Pure Home Water Project
Ghana 2011
Group Report

Bilikpin Consulting

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We are eternally grateful to Mitch, Stephen, and Zach for their significant and enthusiastic contributions to all of the work done at Pure Home Water during our stay there.

Last, but certainly not least, we are deeply indebted to all of the workers at Pure Home Water who devote so much of their time and energy to the construction and operation of the factory. Without all of their help, we would still be digging holes in the clay!

EXECUTIVE SUMMARY

The Bilikpin[1] Consulting team consists of five MIT graduate students in the Department of Civil and Environmental Engineering. Five projects were conducted under the supervision of Susan Murcott, a Senior Lecturer in the department and the co-founder of Pure Home Water (PHW), a non-profit organization based in Northern Region, Ghana:

- Establishing H2S Producing Bacteria as a Fecal Coliform Indicator;
- Designing Sanitation Projects in Rural Ghana;
- Measuring Clay Property Variation and Effects on Ceramic Pot Filter Performance;
- Ceramic Filter Manufacturing in Northern Ghana: Quality Control;
- Evaluating the Technical Performance and Social Acceptability of Keg-Shaped Ceramic Water Filters in Northern Ghana.

Recommendations for Pure Home Water are as follows:

- Perform additional research on H2S, detailed in Chapter 2, in order to determine viability. Chapter 2 suggests that H2S and Easygel are potentially applicable for use in Northern Ghana for presence/absence and enumerative testing purposes respectively.

- Continue piloting EcoSan latrines in rural Northern Ghana and explore alternative designs (such as the Bin-Bin and Sanergy latrines). Follow-up with the PHW latrine near the factory and continue sanitation and hygiene education with the PHW staff.

- Continue using the Gbalahi site as a clay source for ceramic filter manufacturing. However, it is possible that a mixture of clay from different sites could improve performance. Finalizing the filter recipe should be a priority for PHW.

- Improve PHW quality control procedures through the following research:
  - Determine the relationship between flow rate, surface loading rate, and bacterial removal efficacy on filters *with and without* silver applied.
  - Establish the maximum flow rate allowable for the PHW filter based on acceptable removal efficiencies (assuming flow rate testing is the most viable 1st quality control parameter).
  - Determine the relationship between the extent of firing and filter flow rate, surface loading rate, strength, and bacterial removal efficiency.

- Invest in further research for The Kosim Water Keg as it has good potential to be a valuable HWTS product.

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1. [1] *Bilikpin* means "water bird" in the Dagbani language.

Table of Contents

List of Figures

List of Tables

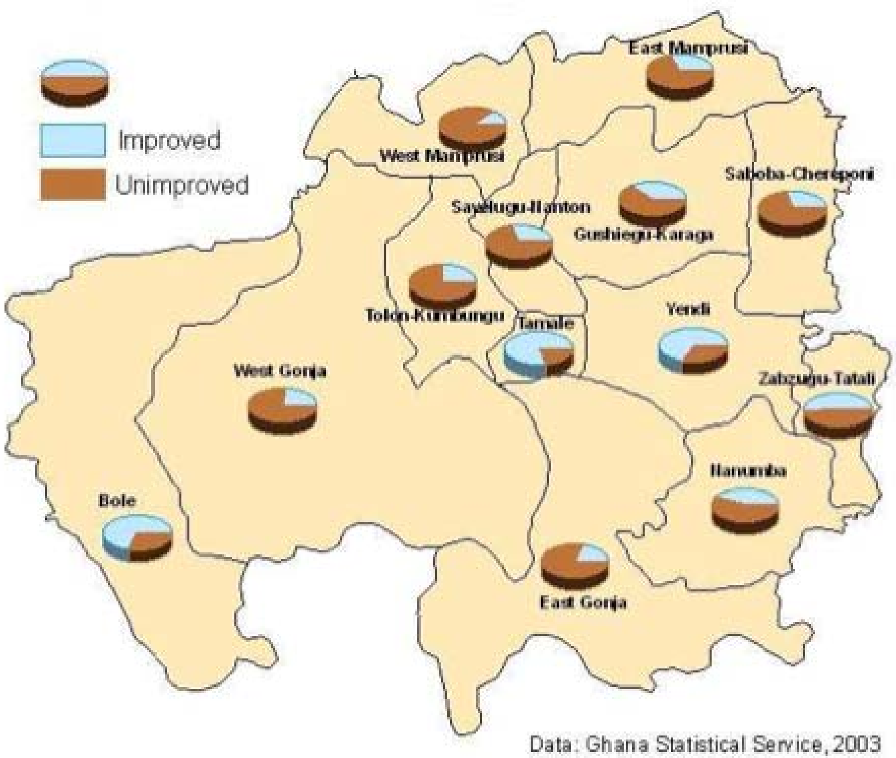
Abbreviations and Acronyms

AfD	Agence Francaise de Développement
CEE	Civil and Environmental Engineering
CIDA	Canadian International Development Agency
CPF	Ceramic Pot Filter
CT	Ceramica Tamakloe Ltd.
CWSA	Community Water and Sanitation Agency
DA	District Assemblies
EU	European Union
EcoSan	Ecological Sanitation
GHS	Ghana Cedis (US $1 = GHS 1.4, January 2011)
IDE	International Development Enterprises
IDA	International Development Association
JICA	Japanese International Cooperation Agency
KWK	Kosim Water Keg
MIT	Massachusetts Institute of Technology
MEng	Master of Engineering
NGO	Non-Governmental Organization
PHW	Pure Home Water
SIDA	Swedish International Development Cooperative Agency
REVSODEP	Rural Education Volunteer and Social Development Programme
UNDP	United Nations Development Programme
UN-HABITAT	United Nations Human Settlements Programme
UNICEF	United Nations Children's Fund
USD	United States Dollar (US $1 = GHS 1.4, January 2011)
VIP	Ventilated-Improved Pit
WHO	World Health Organization
WSP	World Bank Water Sanitation Program

1 Introduction[2]

Overview of Water Resources in Northern Ghana

The United Nations and the World Health Organization (WHO) categorize water sources as either “improved” or “unimproved.” Improved refers to protected water sources including household connections, public standpipes, boreholes, protected dug wells, protected springs, and rainwater harvesting. Unimproved refers to unprotected wells, unprotected springs, vended water, tanker truck water, and all surface waters. These metrics define the Millennium Development Goals targets relating to water. Figure 1-1 pictorially shows the percentage of improved vs. unimproved sources in the districts of the Northern Region of Ghana. With rare exception, most areas suffer from a severe lack of improved water sources, and in total about half of the people in the Northern Region drink water from unimproved supplies.



Data: Ghana Statistical Service, 2003
Map: J. VanCalcar, 2006

Figure 1-1: Improved and unimproved water sources in Northern Ghana

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2. [2] Written with team members Shanti Kleiman, Samantha O’Keefe, Joanna Cummings, and Jonathan Lau.

With unimproved water sources comes the increased risk of unsafe water that contains dangerous pathogens. These pathogens include the bacteria, protozoa, and viruses responsible for causing cholera, typhoid, hepatitis A & E, guinea worm, and other water-related diseases. In Ghana, diarrhea accounts for 12 percent of all deaths of children under five prompting the need for further action in the area of water supply, water treatment, sanitation, and hygiene (World Health Organization 2006). Figure 1-2 demonstrates the severity of this problem, especially in the Northern and Upper West Regions of Ghana where the mortality rate for children under five is 154 and 208 per 1000 births respectively. In contrast, the under five mortality rate in the USA is 7.8 per 1000 births (World Bank, World Development Indicators 2011).

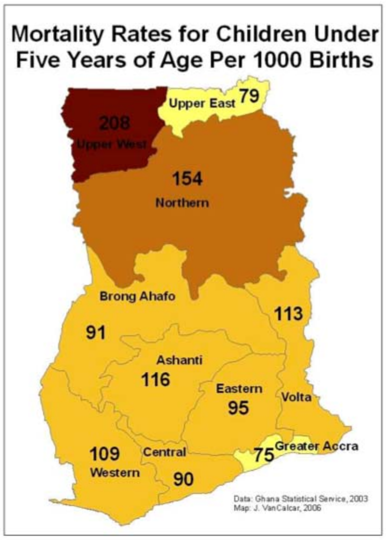


Figure 1-2: Mortality rates, Ghana

Sanitation in Ghana

Although Ghana ranks 152 out of 182 on the UNDP Human Development Index, it has the 4th lowest rate of sanitation coverage worldwide (UNICEF/WHO 2010). There is a serious need for increased sanitation awareness and better wastewater management, especially for lower-income households and rural areas.

Pure Home Water seeks to expand its safe drinking water work to the sanitation sector, starting with the region around Tamale. The primary means of human waste disposal in Taha, outside of Tamale, is open defecation, which is typical of many rural areas. Villages in rural Ghana have an average basic sanitation coverage rate of 11%. (WHO 2010)

However, some non-profits in the region, such as REVSODEP, have been working to improve sanitation. Last year, REVSODEP built five ventilated-improved-pit latrines in Taha Village, which provide a safer and more hygienic means of disposal of human waste for several families in the village. They have also started latrine projects and sanitation education campaigns in over a dozen other rural villages near Tamale. Pure Home Water hopes to work with these experienced organizations in tackling the rural sanitation problem in Northern Ghana.

Ceramic Filter Manufacturing

Ceramic filters are available around the world in different forms; candle filters, disk filters, and colloidal silver enhanced ceramic pot filters. Pure Home Water (PHW) manufactures colloidal enhanced ceramic pot filters in Ghana's Northern Region, and is one of approximately 35 operational filter factories in 18 countries producing this type of filter (Rayner 2009).

The filter was originally developed by Dr. Fernando Mazariegos in Guatemala in 1982, and after Hurricane Mitch in 1998, Ron Rivera of Potters For Peace (PFP) began trainings in standardized small factory production. In 2010, the Ceramics Manufacturing Working Group (CMWG) published a study on the *Best Practices for Ceramic Filter Manufacturing*, which surveyed 34 filter factories on their production and quality control procedures (CMWG 2010). Based on an extensive literature review and survey results from the 25 factories that responded, they produced best practice protocols and standardization recommendations for existing and future factories.

Manufacturing the filter is a multistep process that requires quality checks and standardized procedures at each stage. The production process can broadly be broken down into the following areas.

- Sourcing material
- Mixing clay & burnout material
- Pressing clay into filter pots
- Trimming pressed filters
- Drying
- Firing
- Visual and auditory inspection
- Flow rate testing
- Applying silver
- Pressure (crack) tests
- Water quality testing
- Packaging and delivery

Work done at PHW in January 2011 by the MIT Master of Engineering team focused on research, standardization, and improvement of manufacturing protocol for the ceramic pot filter and introduction of potential new products for expansion of the PHW line.

Pure Home Water Organizational History

Founded in 2005 by MIT Senior Lecturer Susan Murcott with local partners, PHW is a non-profit organization in Ghana whose mission is to provide safe drinking water to the people of Northern Ghana - the poorest part of the country. The organization's goals are:

1. To reach the people most in need of safe drinking water and

2. To become financially and locally self-sustaining

Early student teams from MIT researched performance of, consumer preferences for, and consumer willingness to pay for water treatment techniques in order to find the best system for the region. In addition to considering several types of ceramic filters, they investigated biosand filters, chlorination systems, and solar water disinfection (SODIS). Through these studies, PHW determined that, of the options for household drinking water treatment and safe storage (HWTS) available in Northern Ghana, ceramic pot filters (CPFs) with safe storage containers offered the simplest and cheapest method to effectively treat drinking water in Northern Ghana at the household scale. From 2006-2009, PHW focused on distributing CPFs that were made at Ceramica Tamakloe Ltd. in Accra, Ghana, teaching people how to use them and monitoring how effective and durable they were over time. They chose ceramic water filters because they are effective in removing *E. coli*, have been shown to be linked to the reduction of cases of diarrhea, can be manufactured almost entirely out of local materials, and are culturally appropriate since water is generally stored in large clay vessels in Northern Ghana (Johnson et al. 2008).

