineering students' theses related to monitoring and evaluating HWTS, to further inform the survey design.

The target sample size for beneficiary households in Yipelgu was calculated using the Raosoft Sample Size Calculator, an online tool. The computed sample size was 85, which takes into account 700 households, 10% margin of error, 95% confidence level, and 50% response distribution. Analysis of the data suggests, but cannot prove direct relationships due to the use of a limited sample size.

In order to achieve the target sample size, a randomization plan was executed. The details of this plan are outlined below:

- The map of the village, shown in **Figure 22**, was divided into quadrants (Northeast, Northwest, Southeast, and Southwest). The divisions were aligned with the main dirt roads.
- A certain number of days were assigned to each quadrant, where more days were designated in accordance to household density.
    - Northeast – 3 days
    - Northwest – 4 days
    - Southeast – 2 days
    - Southwest – 2 days
- Within the assigned days specified for a particular quadrant, as many surveys were conducted from the researcher's arrival at 9:00 AM to 1:00 PM.
- If a compound consisted of more than one beneficiary household, all of them would be surveyed to prevent bias.

This random sampling plan achieved geographic spread, and provided representative surveys for each quadrant. A balance between statistical rigor and logistic feasibility must be reached in planning and implementing a randomization process.

Monitoring and evaluating household water treatment and safe storage (HWTS) technologies entail not only analysis of behavioral indicators measured in surveys and direct observation, but also water quality testing. In order to determine whether the performance of drinking water supply complies with health based targets, indicator organisms are tested. Total coliform (TC) and *Escherichia coli* (*E. coli*) are widely used as indicator organisms. Hydrogen sulfide (H_2S) production can also be used as an alternative indicator (WHO & UNICEF, 2012).

IDEXX Quanti-Tray/2000® and hydrogen sulfide (H_2S) bacteria MPN tests were conducted to measure the water quality parameters of total coliform/*E. coli* and H_2S bacteria respectively. Turbidity was also measured. Water quality tests served as an objective measure for HWTS adoption and Correct Use. Two samples, stored and filtered water, were collected from each beneficiary household. Stored water undergoes pre-treatment, sedimentation and bacteria die-off, prior to filtration. Stored water is defined in this thesis as water that originates from a raw water source and is stored separately from the AfriClay filter system. This water is usually kept in a ceramic, clay storage vessel either inside the household or outside in the compound's courtyard.