Pure Home Water Factory

As PHW grew, importing filters from Accra became less efficient. Initially, many CT filters were broken on the trip from Accra to Tamale, and over time PHW had trouble with the supplier providing pots behind schedule and of uneven quality. In order to eliminate these problems in the supply chain and better serve Northern Ghana, PHW began constructing its own factory in Tamale in late 2009. Construction of the building was still ongoing as of May 2011, but the factory has the molds, supplies, and the kiln necessary for production. In January of 2010, a two-person team of MIT students began work on developing a set of best filter production practices for the new factory. Miller (2010) and Watters (2010) established recommended clay recipes based on flow rate and strength of the filters made with different proportions of combustible material and clay. Further work and research must be done to ensure that filters being produced at the new factory consistently perform well. Preliminary filter production produced some pots that were of uneven quality and too brittle to be sold. The factory currently has orders pending from NGO groups to supply filters for Northern Ghana that can be supplied once quality controls are established and quality production is ensured.

The factory is also set up to produce rammed earth blocks in addition to clay pots. Early attempts to sell the *Kosim* filters at their true production price were unsuccessful. The $18 selling price of the system was well above what rural families were willing to pay – particularly the more vulnerable, rural households that PHW aims to serve. In order to reaize its goal of being self-sustaining, PHW is testing rammed earth block, concrete block, and/or fired brick production as a revenue stream to subsidize *Kosim* filters for rural families. PHW currently has standard rammed earth block molds and a press and has produced the earth blocks for the construction of its own factory, but has not yet constructed a point of sale for the blocks or contacts with other vendors.

2 Establishing H2S Producing Bacteria as a Fecal Coliform Indicator

2.1 Introduction

2.1.1 Motivation

The Millennium Development Goals (MDGs) are eight goals established by the members of the United Nations in 2000 that set targets for improvement by 2015. The seventh goal is to "ensure environmental stability" and within that lies goal 7C: "Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation" (United Nations Development Program 2010). The United Nations at this time promotes the terms "improved" and "unimproved" as standard metrics of determining water quality. Improved refers to protected water sources including household connections, public standpipes and boreholes. Unimproved refers to any type of open surface water or uncovered well. These metrics define the Millennium Development Goal targets around water and sanitation. Improved sources can easily be identified minimally trained individuals and done so "at a glance, so this is a faster and lower cost procedure than actual water testing.

However, improved sources are not necessarily safe sources. In other words, they are not truly indicative of the quality of the water being provided. Ideally, a water quality test needs to be employed to gain a realistic sense of the quality of drinking water worldwide. The 2009 Millennium Development Goals Report acknowledges the improved water sources can easily be contaminated and that many improved sources have when tested, have proven to be contaminated (United Nations 2009). Thus in order to determine the true safety of drinking water sources; microbial testing should be done.

While there are many challenges to solving the problem of unsafe drinking water, one of the first steps in solving this is to increase the available information about the quality of the water in rural and underdeveloped areas.

2.1.1.1 Background on Water Quality and Health Impacts

Contamination of water can be described by four categories: chemical, microbiological, physical and radiological (Murcott 2011). Contamination can originate from a variety of sources including industrial or agricultural runoff, poorly treated or untreated human and animal waste, or naturally certain geologic strata such as arsenic or fluoride. In developing countries the most common form of contamination is microbiological which comes primarily from human or animal feces mixing with drinking water sources. Microbial contamination can occur at many points of contact from source contamination to the transport vessel to the physical handling of the water at the point of use (Murcott 2011).

More tangibly, water quality has a direct relation to public health. Almost 2 million people every year, the majority of whom are children under five, die each year from water related diseases. Accurate water quality tests are needed to determine if water standards are being met, establish source water quality and potentially the effectiveness of a treatment system, to be used as input for health risk assessments and finally to help guide management systems (Sobsey 2002).

2.1.2 Water Quality Testing

2.1.2.1 Indicator Organisms

With the public's health at stake, knowledge of the safety of the water source is imperative. However direct testing for harmful pathogens requires that many individual trials be run as each test screens for only one type of potential pathogen rather than the variety of agents that could cause human diseases (Trottier 2010). This method is not only cumbersome in terms of the volume of tests but has also proven to be more expensive financially. This is to speak nothing of the fact that lab technicians completely the procedures are isolating bacteria that is potentially harmful to them.

As a result of these drawbacks, a new approach to determining water quality began to take form in the late 1800s. Instead of testing for pathogens, indicator organisms are used as a proxy and their presence literally indicates the likelihood that more harmful bacteria is also present. To be considered an indicator organism specific criteria must be met including a determination that the organism is from "...exclusively from fecal origins, is present in higher numbers, is more persistent to environmental stress, does not proliferate in the environment," and that a simple test exists for its detection (HACH 2000).

Overall, testing for indicator organisms is generally far simpler, safer and less expensive than testing directly for pathogens that may be present (HACH 2000).

2.1.2.2 Current Methods

Technologies currently exist that can both identify harmful contaminants and rid water of them. However much of the world, is not benefiting from the application of these innovations. There are two test methods that act as the industry standards at the present time, the most probable number (MPN) and the membrane filtration test. IDEXX Quanti-Tray, maybe the most widely used MPN example, provides counts of both total coliforms and *E.coli* (IDEXX Laboratories n.d.). Unfortunately, there are a number of difficulties associated with achieving the accuracy with these tests including:

1) <u>Complexity</u>: The water tests themselves are complicated often requiring an individual with laboratory training to correctly execute the test and to interpret the results.
2) <u>Resource Availability</u>: Areas of the world where microbial tests are most needed are often not equipped with modern water quality testing laboratory equipment. Remote areas often do not have electricity, which is needed to power the incubators, refrigerators, autoclaves and other devices to execute a number of the current methods.
3) <u>Costs</u>: Large amounts of capital are required to create the laboratory facilities, maintain them and ensure functionality over a long period of time. This is not to

mention the recurrent costs of current microbial tests that are often made for one time use and can range from $1-20 per test.

Thus accurate, simple and low cost methods of microbial water testing are needed. This report specifically explores the potential for use of the Hydrogen Sulfide (H_2S) test as proposed by Manja et.al. (1982)used in conjunction with the Easygel® test, by Micrology Laboratories, for drinking water testing purposes in Northern Ghana and other developing countries.

2.1.3 H_2S and Easygel®

2.1.3.1 Prior Efforts

The basis for further H_2S testing was proposed by Stephanie Trottier in her thesis "Study of Four New, Field Based, Microbiological Tests; Verification of the Hydrogen Sulfide, Easygel®, Colilert, and Petriflm Tests." Trottier's work was conducted primarily in Capiz Province, Philippines with a lesser proportion of samples collected from Cambridge, MA. Her results indicate that a 20ml H_2S test provided the most accurate results when used as a presence/absence test on improved drinking water sources. For unimproved sources, H_2S provided results consistent with the assumption that every unimproved source is contaminated. The 20ml-size H_2S test was recommended based on accuracy as compared with a standard method, case-of-use-and cost considerations.

Trottier also determined Easygel ® to be the most accurate enumerative test. When used in conjunction with H_2S it yielded highly reliable results for both improved and unimproved water source types.

It should be noted that these tests were recommended as appropriate for improved sources only. However, given the small sample size (4 unimproved, 19 improved sources) these results were not deemed statistically significant (Trottier 2010 (Chuang 2010)), hence the importance of the increased trials which are reported on below.

2.1.4 Research Objectives

While microbial water tests do exist, current methods can be improved upon significantly to produce more accurate, easier-to-use and lower cost tests. It is with these goals in mind that the research objectives for this project were established.

1) *To confirm the accuracy of the 20ml* H_2S *tests as an indicator for fecal coliform for all improved water sources.*

In this context, accuracy is defined as the ability of the test to measure its intended target, fecal coliform presence. H_2S tests will be compared to the standard method Quanti-Tray.

2) *To establish the accuracy of Easygel® as a single enumerative test for fecal coliform.*

As with H_2S , so too for Easygel®, accuracy, in this context, is defined as the ability of the test to measure its intended target, fecal coliform presence. Easygel® tests will be compared to the standard method Quanti-Tray.

3) *To verify the accuracy of the 20 ml* H_2S *test used in conjunction with the Easygel® enumerative method and compare its effectiveness with the Quanti-Tray method.*

Evaluation will be done using the same metrics as in Stephanie Trottier's 2010 thesis: accuracy, cost and practicality. To confidently verify the 20 ml H_2S and Easygel® methods, a testing plan must be executed across a range of water sources and a minimum of 30 samples to be considered statistically significant. Over one hundred samples collected in Ghana will be used to confirm the accuracy of the proposed microbial methods.

2.1.5 Research Plan

2.1.5.1 Fall 2010

2.1.5.1.1 Laboratory-Made H_2S Strip Test Reagent Preparation

In December of 2010 H_2S test reagents were made at MIT in Cambridge, MA. Based on recommendations in the literature, only the M2 media was prepared in strip form. Forty-two sterile bottles with strips were prepared for transport to Ghana. Additionally, forty-two strips were prepared and brought to Ghana to be used in re-sterilized bottles. Finally, a dry ingredient mixture for M2 was carried in a plastic bottle should additional strips need to be made on location. During this period preparations were also made for field-testing including mapping of potential sites, daily schedule outline and necessary materials gathered and packed.

2.1.5.1.2 Preliminary Laboratory Testing at MIT, December 2010

In November and December of 2010, initial lab testing was completed at MIT. The purpose of the testing was two-fold: first, to become familiar with testing methods, both execution and interpretation of results, and second to check that the laboratory prepared H_2S test strips did in fact correlate with the standard methods of testing. The source of water included Charles River Water and Cambridge municipal tap water. The results of these initial tests in not included in the data set used for analysis.

2.1.5.2 January 2011

2.1.5.2.1 Fieldwork in Tamale Ghana

During the month of January 2011, testing and analysis took place at the lab in the Pure Home Water House in Kalpohin Estates, just outside of Tamale, Ghana. An incubator and Quanti-tray sealer were borrowed from the Innovations for Poverty Action (IPA) lab. Over the course of her stay, the author sampled 14 unique water sites from a range of improved and unimproved sources collecting 114 total samples. It should be noted that the number of trials per test type that were able to be performed varied due to limitations on materials available in the field. Figure 2 visually depicts the villages in the greater Tamale area that were travelled to from the base at Pure Home Water.

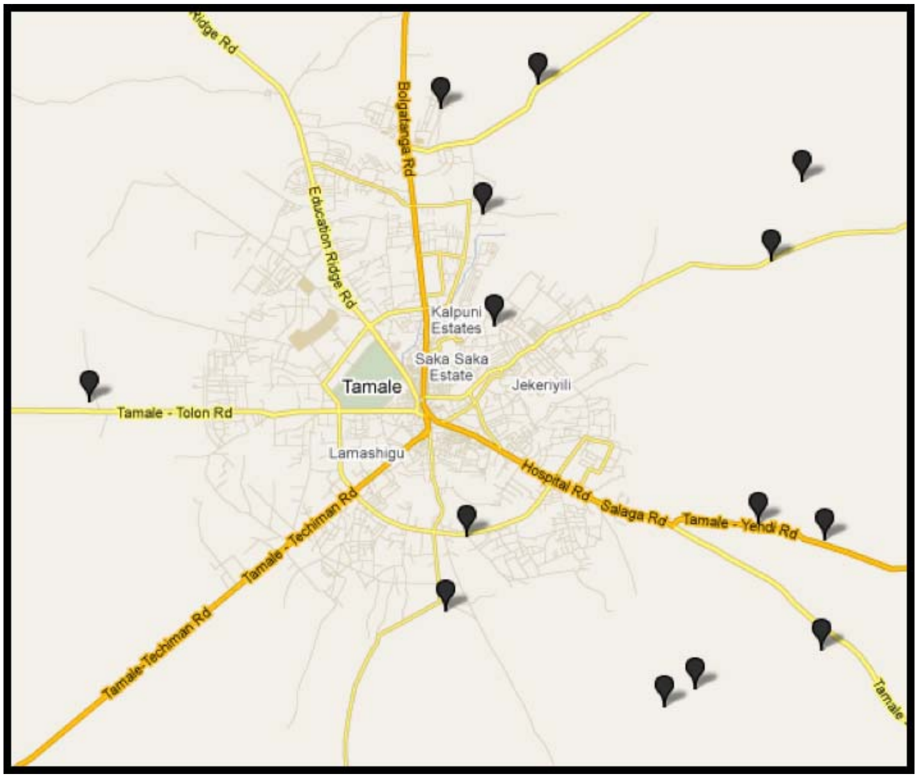


Figure 2-1 A map view of villages sampled around Tamale during January 2011

2.2 Microbial Tests

The H_2S is a simple presence/absence test meaning that the results do not indicate the degree to which the water is contaminated, but rather whether or not there is any fecal contamination present. Unlike established microbial tests, the H_2S test does not directly measure the presence of coliforms, fecal coliforms or *E.coli*. Instead, the H_2S test checks water for the presence of H_2S producing bacteria. The presence of bacteria with this has been demonstrated to correlate with the presence of fecal coliforms (Sobsey 2002, Manja 1982). Simply put, H_2S producing bacteria are acting as a proxy for a fecal coliform indicator, namely *E.Coli* (Chandras 2001).

To perform the H_2S test, Hydrogen Sulfide test strips are added to a water source. The reagents on the strip include bacteriological peptone, dipotassium hydrogen phosphate, ferric ammonium citrate, sodium thiosulphate and sodium lauryl sulfate (Manja 1982) (Chandras 2001). If there is H_2S present in the sample, a reaction will produce iron sulfide, an easily identifiable black precipitate. Any test where a precipitate forms is deemed a "positive" result. Conversely, a test where no precipitate forms is categorized as "negative." Figure 1 is a side-by-side comparison of a "blank" or a sample where the H_2S test media was not added (left) and a sample to which the media was added that presented as positive for H_2S and therefore fecal coliforms. The extreme readability of the H_2S test is touted as one of its major positive aspects.

Figure 2-2 Negative (left) and Positive (right) Test Results

When exploring the use of a potential new product, the cost of materials per test is an added consideration. This value includes both the variable and fixed costs of the execution of the H_2S test assuming materials are purchased in the United States. The H_2S test has been calculated to cost approximately \$0.07 for the 10ml test, \$0.14 for the 20ml test and \$0.35 for the 100ml test (Trottier 2010). The volume sizes in this case refer to the volume of sample water that would be tested at one time. Conversely, the Quanti-Tray, not including the purchase of the necessary sealing and incubating equipment that can run up to \$4-5000, is estimated to cost approximate \$15 per 100ml test (Samantha O'Keefe 2011).

2.2.1 H_2S in the Global System

One cause of uncertainty in the H_2S test currently is the large variety of sources in the environment that also produce H_2S outside of the bacteria that correlate to fecal coliforms. These additional sources of H_2S could produce a positive result without being associated with the presence of fecal coliforms. The global sulfur cycle explains the reason for this phenomenon in as displayed in Figure 4. The largest sinks of sulfur exist in the atmosphere and Earth's. Bacteria play a major role in the cycle, deriving energy from sulfur by moving it between various oxidized and reduced forms. Bacteria in some environments are more prone to this method of energy generation, for example near geothermal activity (Trottier 2010). In looking at the processes that take place throughout the cycle, there are three in which H_2S is either produced or is present in an intermediate step. These are 1) mineralization of organic sulfur 2) oxidation of elemental sulfur and 3) reduction of sulfates in sulfide (Chisholm 2010).

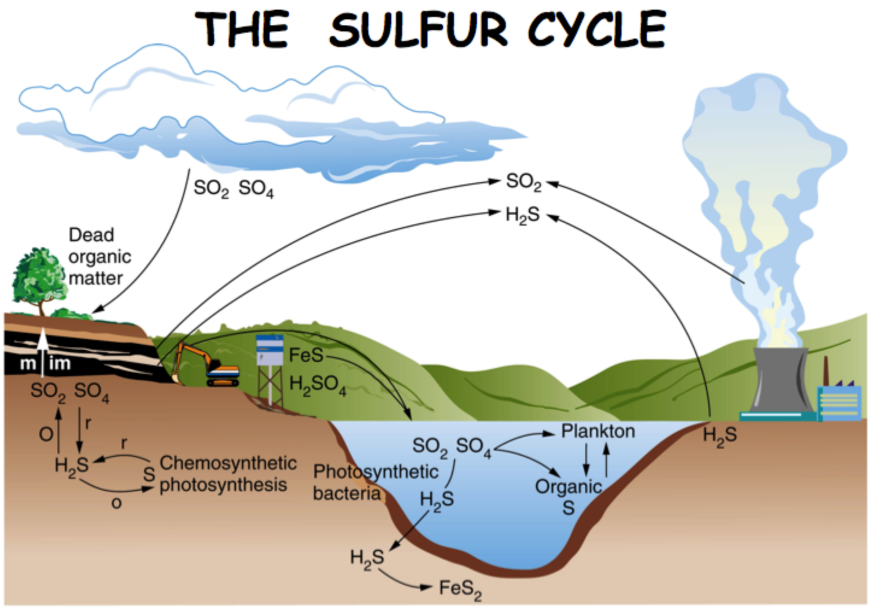


Figure 2-3 H2S in the Global Sulfur Cycle

As positive results are produced by all hydrogen sulfide producing bacteria, including those not associated with fecal coliforms, the tests has a slight propensity for false positives (HACH 2000) (Sobsey 2002).

2.2.2 Easygel®

Easygel® is an enumerative 5ml tests that contains a sugar that upon interacting with coliforms will turn pink. A second sugar is linked to a blue-green dye that is activated when a reaction with *E. coli* occurs. This allows counts for both total coliforms, indicated by pink colonies, as well as *E.coli*, indicated by be purple colonies (Micrology Laboratories 2008).

Easygel® is particularly attractive as a test in developing countries for it's lack of incubation requirement. Prior to use, Micrology Laboratories recommends that you "freeze" the agar replacement media, which generally implies the use of a commercial or residential freezer with temperature range from -15 to 15 degrees Fahrenheit. However, the media can be left at ambient temperatures for up to one month, making the test increasingly viable in short term-field testing (Micrology Laboratories 2008).

2.3 Data Analysis

The main goals in completing a statistical analysis is to verify the accuracy of H_2S and Easygel® tests as individual presence absence and enumerative indicators for microbial contamination, as well as to determine statistical improvement in accuracy when the two are used in combination as compared to a standard method, IDEXX Quanti-Tray, in this case.

Generally a sample size (n) greater than 30 is considered adequate to draw statistically significant conclusions.

2.3.1 Analysis Methodology

Data collected from the aforementioned water tests were analyzed using Microsoft Excel. The statistical methods employed are consistent with those performed in Trottier's 2010 Thesis titled "Study of Four, Field-Based, Microbiological Tests: Verification of the Hydrogen Sulfide, Easygel®, Colilert and Petrifilm Tests," as well as the similarly titled 2011 paper by Chuang, Trottier and Murcott "Comparison and Verification of Four Field-Based Microbiological Tests Against Quanti-Tray." This was done purposefully in order to ensure comparability across data sets. The following sections describe the statistical methods used to analyze the presence/absence tests water tests performed in Ghana.

2.3.1.1 Contingency Tables

A contingency table, or as cross tabulation table, is often used when comparing n results that are classified into two criteria A and B, each with the potential to have varying results within their classification i.e. A1, A2, A3 etc.

Table 2-1 Critera A and B

A	B1	B2
A1	n11	n12
A2	n21	n22

While there are limitations on the usefulness of this type of model, it can be used to determine statistical independence between two identified criteria A and B. To give an example relevant to the dataset to be used in this analysis, let A and B refer to the "New Test" method and the "Standard Method" respectively (Kirkman n.d.). Lower case letters indicate the number of results that fall within the definition of each cell.

Quanti-Tray

Table 2-2 Quanti-Tray

H_2S Test	Presence	Absence
Presence	a	b
Absence	c	d

From this depiction it is easy to see at a glance if the two variables, A and B, have contingency, or that the number of results in a column vary significantly over the subsequent rows. If results in a column are relatively consistent over the rows then it is likely that the variables are independent, that is, any differences could be attributed to chance (Kirkman n.d.) (Lowry n.d.).

2.3.1.2 Chi Squared Test

Using the results found in a contingency table, a chi-squared test could be used to determine quantitatively if the relationship between variables can be attributed to chance. The test assumes the base assumption of the null hypothesis, meaning that there is no relationship between the variables, thus the greater the chi squared value, the greater the correlation between them.

The steps to compute the chi-squared value are as follows.

1) Propagate a contingency table with relevant variables.
2) Calculate the expected frequency for each cell in the contingency table. This can be done by multiplying the row total by the column total and dividing by the total number of results.
3) Calculate the chi-squared value by the equation using observed and calculated expected frequencies.

$$X = (\text{Observed-Expected})^2 / \text{Expected}$$

2.3.1.3 Fisher's Exact Test

It is important to recognize that the chi-squared test cannot be used to calculate statistical relationships between variables if the expected value is less than five as determined by in 2x2 contingency tables. In a chi-squared test, it is assumed that the data follows a Gaussian distribution and this assumption assists in simplifying the statistical calculations (Lowry n.d.).

In a Fisher's Exact Test, there are no assumptions made with regard to the distribution of data and thus it is appropriate for the H_2S, Easygel® data set collected during January 2011.

Fisher's test is performed with the values derived from a 2x2 contingency table and follows the equation below (Lowry n.d.).

$$\Pr(a,b,c,d) = \frac{(a+b)!\,(c+d)!\,(a+c)!\,(b+d)!}{n!a!b!c!d!}$$

2.3.1.4 Statistical Significance

Statistical significance in basic terms is a method of verifying the reliability of a produced result, or that the result is unlikely to be produced by chance. More specifically, establishing that a result is significantly significant requires calculation of the degree of confidence or p-value. In chi-squared and Fisher's Exact Test, the null hypothesis that is assumed at the start of the analysis is that there is no relationship between the variables (Vassar College n.d.). With a p value less than 0.05, then the null hypothesis is rejected and thus there is a relationship assumed. Further guidelines for interpreting a range of p-values are included in the table below.

Table 2-3 Interpreting P-Values

p-value (p)	Significance of p
p<0.001	**Results are very highly significant**

0.001≤p<0.01	**Results are highly significant**
0.01≤p<0.05	**Results are significant**
0.05≤p <0.01	**There is a trend toward significance.**
p>0.05	**Results are considered not statistically significant.**

2.3.1.5 General Statistical Methods

In keeping with the analysis performed by Trottier and Chuang, a number of common statistical tests were performed in order to provide further detail as to the nature and accuracy of the H_2S and Easygel® test results. The methods, definition and equation with reference to the 2x2 contingency table are listed in the table below.