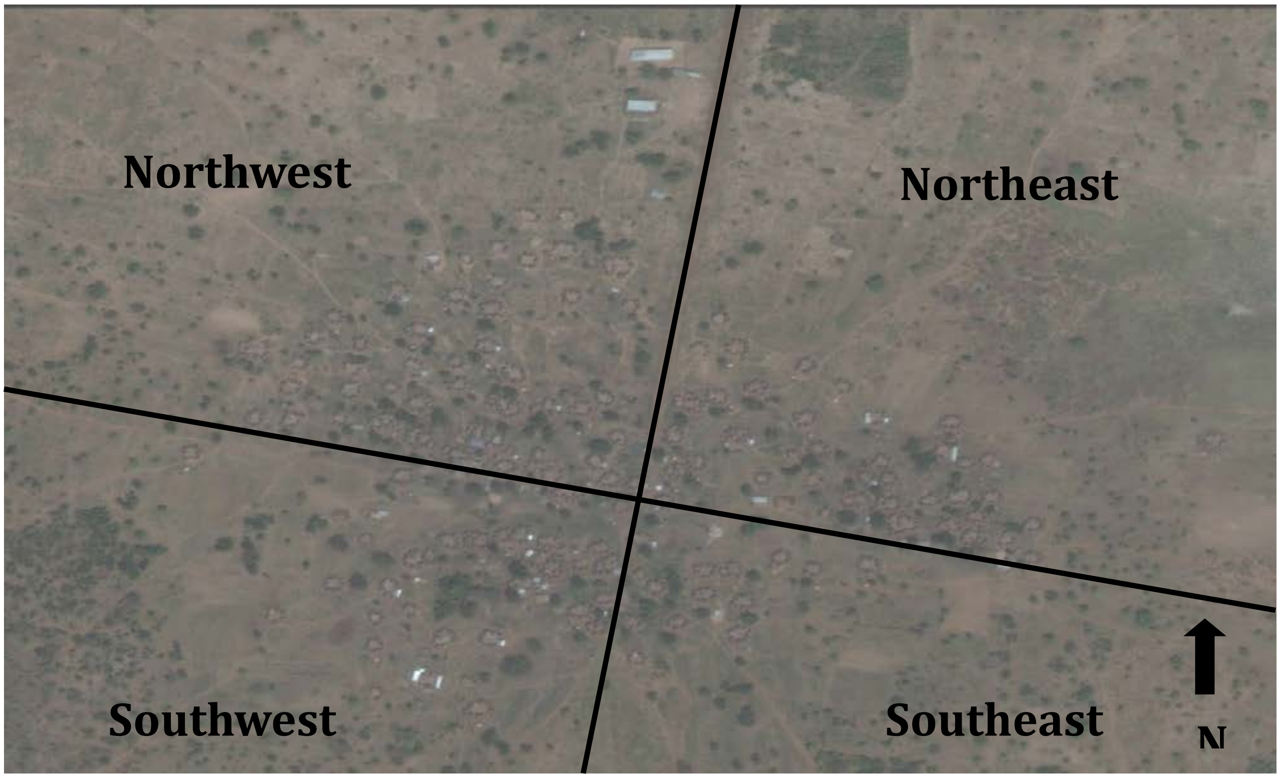

Figure 22: Final random sampling plan.

Filtered water was sampled directly from the AfriClay filter tap. The source waters of the village were also sampled. The testing of blanks and duplicates (2% of the total number of each test) was conducted to prevent contamination and guarantee precision. All water quality tests were carried out as per the 22nd edition of *Standard Methods: for the Examination of Water and Wastewater*.

The statistical methods used in this study are outlined as follows. The sequence of using applicable statistic methods, specifically (1) histograms, (2) significance tests, and (3) simple linear regression, ultimately helped the author to identify important survey variables that might affect filter performance in the household setting. Detailed descriptions of each statistical analysis method can be found in Cheng (2013).

(1) A histogram divides a range of values of the variable into classes. It displays either the count or percent of observations that are categorized into each class (Moore, McCabe, & Craig, 2012). Histograms of total coliform and *E. coli* LRV are generated to visualize the range and frequency of filter performance, as well as to pinpoint filters that performed at the high and low ends.
(2) A significance test is a method to compare observed data with a hypothesis (Moore et. al, 2012). Significance tests were used to determine the Correct Use variables that might affect filter performance.
    a. Chi-square test – to compare Correct Use checklist categorical variables
    b. Two-sample t test – to compare Correct Use survey interval variables

c. Matched pairs one-sample t test – to compare IDEXX Quanti-Tray® and H_2S LRVs

(3) A regression line describes the relationship between two variables (Moore et. al, 2012). Simple linear regression analysis can verify if there is a significant relationship between the Correct Use variable and filter performance.

Before statistical analysis can take place, the filter's performance must be normalized in such a way that can facilitate comparison with international standards. The performance of the AfriClay filter was measured against WHO's tiered approach in establishing levels of performance (**Table 3-1**) as specified in *Evaluating Household Water Treatment Options: Health-based Targets and Microbiological Performance Specifications*. There are three recommended performance levels for bacteria, virus, and protozoa reduction based on disability-adjusted life years (DALYs) and projected as log reduction values (LRVs). For the target of bacteria, a technology that exhibits a LRV ≥ 4 is considered performing at a "highly protective" performance level and LRV ≥ 2 represents a protective level. In this study, the "interim" target as specified in **Table 3-1** will be modified to represent $1 \leq x < 2$ $\log_{10}$ reduction for bacteria. In order to evaluate PHW's AfriClay filter, log reduction values for total coliform, *E. coli*, and turbidity were calculated and analyzed as follows (**Figures 23 and 24**).