Table 2-4 General Statistical Methods

	Abbrev.	**Definition**	**Equation**
True Result	**TR**	**The percentage of samples for which the New Test produced the same result as the Standard Method.**	**(a+d)/(a+b+c+d)**
False Positive	**FP**	**The percentage of positive samples of the New Test that produced a negative result by the Standard Method.**	**b/(a+b+c+d)**
False Negative	**FN**	**The percentage of negative samples of the New Test that produced a positive result by the Standard Method.**	**c/(a+b+c+d)**
Sensitivity	**Sn**	**The capacity of the New Test to determine a true positive result as defined by the Standard Method.**	**a/(a+c)**
Specificity	**Sp**	**The capacity of the New Test to determine a true negative result as defined by the Standard Method.**	**d/(b+d)**
Positive Predictive Value	**PPV**	**The capacity of a positive New Test to predict the presence of *E.coli.***	**a/(a+b)**
Negative Predicative	**NPV**	**The capacity of a negative New Test to predict the**	**d/(c+d)**

Value		**absense of *E.coli.***	
Error	**-**	**The sum total of all false results by the New Test.**	**(b+c)/(a+b+c+d)**

2.4 **Project Results**

2.4.1 Overall Regional Microbial Contamination

The chart below represents the degree of microbial contamination found around Tamale during January 2011 sampling as quantified by Quanti-Tray tests performed at the Pure Home Water lab. Nearly all of the 14 villages sampled demonstrated extremely high levels of *E. coli* presence with thirteen of fourteen exceeding the World Health Organization's guideline of 0 colony forming units (cfu)/100ml standard (The World Health Organization 2006).

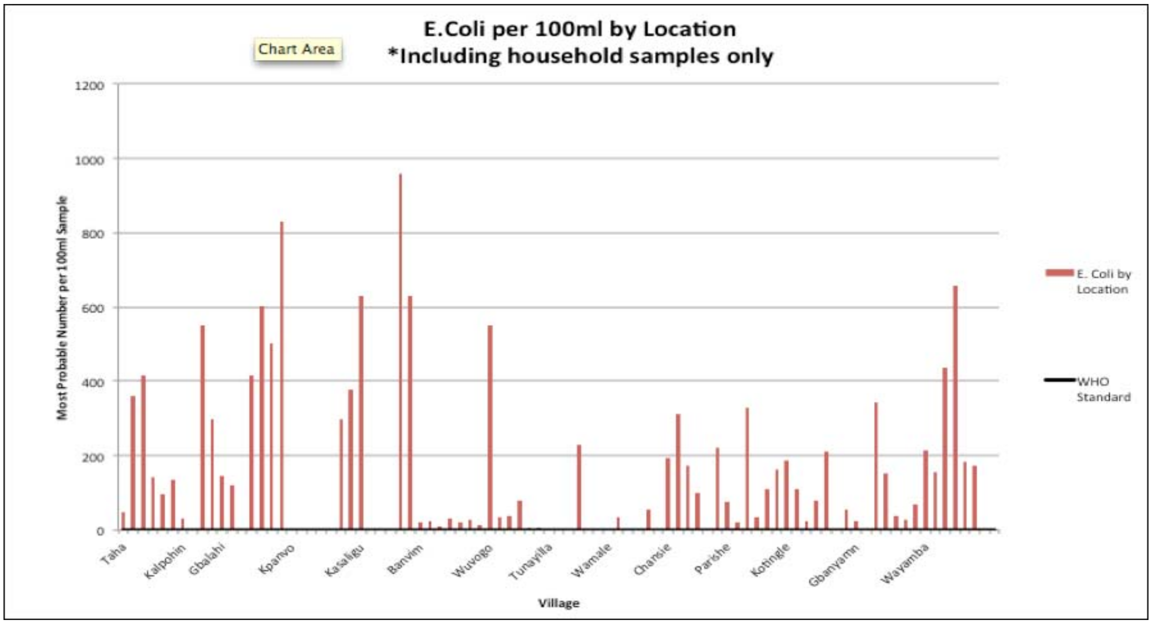


Figure 2-4 E.Coli Presence in Drinking Water Samples, Northern Ghana

2.4.2 20ml H_2S Compared to Quanti-Tray

During the course of this study the laboratory made M2 H_2S media in strip form was used to test 114 unique water samples from the greater Tamale region. Samples were collected from a variety of sources including protected and unprotected wells, dugouts, traditional household vessels, safe storage containers, open dug wells, household and community taps. The contingency table for H_2S, as the New Method, and Quanti-Tray, as the Standard Method is presented below.

Using the statistical analysis methods detailed in a previous section, the following results were produced.

Table 2-5 2x2 Contingency Table, 20ml H2S vs. Quanti-Tray

		Quanti-Tray		Total
		Presence	Absence	
20 ml H_2S Test	Presence	85	0	85
	Absence	11	15	26
Total		96	15	111

The contingency table comparing H_2S and Quanti-Tray indicates that both tests were performed on a total of 111 water samples. Since one of the cells, the intersection of a presence result for the 20ml H_2S with an absence result for Quanti-tray, had zero incidences of occurrence, the chi-squared test is not appropriate.

Table 2-6 Statistical Results, 20ml H2S vs. Quanti-Tray

True Value	90%	Sensitivity	88%	Positive Predictive Value	100%
False Positive	0%	Specificity	100%	Negative Predictive Value	57%
False Negative	10%	Error	10%		

20ml H_2S vs. Quanti-Tray
Fisher's Exact Probability: 0.0001
Extremely Statistically Significant

Interestingly, the results demonstrate a propensity for False Negatives, indicating that there was contamination present that the test did not detect. Traditionally, the H_2S commonly shows False Positives due to the presence of hydrogen sulfide producing bacteria naturally occurring but this was not the case here. This lack of false positives could be attributed to the types of water sources samples, with few (<10) being directly ground sources. Another potential reason for this anomaly may be due to the low concentrations of contamination present in several improved sources sampled, specifically municipal piped water.

As compared to Trottier's work in 2010, the 20ml H_2S tests performed in Ghana were 6% more accurate by way of True Results. The overall error for the test is lower.

It is important to note that while the chemical makeup of the H_2S test is the same, the nature of the samples in terms of temperature, turbidity, pH and specific source type varied and thus the H_2S can be said to perform slightly differently depending on the environment in which it is used. However, in both cases, Fisher's Exact Probability and the high True Value percentage give confidence to the H_2S as an indicator for the presence of *E.coli*.

2.4.3 Easygel® Compared to Quanti-Tray

During the course of this study Easygel®, was used to test 49 unique water samples from the greater Tamale region. Samples were collected from the same sites as the initial 49 H_2S sites, however tests were limited due to the number of supplies the team was able to transport to Ghana.

Using the statistical analysis methods detailed in a previous section, the following results were produced.

Table 2-7 2x2 Contingency Table, Easygel® v. Quanti-Tray

		Quanti-Tray		Total
		Presence	Absence	
Easygel® Test	Presence	39	1	40
	Absence	4	5	9
Total		43	6	**49**

The contingency table comparing Easygel® and Quanti-Tray indicates that both tests were performed on a total of 49 water samples. Overwhelmingly both tests produced positive results for fecal contamination. With three of four cells had extremely low incidence occurrence, the chi-squared test is not appropriate in this case.

Table 2-8 Statistical Results, Easygel® v. Quanti-Tray

True Result	90%	Sensitivity	91%	Positive Predictive Value	98%
False Positive	2%	Specificity	83%	Negative Predictive Value	56%
False Negative	8%	Error	10%		

Easygel® vs. Quanti-Tray
Fisher's Exact Probability: 0.0004
Extremely Statistically Significant

Like, H_2S, Easygel® proved to be a highly accurate indicator for *E.Coli*. In this case the Ghana dataset improved on nearly every aspect of the Standard Statistics as well as produced an extremely statistically significant exact probability.

Still, the lower specificity and Negative Predictive Value as combined with the higher percentage of False Negative indicate that the test has trouble identifying positive sources at times and that the presence of a negative test can at times not indicate the absence of a contaminant.

In order to alleviate issues regarding the Easygel®, a low-end detection limit must be found to determine whether the False Negative play a significant role in the nature of the test or if the concentrations in specific samples were outside of the scope of this study due to the test volumes that were used.

2.4.4 20ml H_2S +Easygel® Compared to Quanti-Tray

In order to compare the accuracy of the 20ml H_2S test used in conjunction with Easygel® to the results achieved with Quanti-Tray it is necessary to construct at 3x3 contingency matrix. To translate the results of Quanti-Tray and the Combination Method to each other the World Health Organization's established risk levels are utilized (The World Health Organization 2006).

Table 2-9 Modified WHO Risk Levels and Corresponding Microbial Test Results

WHO Risk Level	**Quanti-Tray *E. Coli* Result (MPN/100ml*)**	H_2S **Result**	**Easygel® (*E.Coli* CFU**) (Adapted for a 5ml Sample)**
Conformity	<1	Yellow	0
Low	1-10	Yellow	0
Intermediate	10-100	Black	0-4
High	100-1000	Black	5-50
Very High	>1000	Black	>50

***MPN indicates most probable number**
****CFU indicates colony-forming units**

Most probably number is a statistical method for determining a likely number of colony forming units (CFUs) present. Though they are generated differently, with colony-forming units physically counted in a sample, MPN and CFU values are both used to indicate contamination levels in drinking water samples.

After assigning each sample to a risk level based on the corresponding risk level, a 3x3 contingency table was created.

Using the statistical analysis methods detailed in a previous section, the following results were produced. The gray shaded section of the contingency table (Chart 8) indicates a situation in which the H_2S +Easygel® either over-predicted or accurately predicted the level of risk of a water source. This estimate is included in the results as the conservative estimate.

Table 2-10 3x3 Contingency Matriz, 20ml H2S +Easygel® vs. Quanti-Tray

		Quanti-Tray			
		Conformity/Low	Intermediate	High/Very High	Total
H_2S **+Easygel®**	Conformity/Low	8	1	0	9
	Intermediate	0	7	4	11
	High/Very High	0	2	27	29
Total		8	10	31	49

Table 2-11 Statistical Results, 20ml H2S +Easygel® vs. Quanti-Tray

TR	86%	Sensitivity	Conformity/Low	100%	PPV	89%	n=8
TR (Cautious)	90%		Intermediate	70%		66%	n=10
Error	10%		High/Very High	87%		93%	n=31

Overall, when used in conjunction the two combined tests, H_2S and Easygel® produce a slightly lower true value than the tests used individually. When accounting for over-estimation of risk, the true value as well as the error appears the same as H_2S and Easygel® used separately. However, since results of the individual tests proved to be highly accurate on their own, using the tests as a pair does not appear to offer a significant improvement in determining microbial contamination of a drinking water source.

2.5 Conclusion

The primary purpose of this research was to build upon the work of Trottier in 2010 looking specifically at the verification of H_2S and Easygel® as presence/absence and enumerative tests respectively for microbial water contamination. In additional the 20ml H_2S in combination with Easygel® was explored for increased statistical accuracy.

From the results of the analysis completed with the Ghana 2011 dataset is can be concluded that both H_2S and Easygel® are applicable for use in Northern Ghana for presence/absence and enumerative testing purposes respectively. The results for the two combined tests performed well. However, there was not a substantial improvement to warrant using them in conjunction as opposed to selecting either the H_2S or the Easygel® for cost-saving and ease-of-use purposes.

2.5.1 Recommendations for Future Work

Despite favorable results in this study, there exist further questions surrounding the H_2S that require verification.

- Detection Limit of Easygel®

As was discussed in the Easygel® results, a low end detection limit must be found to determine whether the FN play a significant role in the nature of the test or if the concentrations in specific samples were outside of the scope of the test.

- Lifetime of the H_2S Test Strips

A long-term study to substantiate the actual lifetime of both laboratory produced and industry made H_2S strips is necessary to substantiate the period of time in which tests must be used, as well the ideal conditions for storage.