Table 3-1: Derivation of targets (WHO, 2011a).

Target	Log_{10} reduction required: **Bacteria**	Log_{10} reduction required: **Viruses**	Log_{10} reduction required: **Protozoa**
Highly protective	≥ 4	≥ 5	≥ 4
Protective	≥ 2	≥ 3	≥ 2
Interim*	Achieves "protective" target for two classes of pathogens and results in health gains		

In order to identify which Correct Use variables influence high and low performance based on LRVs, as outlined in (2) on the above, two groups for each type of log reduction value were designated. These groups were further investigated through the information associated with those filters to identify influential variables. The four groups are listed in **Table 3-2.** "Poor-performing" in this study is defined as achieving < 1 LRV. An equal number of filters in the "well-performing" group, defined as achieving > 2 LRV, were analyzed.

Table 3-2: Investigated groups based on LRV type and performance level.

Total Coliform LRV	***E. coli* LRV**
1. Well-performing (N = 20)	2. Well-performing (N =13)
3. Poor performing (N =20)	4. Poor performing (N=13)

A brief summary of the AfriClay filter's performance based on this field study is presented in the following discussion.

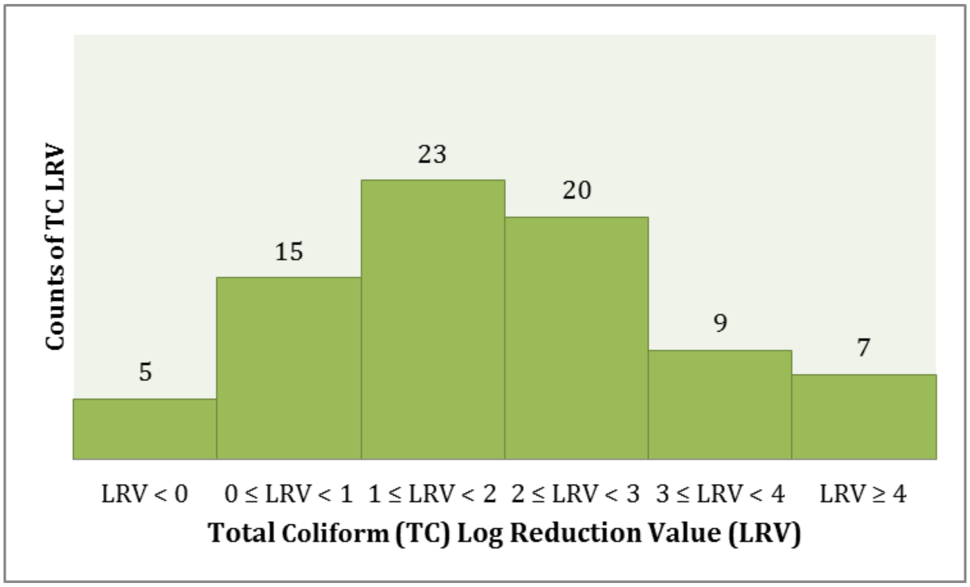

Figure 23: Comparison of total coliform (TC) log reduction values by range category (n=79 filters).

Fifty-nine filters out of the 79 filters tested for total coliform safely achieved a log reduction value (LRV) ≥ 1, 36 of which reached a LRV ≥ 2 (**Figure 23**). This first mass distribution of PHW's AfriClay filter generally achieved a LRV ≥ 1, but not consistently ≥ 2 LRV. Twenty filters performed at ≤ 1 LRV, and 7 filters performed exceptionally well at ≥ 4 LRV. In terms of WHO's health-based household water treatment performance targets for bacteria, 46% of the filters demonstrated protective standards (≥ 2 LRV) and 9% exhibited highly protective levels (≥ 4 LRV), for a total of 55% falling into the protective or highly protective categories. Twenty-nine percent of monitored filters performed in the range of 1 ≤ x < 2 LRV, falling into the interim category.

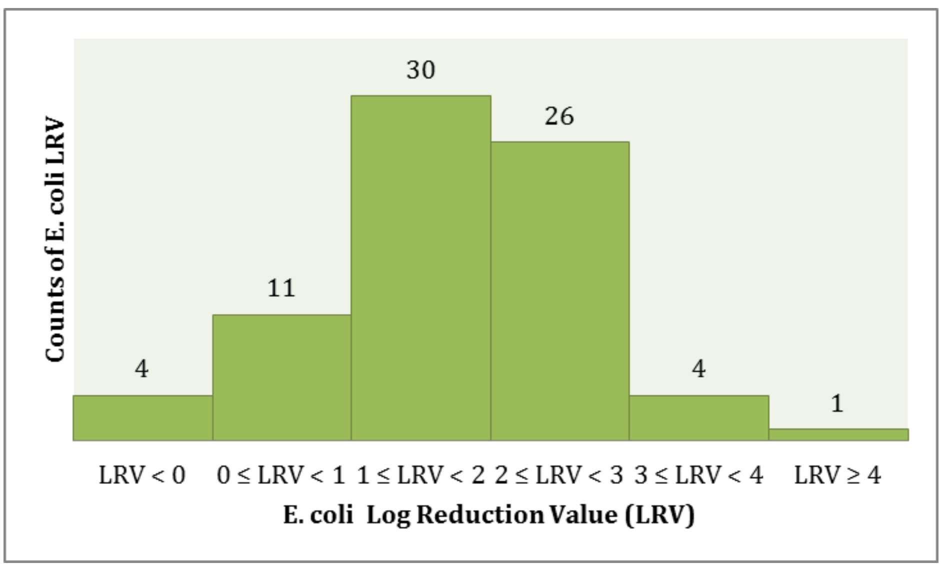

Figure 24: Comparison of *E. coli* Log Reduction Values by range category (n=76 households).

As seen in **Figure 24,** 61 out of the 76 filters analyzed for *E. coli* achieved ≥ 1 LRV, 31 of which obtained ≥ 2 LRV. The majority of filters performed in the range of 1 – 2 LRV. Fifteen filters performed poorly with results ≤ 1 LRV, and 1 filter performed at ≥ 4 LRV. With regards to the health-based household water treatment performance targets for bacteria, 41% of the filters demonstrated protective standards (≥ 2 LRV) and 1% exhibited highly protective levels (≥ 4 LRV). A total of 42% of filters performed at a protective or highly protective level, while 39% performed at the interim level. The filter performance based on total coliform bacteria LRV's and *E. coli* LRV's exhibit similar patterns with a few performing at the extremes and the majority achieving 1 to 2 LRV as seen in **Figures 23 and 24**.

As mentioned previously, hydrogen sulfide (H_2S) testing was also conducted. The author reports on results from 9 measurements of H_2S Most Probable Number (MPN). The H_2S bacteria MPN and IDEXX Quanti-Tray® MPN methods were investigated for possible correlations. Pure Home Water is transitioning to H_2S MPN bacterial testing from the IDEXX Quanti-Tray® MPN due to its accessibility, low-cost, and quantitative results. Relationships were investigated through establishing LRV thresholds, as well as significance tests for regression slope and correlation. Matched pairs t tests were also used to determine the presence or absence of statistically significant differences in the QT and H_2S LRVs. The LRV established thresholds did not yield any substantial relationship between the two methods. The significance tests for regression slope and correlation showed that there were no statistically significant linear relationship and correlations.