- Sensitivity of the 20ml H_2S Test

The H_2S test has been recommended for use between 20 and 44 degrees C, however within 28 and 37 degrees the test has been demonstrated to produce results more rapidly (HACH 2000). Additionally, at lower concentrations the test requires longer to produce positive results. Investigation into the relationship between true results, time and temperature should be completed for a 20ml test size.

- WHO Indicator Organism Criteria

Before H_2S is fully accepted by the water testing industry for the purpose of detecting microbial contamination, it must meet the WHO standards for indicator organisms. The majorities of these efforts surround an increased understanding of the hydrogen sulfide producing bacteria themselves and include but are not limited to the following

- How do H_2S producing bacteria respond to disinfection, for example chlorine, ozone or boiling?
- How do laboratory made H_2S strips compare to commercially made H_2S strip, specifically the HACH pathoscreen tests.

Given the favorable initial results found in this research questions on the feasibility of dissemination of the H_2S on a broad screen also come into the

- What is the most feasible method of mass production for the laboratory made strips?
- How should the paper strips be packaged to be easily portable and retain the longest possible shelf life?
- How to market the H_2S testing method so that it becomes more widely used in areas and circumstances where it is most appropriate?

3 Designing Sanitation Projects in Rural Ghana

3.1 Introduction

3.1.1 Project Background

In January 2011, Jonathan Lau traveled to Ghana with a team of students and faculty to work with Pure Home Water. During that month, he conducted a pilot Ecological Sanitation (EcoSan) latrine project at the site of the PHW factory as well as sanitation surveys around the area. These field experiences have provided a basis for understanding the current sanitation situation in rural Northern Region, Ghana.

Additionally, Jonathan Lau and his thesis supervisor, Susan Murcott, were able to connect with social workers at a local non-profit Rural Education Volunteer and Social Development Programme (REVSODEP). Their insights into the local culture and experiences working in the sanitation sector have been invaluable throughout this project planning and implementation process.

3.1.2 Research Goals and Motivation

Ghana currently ranks 152 out of 182 on the Human Development Index, but has the 4th lowest rate of sanitation coverage worldwide (UNICEF/WHO 2010). While there are numerous organizations working in sanitation in the Northern Region, Ghana, including REVSODEP, Irish Aid, and CIDA, the sanitation challenge remains huge.

Through field surveying, it was estimated that in the villages around PHW in Northern Region, Ghana, less than 10% of the population has access to improved sanitation. However, the Ghanaian government spends less than 0.1% on rural sanitation projects, relying mainly on external agencies and donors (Lau 2011).

Poor latrine designs have led to ineffective projects. A standard household, two-seater, single-pit VIP latrine costs over GHS 2000 (US $1420) (Lau 2011). It would require hundreds of thousands of dollars just to provide *one* village with improved sanitation using this design. Moreover, construction of VIP latrines is slow and there is no easy way of removing the fecal material after the pit fills up.

This project investigates the major challenges with rural sanitation in Ghana and how best to design effective and appropriate sanitation projects. The following questions are addressed:

- What latrine designs are appropriate for rural areas in Ghana?
- What design adjustments can be made to reduce latrine costs?
- How can we improve collaboration between international aid agencies, local NGOs and government workers?

3.2 Background for PHW Pilot Project

This chapter introduces the pilot projects that were conducted during January 2011 to assess the feasibility of EcoSan in rural Northern Region, Ghana. Initiated in response to a need for sanitation facilities on the Pure Home Water (PHW) factory site, the PHW Project was led by the author, Jonathan Lau.

3.2.1 PHW Project Background

In September 2010, Pure Home Water was looking to expand its safe drinking water work to the sanitation sector. Additionally, the PHW factory did not have sanitation facilities and it was decided that as part of the MIT Civil and Environmental Engineering Department Masters of Engineering program, Lau would pilot an EcoSan latrine design on the Pure Home Water factory site. The project would serve the dual purpose as both the sanitation facility for the factory workers as well as an investigation into the potential for implementing ecological sanitation in villages around the factory and beyond.

This pilot project would provide essential data and experience for future sanitation-related work. Pure Home Water is currently finalizing a new contract sponsored by several Rotary Clubs (Medford, Cambridge, Tamale, Dunwoody), which includes an intended sanitation program in 2011-2012. In the future, EcoSan-related products could potentially be sold to higher-income communities and to non-profit organizations.

3.2.2 Project Planning

The following 8-step design process and schedule was followed, based upon the structure of the Masters program and the resource constraints those students at MIT face:

Table 3-1 Project Schedule

Fall Semester
1) Background research and literature review
2) Establish a local partnership with REVSODEP
3) Preliminary latrine designs
Independent Activities Period (IAP)
4) Field Experience and Pilot Projects
5) Project evaluation
Spring Semester
6) Refined Design
Summer and beyond
7) Follow-up with pilot projects
8) Further research and scaling up

3.3 **Assessment Criteria and Latrine Design**

The following assessment criteria are used to compare different designs. For more Lau's 2011 M.Eng thesis: "Designing Sanitation Projects in Rural Ghana" (Lau 2011).

1. Longevity and durability
    - Will it last under the rainy season in Ghana?
    - Is it appropriate for flood-prone areas?
    - Can it be repaired easily?
2. Local availability of materials
    - Are materials available locally and can be accessed?
    - Are there enough materials available?
    - Are the materials readily available to local villagers for maintenance?
3. Comfort and Privacy
    - Are the toilet seats comfortable?
    - Does the superstructure provide privacy?
4. Maintainability
    - Can the latrine be maintained easily?
    - Can broken parts be replaced without too much delay?
5. Scalability
    - Is the latrine design suitable at the village scale?
    - Can the design be implemented on a regional scale?
6. Social Acceptability
    - Is the design compatible with local customs and practices?
    - Is there local demand for this product?
7. Cost-effectiveness
    - Compared to other latrine designs, does it have a low upfront cost? And a low maintenance cost?
    - Is the latrine design cheap enough to be implemented on a larger scale?

3.3.1 Design Factors

Three major design factors will be discussed in this section:

- Superstructure stability and materials
- Pit stability and lining
- Fecal materials management

3.3.1.1 Superstructure and appropriate materials

Many latrines that have been built in the Northern Region, Ghana are Ventilated-Improved-Pit (VIP) latrines, with concrete superstructures (Akkakia, personal communication, 2010). There has been little experimentation with cheap superstructures with locally available materials. Compromise designs such as the use of concrete lined-pits but locally made superstructures are not commonly seen, primarily because of durability concerns. Ernest Akkaki, from REVSODEP, says that there is "not much chance of people maintaining a mud-superstructure latrine".

Concrete superstructures are more durable than mud/earth superstructures, which need to be maintained on a yearly basis, after every rainy season. At the same time, concrete superstructures can cost between several times that of a mud superstructure. The quality of earth structures varies depending on the soil type in that region, the construction expertise, as well as how often the users maintain it. Often, the walls are plastered with cow dung, which need to be maintained after the rainy season. With some degree of attention and care, local houses build with mud blocks have been reported to last 10+ years with minimal maintenance (Akkaki, personal communication, 2010). A list of common construction materials that could potentially be used in a latrine are shown in Table 3-2.

Table 3-2 Common Construction Materials in Ghana

Part of building	Common Construction Materials
Outside wall	Mud or mudbricks or earth; Cement blocks or concrete; Wood; Sandcrete or landcrete
Roof	Corrugated Metal Sheets; Thatch, palm leaves or raffia; Slate or asbestos roofing sheet
Floor	Cement or concrete; Earth or mud brick

Small-scale and appropriate technologies and the production of building materials from local raw materials have not gone beyond a pilot project phase in Ghana. Consequently, low-income groups are compelled to use expensive imported materials. Incentives must be given to local enterprises to produce local materials for roofing, walls, fittings, locks and keys (UN-Habitat 2004).

For over 30 years, research has demonstrated the appropriateness of low-cost building materials produced from local raw materials (Houben 2008). The results have not been properly disseminated in Ghana and are often presented poorly as low-income building materials for the poor, and not as low-cost building materials for low-income *and* medium/high income building construction.

3.3.1.2 Pit Stability

During the summer months with heavy rainfall, an unlined pit in the areas around PHW will likely collapse, as reported by several contractors who were interviewed. Local experience suggests that a strong pit lining is important.

A contractor reported that the groundwater table was at 60m below the surface near Taha Village during the month of November. (Akkakia 2011) However, the water table is likely to be higher during the rainy season. The groundwater table is not expected to rise to 10 feet below grade according to local engineers, thus the pits are expected to remain above the water table throughout the year. (Akkakia, personal communication, 2011)

Secondly, Joshua Hester, another MIT student conducted a study of clay content at several locations near the Pure Home Water factory. The results and methodology for that analysis can be accessed from his MIT thesis, "Measuring Clay Parameter Variation and Effects on Ceramic Pot Filter Performance" (Hester 2011). Additionally, soil samples at a pit on the Pure Home Water Factory site were collected and the data is presented below. Samples were taken at 1.5 feet increments from an eight-foot pit and were analyzed by a local university laboratory (Table 3-1).

Table 3-3 Particle Size Analysis at Pure Home Water

Layer	Soil Type	Soil Composition		
		%SAND	%SILT	%CLAY
1	Sandy Clay Loam	56.40	22.80	20.8
2	Loam	48.40	42.80	8.80
3	Loam	28.40	48.80	22.80
4	Clay	18.40	30.80	50.80
5	Clay Loam	34.40	38.80	26.80

According to Duncan Mara's design handbook, soils that contain more than 30% clay can be considered stable and pits do not need to be lined (Mara 1984). Our data suggests that pit-linings are necessary in this area, especially because of the rainy season during the summer months that is likely to cause pit collapsing.

3.3.1.3 Fecal material management

How does one empty pits full of human waste when full? In rural areas where access by roads is limited and emptying services are unavailable, there is no easy way of disposing of the human waste. Pits latrines in the area are designed to last between 5-10 years before they fill up, but afterwards the latrines will need to be relocated or emptied.

For composting latrines, maintaining a compost pile requires some degree of attention and is often the roadblock to successful implementation. The moisture, temperature, C:N ratio requirements make successful composting a difficult task to achieve in rural areas.

Alternatively, dehydration of the fecal material requires less complicated maintenance and may be more suitable. Pilot projects are conducted to explore the acceptability of different EcoSan designs with the local community. Additionally, data is needed in order to size the composting chambers properly. The amount of fecal material produced per person has been examined in various research papers, but real numbers will inevitably vary by region and cuisine. Conservative estimates are be used to size chambers.