The matched pairs one-sample t tests could not gather enough significant evidence to reject the null hypothesis. Therefore, based on the observed data, there is no statistically significant difference between either QT total coliform and H_2S LRVs or QT *E. coli* and H_2S LRVs. A larger sample size will likely provide further conclusions and verify if there is a significant difference between the reported LRVs of the two methods (QT and H_2S MPN tests). However, it can be said that LRVs reported from H_2S tests exhibit a low bias and high variability if QT LRVs are considered the ideal value. A low bias meaning H_2S LRVs are not far from the ideal value, and high variability denoting scatter around the target value. In other words, both methods are relatively centered on the same LRV, which is a favorable result and supports the substitution of the H_2S MPN in place of the IDEXX Quanti-Tray®/2000 MPN test.

From this overall summary, it can be concluded that the AfriClay filter exhibited a wide range of performance but generally achieved 99% total coliform (TC), 98% *E. coli*, and 80% turbidity reductions (geometrically averaged). In order to explain this observed performance variability, water quality and Correct Use survey data were analyzed concurrently through statistical significance tests.

The variables of "fill frequency per day" and "duration of turbid water settling" were found to be statistically significant in possibly influencing the filter performance level from the observed data. Since it is promoted to fill the system regularly during the day to meet the needs of the household, further examination was conducted to verify if this instruction is inconsequential or detrimental to the filter's performance. The author suspected that combining filling and cleaning frequency may inform this issue further.

Fill and cleaning frequency variables were noted separately during each survey. Combining the variables to create a new variable of "number of fills per cleaning" was calculated with the information already collected. The two-sample t test was employed in order to test its significance in regards to well or poor-performance based on total coliform and *E. coli* log reduction values. It can be said that on average, filters that performed well based on total coliform and *E. coli* log reduction values reported a lower number of fills per cleaning than those in the poor performing categories.

Further statistical analysis determined that in general, it would be in the best interest of the user to clean the filter for ≤ 4 fillings. If a beneficiary fills the filter in the morning and evening, which is recommended as per training session and manual, then it can be recommended to clean the filter after every 4 fillings or every 2 days. To avoid complex instruction, it is recommended that the trainer to teach the user to clean the filter every 2 days. Therefore, a filter on average can achieve a TC LRV classified in the protective performance target (LRV ≥ 2) if cleaned every 2 days. More data collection and research is recommended to further validate this claim.

It is further recommended that some filters from different batches be tested at the PHW factory and/or laboratory. The filters can be "overstressed." A future researcher can experiment and investigate the number of fills before the entire system is cleaned that would yield an unacceptable performance level, i.e. achieving < 1 LRV. It is suggested that the researcher start with 4 fills before the system is cleaned as the benchmark to validate the claim recommended above. It should be noted that "number of fills per cleaning" or "fills per cleaning" does not refer to the fills each day, rather the number of fills between the time the respondent cleans the filtering system.

Information gathered through monitoring and evaluating efforts, as done in this study, can give a dependable assessment of the technology, which can be used to modify programs, distributions, and training, and maximize the benefits incurred from use. The recommendations and issues that were addressed in Cheng (2013) are consolidated and summarized in **Table 3-3**. For more detailed and thorough discussion about the topics covered in this executive summary, please refer to Cheng (2013).

Table 3-3: Summary of recommendations and revisions.

Future Survey Recommendations

- Pre-test surveys to mitigate courtesy responses, address translation issues, and add/remove relevant survey variables.
- Place more emphasis on (1) objective measure and/or (2) direct observations as opposed to self-reporting of filter use.
- Longitudinal study should be conducted that addresses Correct, Consistent, and Continuous Use.

Training Manual Revisions

- Tap fixture should remain fixed while cleaning safe storage unit.
- User should clean tap fixture daily.
- Emphasize hand-washing at critical times
- Clean the AfriClay system after every 4 fills or at most every 2 days (for households using highly turbid water such as those in Yipelgu).

Training Session Recommendations

- Maintain organization of training sessions as conducted in Yipelgu. This scheme provides multiple opportunities for beneficiaries to ask questions and clarify information.
- Teach users to fill the filtering element as much as possible in order to meet the needs of the day.
- Insist on a permanent base for the filter.
- Direct users to monitor children around filter.
- Keep area around filter clear of objects and debris.
- Allow the stored water to settle overnight or at least for more than 1 hour.
- Use a different, dedicated vessel for filling and another for drinking.
- Drinking vessels should remain on top of the filter for accessibility and contaminant prevention.

Pure Home Water Logistic Recommendations

- Replacement parts need to be accessible to beneficiary; follow-up visits or stockpile in village (business model or subsidized basis).
- Consider testing community water sources (prior to distribution) to determine the least polluted and recommend to the village to fetch from this source. Turbidity tubes can be used for this purpose.
- Increase level of community monitoring either via follow-up visits or community water engagement. Funds can possibly come from community contributions.

Factory Production Variables

- Higher flow rate is a desirable trait in future iterations of hemispheric filter without sacrificing bacterial removal efficiency.
- Consider implementing a child proof tap.
- Lids should easily fit around the lip of the filtering element.

Future Research

- A larger sample size for H_2S MPN should be tested to verify O'Keefe (2009) study H_2S P/A results and to conduct more conclusive matched pairs one-sample t significance tests.
- Perform a bench scale test at PHW office/laboratory to determine the critical number of fills per cleaning that yields an unacceptable performance level.

5. Household Water Treatment and Safe Storage Product Development

Microbial and/or chemical contaminants can infiltrate into piped water systems, especially when the system is intermittent. Ghana has been suffering from aged and intermittent piped water networks, and an added barrier of protection is needed for improved public health. Household water treatment and safe storage (HWTS) products, such as ceramic pot water filters, can be great complements to piped water systems. This thesis focuses on developing a new household water treatment product, targeted middle and upper class families, to help provide safe and affordable drinking water in Ghana at the household scale.

Pure Home Water (PHW), a registered nonprofit organization in Tamale, Ghana, manufactures and disseminates a ceramic pot water filter called “AfriClay Classic Filter”. PHW sold over 2200 AfriClay Classic Filters in 2012, most of which are sold to large NGOs and agencies such as UNICEF and Rotary International. And those organizations have worked with PHW and District Assemblies (DA) to disseminate the AfriClay Classic Filters in rural villages of Northern Region Ghana for free.

Figure 25: AfriClay Classic Filter

Currently, AfriClay Classic Filter is the only filter model from PHW. Though the retail price is slightly higher than the production cost, the organization still runs at a deficit each year. In order to help PHW become financially self-sustaining, the development of a new product, the AfriClay Deluxe Filter, is proposed. PHW intends to design the AfriClay Deluxe Filter and disseminate among the middle and upper income communities at a higher price. The deluxe model is expected to create profits to subsidize the fixed cost from the classic model. This thesis project was conducted in partnership with PHW to research and develop this “AfriClay Deluxe Filter”, and serve as a high-end product in urban areas.

The R&D process has consisted of analysis of alternative products in the global market, selection of designs, field research and proof of concept, selected products evaluation, and final design recommendations. Four HWTS products have been studied and analyzed thoroughly. The field research was done in January 2013 in Ghana, and included 40 household surveys and multiple field trips to a local water treatment plant, plastic manufacturers, and Ghana Water Co

Ltd, the national piped water-supply agency in Accra. The products analyses and field research data are then synthesized in a products assessment and final recommendations are made. In addition, this thesis documented PHW's concrete mold-making process, which is an essential step of manufacturing the clay filter element.