3.3.2 PHW Preliminary Designs

Firstly, it was pre-determined that the project would explore the possibilities of Ecological Sanitation. Figure 3-1 categories various EcoSan latrine designs:

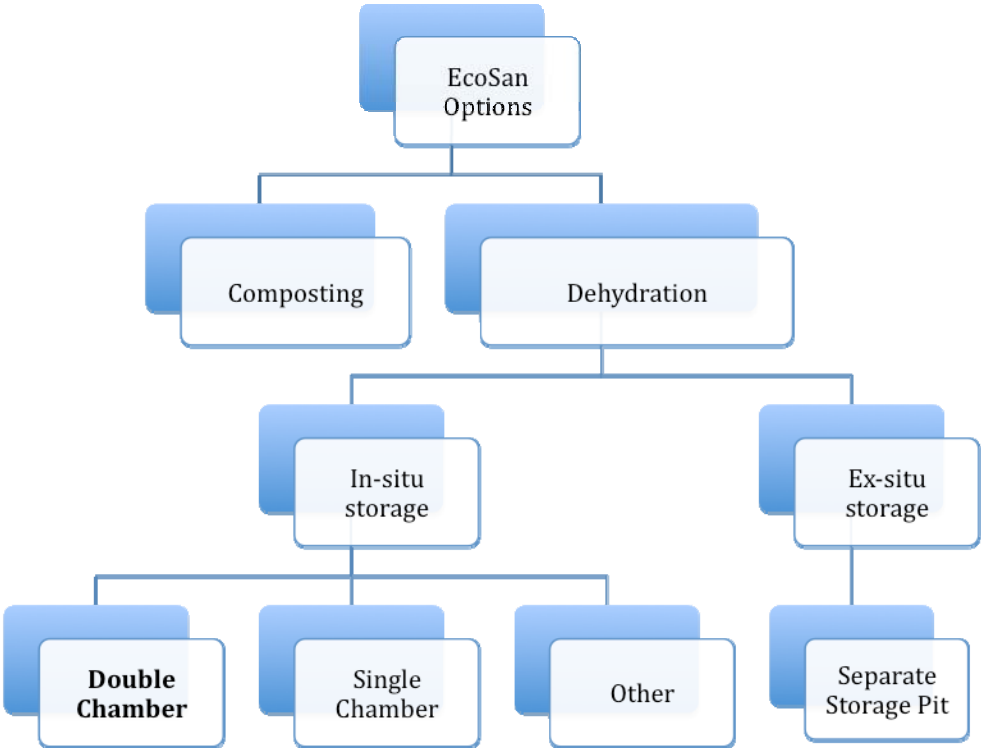


Figure 3-1 EcoSan latrine designs

Secondly, the choice between composting versus dehydration was simple: Maintaining a compost pile requires a high degree of maintenance, whereas dehydration only requires the fecal material to be left to dry out and stored until pathogens die-off to an acceptable level after 6-12 months. Because the Pure Home Water workers wanted a low maintenance design, a dehydration process was selected.

Thirdly, from REVSODEP experiences and interviews with PHW staff, it was found that movement of human fecal material is not very culturally acceptable among the local people. Thus, an in-situ storage option was chosen.

Finally, the decision to choose a double-chamber design was due to single chamber designs requiring more maintenance (shifting of new fecal material to one side and old fecal material to the other). Also, other in-situ storage methods, such as underground tanks/pits, are more costly and therefore eliminated as design options.

3.3.2.1 Design Schematics

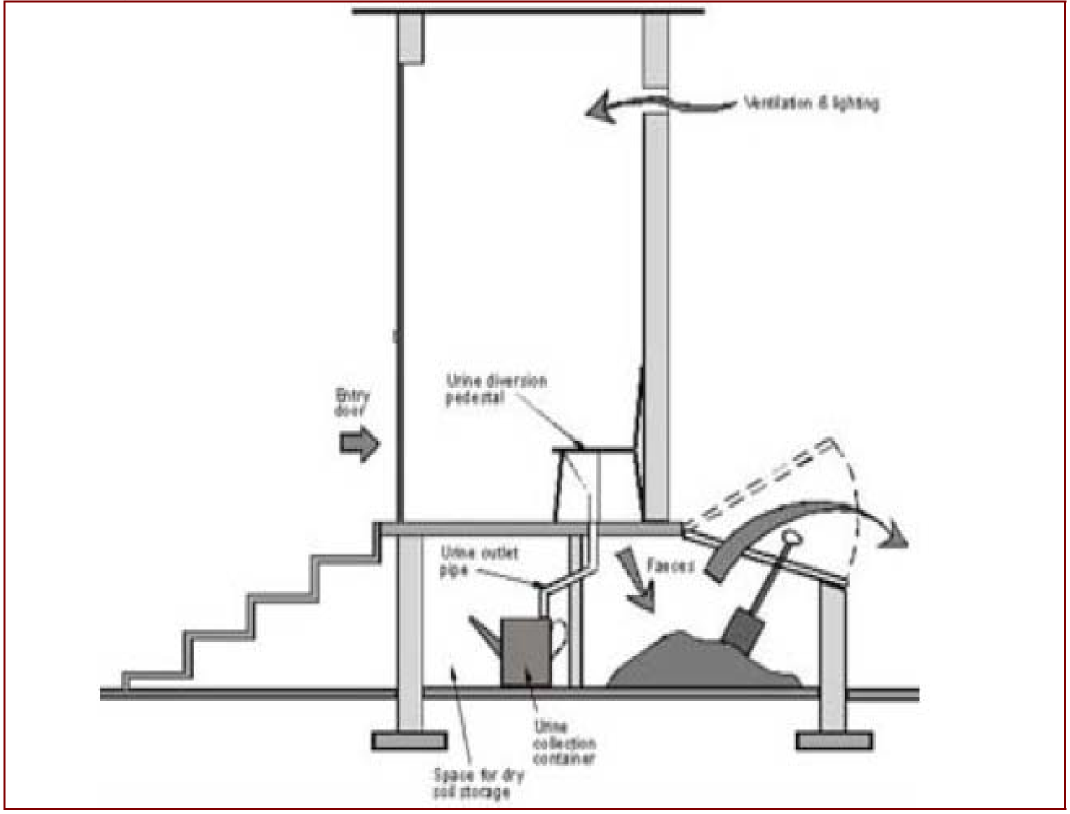


Figure 3-2 PHW Design Schematic (Sustainable Settlements 2011)

The PHW latrine follows the schematic shown in Figure 3-2. Importantly, the PHW Factory has been experimenting with rammed earth block production in the past year. The objective was to source locally available clay, mix it with small amounts of cement, to produce a strong and durable low-cost construction material. A typical comparison with concrete block is presented in Table 3-4.

While there was a variety of low-cost materials options available, including mud-brick, wattle and daub and wood, it was decided that the PHW rammed-earth blocks would be used for the superstructure walls because the PHW staff wanted a low-maintenance and highly durable latrine, which screened out the other options except concrete. Moreover, using the rammed-earth blocks would allow PHW to test the durability of the current formulation.

Table 3-4 Comparison of Rammed-Earth Block to Concrete Block (adapted from UN-Habitat 2009 and PHW research)

	Economy	**Durability**	**Environment**	**Resistance to Elements**
Rammed Earth Blocks	Typically very affordable, but depends on amount of cement mixed in and type of plastering	If well maintained, and plastered building can have a long life	Little waste or energy involved, unless cement is added	Medium/Strong
Concrete Blocks	1.5-2 times more expensive than rammed earth blocks (From research conducted using PHW production methodology)	Can last decades with little maintenance	A lot of energy needed to produce cement used in concrete	Strong

3.4 Pilot Project Results

3.4.1 PHW Project Summary

In January 2011, during the Independent Activities Period (IAP) of the MIT academic year, the author collaborated with local workers in the design and construction of a double-chamber, urine-diverting, dehydration EcoSan latrine on the site of the PHW factory. The project included sourcing appropriate local materials, optimizing the design to create the most cost effective latrine for the factory site, as well as conducting surveys in the local community in partnership with REVSODEP.

Using urine-diverting toilet seats (Figure 3-4) that were donated to PHW from REVSODEP, a double-chamber urine-diverting dehydration EcoSan latrine was successfully built on the site of the Pure Home Water factory. However, materials unavailability, miscommunication between workers and the author, as well as on-site alterations to the latrine design led to construction delays and escalated costs.

Figure 3-4 The type of urine-diverting seat used for the composting latrine

The total construction time was 21 days and the total cost to construct the latrine was GHS 936 (USD $674). Because the design of the latrine was new to the construction workers, and most of them had only previously built pit-latrines, there was some difficulty in communicating the details of the construction plans. Moreover, the workers would often make design recommendations based on their previous construction experience, but oftentimes these recommendations were not applicable to the project at hand.

Additionally, there were difficulties when initially presenting the project plans to the factory manager, John Adams, as well as the local workers. The concept of Ecological Sanitation was new to them and the design plans caused some confusion among the PHW staff. Concern was raised with the management of the fecal material. In particular, the Muslim workers were particularly unreceptive to the idea of being in contact with fecal material, especially during the maintenance phases where the feces pile needed to be turned and mixed. The Christian workers, on the other hand, were accepting of the idea of handling fecal material.

It must be noted that composted animal fecal material and food scraps was commonly used in subsistence farming around Tamale (Akkakia 2010). However, the concept of re-using human waste was new to most of the workers. (As it would likely be to many people in North America & Europe as well.)

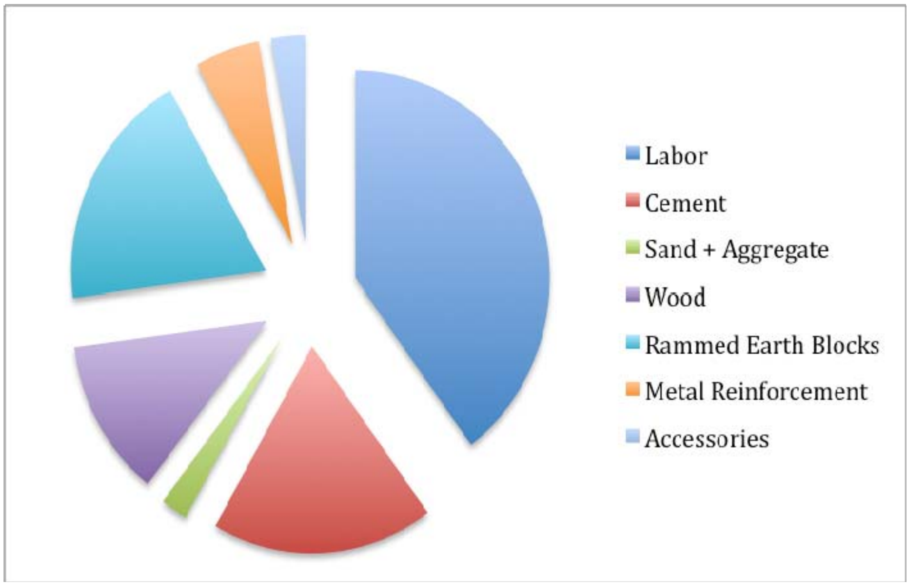
Figure 3-5 The finished structure with the construction team

3.4.2 Final Costs

The materials and labor costs for the PHW latrine are presented in Table 3-5 and Figure 3-3:

Table 3-5 PHW Latrine final costs (GHS)

	Material	**Quantity**	**Price (GHS)**	**Total Cost (GHS)**	**Total Cost (USD)**
Foundation	Cement (bags)	3	15	45	32
	Aggregate (per wheelbarrow)	9	2	9	6
	Sand (per wheelbarrow)	6	1	6	4
Chamber Structure	Rammed Earth Blocks	90	0.5	45	32
	Cement (bags)	2	15	30	21
Seat	Rammed Earth Blocks	22	0.5	11	8
	Urine-diverting seat	1	80	80	57
Floor Slab	Cement (bags)	2.5	15	37.5	27
	1/2 Inch Rod (18 feet long)	5	8	40	29
Superstructure Walls	Cement (bags)	3	15	45	32
	Rammed Earth Blocks	210	0.5	105	75
	Sand	4	1	4	3
Roof	Corrugated Tin	2	7.5	15	11
	Nails	10	0.5	5	4
	1x4	6	4	24	17
Main Door	2x6	1	12	12	9
	WaWa Board	2	9	18	13
	Hinge	2	2	4	3
Chamber Door	2x6	1	12	12	9
	WaWa Board	2	18	36	26
	Hinge	4	2	8	6
Accessories	Lock/Key	1	2	2	1
	4" Pipe	1	9	9	6
Labor	Steel banner	1	10	10	7
	Carpenter	3	10	30	21
	Mason	15	10	150	107
	Mason	15	10	150	107
			Grand Total	**GHS 943**	**$674**



3.4.2.1

Figure 3-3 Distribution of Costs (out of a total of GHS 936/US 674)

3.4.3 Follow-up

Because time was limited during January, there was insufficient education and training of the PHW Staff in using the latrine. In March 2011, a follow-up was conducted, and it was found that no one was using the latrine. The latrine door was locked and only one person had a key, so it was inconvenient for workers to ask for the key each time. It was also unclear whether the workers fully understood the concept of EcoSan and how to use the latrine, despite attempts to educate the staff in January. It is expected that during summer 2011, an MIT team will return to Ghana and conduct a follow-up investigation as well as use the EcoSan latrine and encourage others to do so.