Intrinsically, the new product is desired to help PHW achieve the goal of becoming financially self-sustaining. Extrinsically, it's expected to be well received in the market. According to previous Master of Engineering (MEng) studies. A 2012 MEng student, Weini Qiu researched six HWTS products in Ghana, of which a hypothetical deluxe model ranked most popular HWTS product among interviewed potential middle class customers.

Table 4: Customer Preferences on HWTS Products (Qiu 2012)

Rank	Product	Score
1	AfriClay Deluxe	174
2	AfriClay Classic	142
3	Life Straw Family	88
4	PUR	70
5	Aquatab	53
6	CrytalPur/Tulip Siphon Water Filter	51

In order to achieve the thesis research goal, this research and development project has the following objectives:

1. Conduct a household survey and characterize consumer preferences for HWTS products,
2. Assess PHW's current AfriClay Classic Filter product and a small selection of three other HWTS products in the global market that are or could be readily available in Ghana,
3. Evaluate the four products against multiple criteria and analyze a distribution model of the AfriClay Deluxe Filter,
4. Document the concrete molding making process to facilitate new product development on site at the PHW factory in Taha, Ghana. This document transfers the mold making capability to skilled PHW workers.

Between January 6th, 2013 and January 20th, 2013, with a sample unit of the newly developed C1 Common Interface product brought from China, the author conducted a qualitative study in rural, suburban and urban areas of Ghana, but with a particular focus on the urban area. The purpose of the survey is two folds: 1. Solicit feedback and explore middle and upper class customer's attitudes towards the C1 Common Interface Filter. 2. Expose potential customers to this new Chinese model of HWTS product. Together with the findings from previous study by Weini Qiu about the Super Tunsai design, this study provides additional information on product feature preferences and consumer reactions in Ghana. This assists the author in determining a viable design choice of a new water filter product for middle and upper income customers.

The author assessed the design of Super Tunsai, C1 Common Interface, Ecofiltro, and AfriClay Classic Filter against multiple criteria, and concluded that Super Tunsai represents a better model for PHW to adopt.

Figure 26: Proposed AfriClay Classic Filter

In Cambodia, Hydrologic priced their product, Super Tunsai, at $22 per unit during pilot implementation. The enterprise, namely Hydrologic, was unable to recover the entire cost from the sales of its product. If PHW has equally or less efficient operating system than Hydrologic, it needs to price the product higher in order to make the project profitable.

Based on the Bass Diffusion Model demand forecasting, the average yearly demand for the AfriClay Deluxe is 1,500. From the Cambodian pilot implementation, the sales rate was approximately 500 per sales agent. Therefore, PHW needs at least three sales agents for the distribution of this high-end product.

After PHW conducts the pilot implementation, and when the enterprise decides to purchase injection molds for local production, Qualiplast, the largest household plastics manufacturer in Ghana, can be a potential partner. PHW also has the option of contacting Hydrologic's injection molds supplier in China for negotiation.

The recommended price for the AfriClay Deluxe Filter is $30 per unit. PHW should work closely with larger NGOs for the dissemination of its products. One possible sales strategy could be that PHW issues $10 coupons for the AfriClay Deluxe in the sales region, and potentially claims the coupons from larger NGOs, such as UNICEF or Rotary as a way to subsidize the filter cost. Customers are encouraged to pay in order for them to value the benefits of the products.

During pilot implementation, PHW needs to sell the 1000 units in 212 days in order to break even on expenses. At this period, sales will be the bottleneck of the supply chain; hence, PHW should focus on marketing and product promotion in order to maximize profits and utilization of the business.

During local production, if PHW chooses to disseminate both AfriClay Classic and AfriClay Deluxe, and to different target markets, manufacturing capacity will soon become the bottleneck of the business. PHW factory will fall short on production due to the higher demand in the market. At this period, the enterprise should primarily focus on increasing manufacturing performance in the factory. When manufacturing capacity is brought up, the distribution capacity should be increased accordingly by adding more distribution force or adopting better distribution models.

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