3.5 Conclusions and Recommendations

Through the PHW project, it was found that EcoSan latrine designs are significantly cheaper than a VIP latrine. The PHW EcoSan latrine costs GHS 936 (US $674) whereas a standard household, two-seater, single-pit VIP latrine costs over GHS 2000 (US $1420) (Lau 2011). Additionally, improved materials selection can significantly reduce costs of all latrines.

Adoption of the technology remains difficult, but possible. At the PHW factory, additional training of the workers is needed for the latrine. In 2010 REVSODEP implemented a successful EcoSan pilot project and reported that several households were using their EcoSan pilot latrine.

3.5.1 Recommendations

- What are latrine designs are appropriate for rural areas in Ghana?

Move away from single-pit VIP latrine designs; Pilot and scale-up other designs, including the Bin-Bin, Sanergy and Easy latrines (Lau 2011), in order to assess their social acceptability and costs. In the villages surveyed, only standard VIP latrines were found. Organizations should explore other low-cost designs and conduct pilot projects to assess their viability through a Co-Evolutionary planning process. EcoSan designs should be piloted and attempted to be scaled-up at a village and then regional level; Research on user acceptability needs to be conducted.

- What design adjustments can be made to reduce latrine costs?

Investigate low-cost building materials and supply chains that can reduce latrine costs. Pilot and test rammed-earth blocks, mud-bricks and any other suitable, locally available building materials. Investigate centralized latrine manufacturing processes.

For example, using locally made rammed-earth blocks for latrine superstructure or a thatched roof instead of a corrugated metal roof provide significant cost savings. A centralized manufacturing process to produce pre-cast concrete linings or thin-shell concrete superstructures, and a design that allows ease of assembly may further reduce costs. Additionally, EcoSan toilet seats imported from Europe are a major part of the latrine cost and cheaper alternatives should be designed.

- What can be done to improve collaboration between international aid agencies, local NGOs and government workers?

Create an easily accessible online database that summarizes various sanitation projects conducted by different organizations in Ghana to allow for collaboration and idea sharing. As seen in some villages, two or three different organizations may provide latrines for the same village without ever interacting each other. It is important to understand the situation in the area that you are working and to learn from those already with experience, as with REVSODEP. There are many actors involved with sanitation, and the author envisions a website/online database that would allow for effective communication among different parties. Collaboration and communication will be crucial for large-scale sanitation provision.

3.5.2 Final Remarks

Poor sanitation planning and latrine designs have led to ineffective projects with little impact on the local standard of living. We must rethink our attitudes and approaches to sanitation provision! Tackling these serious challenges will require the collaborate efforts of government workers, international aid agencies, local NGOs, and rural villagers. It is the hope that the information presented in the report will provide a hands-on perspective for sanitation projects in rural Ghana and serve as a starting point for the many changes that are to come.

4 Measuring Clay Property Variation and Effects on Ceramic Pot Filter Performance

4.1 Research Objectives

In order to help PHW meet its goal of making consistent and marketable filters, the objectives of this thesis are as follows:

1. Measure the variation of clay plasticity and particle size distribution between the two sites supplying the PHW factory using ASTM standards. These parameters will be measured because it is expected that they will have a significant impact on the performance of the filters.

2. Make filters using samples from the two clay source sites and compare their performance by measuring the removal of sediment and bacteria from contaminated source water passed through the filter. Turbidity, coliform, and *E. coli* will be measured before and after filtration. Turbidity will be measured using a Hach 2100P turbidimeter, and bacteria will be measured using membrane filtration and the IDEXX Quanti-Tray® method.

3. Based on the results of these tests, make a recommendation for which clay site to use for filter production.

4.2 Clay Characterization

The first goal of this study is to measure the variation of clay parameters within and between the two clay sites available for use by PHW. One of the sites is in Gbalahi, a village approximately one mile away from Taha and the PHW factory. PHW has negotiated an agreement with the chief and elders of the community of Gbalahi for the use of the clay from this site in exchange for traditional one-time gifts and agreeing to employ community members in clay digging and factory production. The other site is in Wayamba, which is approximately 5 miles north of central Tamale on the Bolgatanga highway (Figure 4-1). PHW has a 99-year lease on this site. In addition to these two planned clay sites, a thin lens of clay was discovered at the PHW factory site while digging a hole for a rainwater harvesting tank.

4.2.1 Sampling Methodology

Twelve samples were taken from the Gbalahi site and twelve were taken from the Wayamba site. Though the parcels of land have slightly different geometries, a similar grid pattern (approximately 15 meters square) was used in both. For the Gbalahi site, a grid of 2 holes by 6 holes was used, while at the Wayamba site, a grid of 3 by 4 holes was used, each hole spaced approximately 15 meters from every other hole at both sites. Local workers were hired to dig until they reached clay, which was found about 60 cm below the surface on average at both sites. The samples were collected over two days total and kept in separate buckets with covers to maintain sample purity and labels to identify which hole they came from. After all samples were collected, large pieces were broken up with a shovel to speed up the drying process, as is done with regular clay processing at the PHW factory. The samples were then spread in piles on a tarp to air dry so that they could be ground and sieved to remove the gravel. All samples dried in the sun for over 48 hours at an average air temperature of 30-35°C and then were returned to the labeled buckets. Three samples were also collected from the factory site in Taha, but these samples had already been collected and dried for several weeks. It is possible that this could have contributed to differences in the clay test results for those samples.

Figure 4-1: Approximate location of the clay sites in Tamale (Google Maps 2011)

4.2.2 Atterberg Limits Tests

The Atterberg Limits tests are a measure of soil plasticity. Originally, Albert Atterberg defined six "limits of consistency" that describe the behavior of soils. They included the upper limit of viscous flow, the liquid limit, the sticky limit, the cohesion limit, the plastic limit, and the shrinkage limit, but today "Atterberg Limits" generally refers to just the liquid limit, plastic limit, and sometimes also the shrinkage limit (ASTM 2010). These limits are a measure of the water content at which the soil behaves in a certain way.

As water content decreases, the soil exhibits a range of behaviors from liquid to plastic solid. On this continuum, the liquid limit marks the boundary between the semi-liquid and plastic states, and the plastic limit marks the boundary between the plastic and semi-solid states. The difference between the liquid limit and the plastic limit gives the *plasticity index*, the range of water contents over which the soil behaves as a plastic solid. This is relevant to the production of ceramics because only soil that behaves as a plastic solid can be molded or pressed into pots that retain their shape.

The liquid limit and plastic limit are somewhat ambiguous boundaries. The standardization of methods for determining these values has allowed the comparison of these limits between different soils. ASTM Standard D4318 ("Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils") was followed as closely as possible, but due to time constraints and limitations of working in the field, some adjustments had to be made (ASTM 2010). For example, there was only time for one plastic limit test for each sample rather than the two recommended in the standards. Other significant deviations are explained in footnotes as appropriate.

4.2.3 Particle-Size Distribution Analysis

The purpose of this test is to see what percentage of the soil is made up of fine particles ("fines") and how uniform or varied the particle sizes are. For coarse soils such as gravels and sands, particle size analyses are done by pouring a sample through a set of sieves that decrease in opening size. The mass retained on each sieve is then measured to obtain the particle size distribution. This is infeasible, however, for silts and clays since the sieves would have to be impractically fine and would likely be easily damaged. For finer soils, particle-size analyses are carried out by observing the settling of the particles in a water column over a period of at least 24 hours.

A sample of soil is mixed with a dispersing agent (in this case, a 40-gram-per-liter solution of sodium hexamethaphosphate) to separate the particles from each other, and the sample is then mixed into a column of water. At specified time intervals, a glass bulb called a hydrometer (Figure 4-4-2) is inserted into the water column. The buoyancy of the hydrometer, measured by reading marks on its side, is proportional to the density of the water, which decreases as the particles settle out of the water column. The time it takes for particles of a given diameter to settle is governed by Stokes' law, so combining the buoyancy measurements with the time at which they were taken yields the amount of each particle size in the soil.

Due to time and material constraints, researchers at the Savanna Agricultural Research Institute in Tamale performed this test after my departure. following a procedure similar to ASTM Standard D422 (ASTM 2007).

4.3 Filter Production

Filter production began with drying, pounding, and sieving the clay samples as described in Section 4.2.1. Portions of the sieved samples were set aside for testing, but most of the samples were retained in the labeled buckets they were originally collected in.

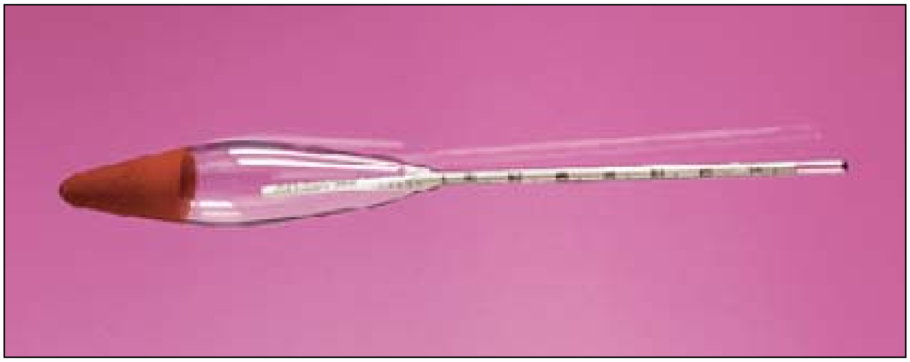


Figure 4-4-2: The VWR Soil Analysis Hydrometer[3]

4.3.1 Preparing the Filters for Firing

The filter recipe recommended by Miller and Watters was used (Table 4-1), with the exception that grog was added since the potter women from Gbalahi and the factory manager felt strongly that it should be included (Miller 2010; Watters 2010). This was an acceptable adjustment because Miller and Watters found no significant impact of grog on filter performance.

Table 4-1: Clay recipe used[4]

Dry material	Quantity Recommended by Watters and Miller (lbs)	Quantity used (lbs)
Clay	11 (68.8%)	7.75 (68.9%)
Grog	1 (6.3%)	0.75 (6.7%)
Rice husk	4 (25.0%)	2.75 (24.4%)
TOTAL	16	11.25

The potter women from Gbalahi used the following procedure to mix, press, and dry the filters:

1) **Composition:** Following the proportions from the recommended clay recipe, the dry materials were measured by weight with a 44-pound scale and then mixed together on a tarp. The total amount of clay was scaled down because Watters and Miller used a press that required more clay per filter[5]:

---

3. [3] Photo credit: VWR International, www.vwrsp.com

4. [4] The scale only measures 1/8 lb increments, so there was some error in the measurements, but not enough to significantly impact the relative proportions of each material, as 1/8 lb corresponds to 1.1% of the total mass.

5. [5] Watters and Miller used a flower-pot style mold in a portable Potters for Peace press, while a paraboloid mold in a Mani press was used here.

2) **Mixing:** An indentation was made in the center of the mound of dry materials and water kneaded in until the clay reached the right consistency, which the potters know intuitively from experience. Weighing the clay at this point revealed that an average of 5.5 lbs (2.5 L) of water were added to each mixture.
3) **Kneading:** After adding the appropriate amount of water, the clay was kneaded for an additional 3-5 minutes on the tarp to achieve a thorough mixture[6].
4) **Weighing:** The entire amount of clay was weighed and some clay removed until approximately 16 pounds remained, the amount required to make one filter.
5) **Shaping:** To start shaping the clay, the clay was pressed by hand onto the bottom of an inverted, previously fired filter.
6) **Mold preparation:** Both the male and female molds of the Mani press were covered with a large plastic bag and a painted wooden ring (a "bat") was placed on top of the bag on the male mold. This bat allowed the filter to be removed more easily from the press at the end of the process.
7) **Pressing:** The clay was formed on top of the male mold and the male mold was guided into place under the female mold.
8) The female mold was lowered with the hand crank and the corresponding cable allowed to become completely slack.
9) A jack was rolled into place above the female mold, and a lever attached to the jack.
10) The jack was operated until the female mold almost touched the wooden ring on the male mold. Clay squeezing out on all sides indicated that the filter was pressed evenly.
11) The jack was rolled away from the center of the female mold and the female mold was raised by hand crank, taking care to not raise it past the level of the hanging jack.
12) The male mold was guided out from underneath the female mold, carefully removing the plastic bag from the female mold.
13) **Minor repairs:** Any minor indentations or imperfections were repaired by hand at this point. If significant sections of the rim were missing due to the clay not being centered at the beginning of pressing, the filter was removed, the clay re-kneaded, and the pressing process restarted from step 5).
14) **Drying:** The filter was removed from the male mold, supported by the wooden ring, and the plastic bag from the male mold was carefully removed from under the filter.
15) The filter was placed on a drying rack in the shade[7].
16) After drying for 2-3 days, the filters were taken off the wooden rings, and any unnecessary fragments on the rim were removed and smoothed over.
17) The filters were then dried for an additional 4 days in the shade[8], and any cracks that began to form were filled in. For some of this time, the filters were on the drying racks, and for at least one day they were on the floor of the factory while the drying racks were under construction.

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6. [6] For some of the filters, the clay may have been kneaded for less than 3 minutes.

7. [7] Filters G3, G6, G7, W1, W7, W8, and W10 were pressed on January 12th, and the rest were pressed on January 13th. These seven filters, therefore, had one extra day of drying time.

8. [8] Drying in the shade is sufficient in the dry season since there isn't much humidity in the air. In the wet season, the filters would potentially be dried in the sun at this point. If that were the case, care would have to be taken to rotate the filters 90 degrees at regular intervals during the day.

4.3.2 Firing the Filters

The filters studied in this thesis were fired on January 19th, 2011 in the larger of the two Mani kilns. The Mani kiln is a downdraft kiln, which is more efficient than updraft kilns because it causes heat to take a longer path through the kiln. The larger Mani kiln was constructed between June and November 2010 and has a capacity of 50 filters (twice the capacity of the smaller "research" kiln that was constructed in January 2010). The filters were stacked on their sides in a way that would allow them to be fired as evenly as possible. The firing curve for the January 19th firing shows temperature readings taken at regular time intervals throughout the daylong process (Figure 4-3).

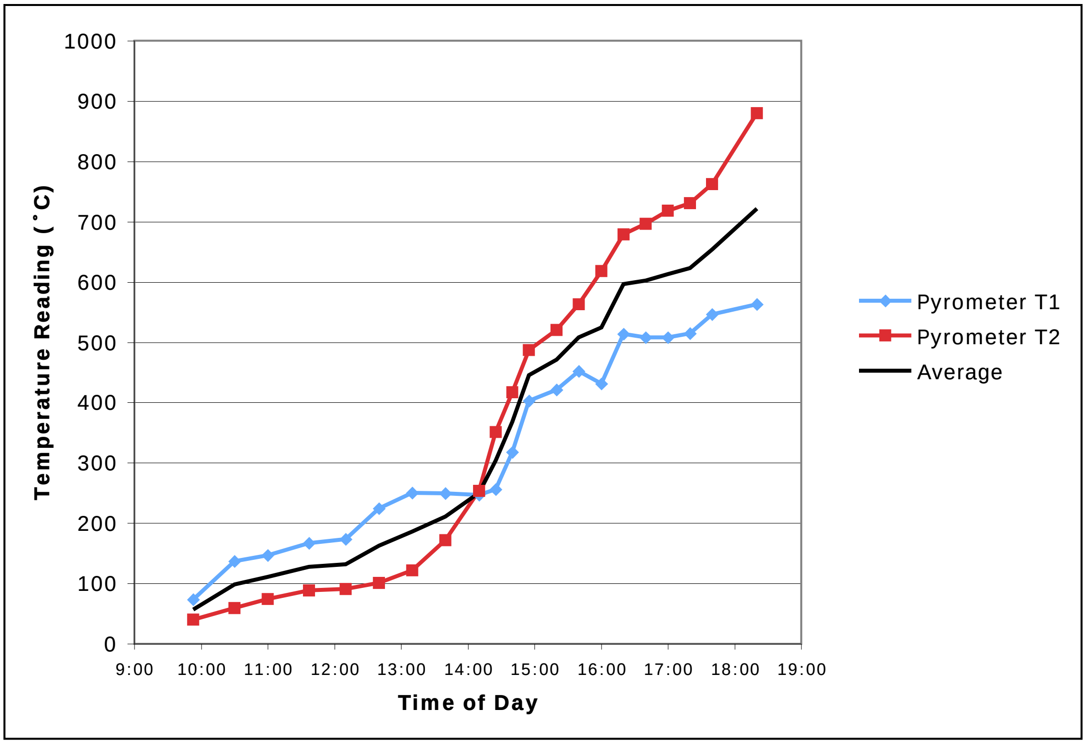

Figure 4-3: Firing curve, January 19, 2011

For the first several hours of firing, a "candle fire" is lit. The purpose of this low-temperature fire (20-120˚C) is to evaporate any remaining moisture in the pore space of the filters and kiln interior (CMWG 2010). During this stage, the door of the kiln is almost completely sealed with bricks, leaving three more courses of bricks at the top to be filled in later. Leaving a gap at the top of the door allows steam to escape more readily. This portion of the firing lasts for about four hours, or until black smoke is seen coming out of the chimney – an indication that the combustible material is burning out. After this, the temperature is raised by sealing up the kiln door completely. The recommended firing schedule determines how much time the kiln should be at each temperature above this. Temperature is increased at a more gradual level at points where the filters are more prone to cracking, especially at the quartz inversion, (550-573˚C). At the end of the firing, the kiln shouldn't get above 887˚C because the filters could become completely vitrified (clay particles welded to glass) and have no porosity left. A set of three pyrometric cones (011, 012, and 013)[9] are used to measure the heat-work done in the kiln. When the 013 cone bends (called the "guide" cone), it is an indication that the firing is almost done. When the 012 cone bends, it is time to let the fire die out and begin the cooling process. If the 011 cone bends, it is a sign that the filters have been over-fired. The kiln is left sealed overnight and allowed to cool gradually for at least 12 hours to prevent cracking.

4.4 **Quantification of Performance**

In order to determine the effects of clay parameters, filter performance was determined by measuring the flow rate of water though a saturated filter, the removal of turbidity, and the removal of coliform bacteria. All testing was intentionally done on filters without colloidal silver application.

4.4.1 Flow Rate Testing

The effectiveness of the filters is directly related to the size of the pores in the fired clay. Proper removal of suspended particles and microbial contaminants depends on the pores being small enough to prevent sediment and bacteria from passing through and large enough to allow water to flow at a rate that will provide sufficient daily drinking water to users. The maximum flow rate, measured when the filter is full, must therefore be within a certain range (1-2.5 liters per hour is what Potters for Peace recommends[10]). After soaking the filters overnight in a saturation tank, the following procedure was followed by MIT Master of Engineering teammate Shanti Kleiman to complete these tests, as described in her thesis (Kleiman 2011):

> The PHW factory made a decision to test filters with a calibrated T-device rather than testing effluent, a specified volume in a collection container. Testing with a T-device will allow us to rapidly measure the drop in water level in multiple pots at once without having to remove the ceramic filter element from the plastic bucket to collect the effluent or having to add water to the each ceramic filter element to determine how much the water level dropped. Using a T-device also ensures that filters are filled to the same level each time providing more consistent testing conditions for measuring maximum flow rate. [...]
>
> On January 21 and 22, 2011, fourteen buckets were set up around the perimeter of the saturation tank to test the filters in two shifts. Filter elements were placed inside the buckets and water was filled up to 21 cm. Miller found in his measurements that 21cm was the approximate height that aligned with the bottom of the filter lip. He concluded that that should be the maximum fill line because flow through the filter lip would distort results

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9. [9] As recommended by Manny Hernandez. Curt and Cathy Bradner recommend 010, 011, and 012 cones.

10. [10] The range of acceptable flow rates will be confirmed by further bacteria testing. Curt and Cathy Bradner suspect that a reduced flow rate may be necessary to ensure the quality of filtered water. Their rule of thumb is that 0.35 L/hr of flow per liter of filter capacity is generally safe. That gives a target flow rate of 2.1 L/hr for the 6L paraboloid filter and 3.2 L/hr for the 9L flowerpot filter.

(Miller 2010). The T devices were placed in each filter element and a timer was set for one hour. After one hour the drop in water level was recorded next to the filter number and the next round of filters were placed in the buckets for testing.

The results from the flow rate tests are shown in Section 4.6.2

4.4.2 Reduction of Turbidity

Though turbidity itself is typically characterized as a physical characteristic of drinking water and as such not a primary health concern but rather an aesthetic characteristic, an increase in turbidity is potentially associated with an increase in pathogens because microbes attach to particles. It is perhaps the most widely used non-microbial indicator of water quality (OECD/WHO 2003), and is commonly determined by measuring the scattering of light through a sample of water, in Nephelometric Turbidity Units (NTUs), using a turbidimeter. A Hach 2100P turbidimeter was used to measure the turbidity of highly turbid local source water before and after filtration in each filter, and this data was used to calculate percentage removal.

4.4.3 Reduction of Microbial Contamination

Since measuring the presence of harmful pathogens is often difficult, it is common to look for “indicator” organisms instead, such as coliform bacteria. While not pathogenic themselves, they are indirect measures of water quality (OECD/WHO 2003). There are numerous tests that make use of indicator bacteria including presence-absence, membrane filtration, and most probable number (MPN) tests. The Quanti-Tray ® test is a form of MPN test and was used in this study because of its speed and accuracy. Its drawbacks are that the supplies are expensive (approximately $6/test) and bulky, making it hard to transport from the USA to Northern Ghana. As a result, subsequent filter testing relied on the membrane filtration test using m-ColiBlue24® media (approximately $3 per test depending on the media used)

4.5 Additional Work since January 2011

From 2010 to January 2011, factory construction had been taking place side-by-side with “research” filter production. However, as of February 2011, the factory was essentially complete and attention could now turn to full-scale production. Curt and Cathy Bradner (referred to throughout as “Bradner”) were hired in February 2011 to get the Pure Home Water factory up and running at full capacity, to train the factory staff in filter production, and to ensure high quality control. From March 10 to April 5, they made and fired filters, adjusting parameters and testing the effects on filter performance. They made several improvements to the manufacturing process and helped add quality control measures at many steps.

In addition to improving the manufacturing and quality control processes, Bradner continued to experiment with the clay recipe, adjusting the percentage of rice husk and also testing different mixes of Gbalahi clay and Wayamba clay. They made each mixture in 66-lb batches (instead of the 25-lb batches made by the author), enough to make 5 filters. The amount of rice husk was measured as a percentage by weight of the 66-lb mixture, and the clay percentages were calculated as a ratio of the remaining weight. Therefore, a mixture with 12% rice husk and a 75/25 ratio of Wayamba clay to Gbalahi clay had 8 lbs of rice husk, 43.5 lbs of Wayamba clay, and 14.5 lbs of Gbalahi clay. Grog was not used in their mixture because in their experience there are no significant advantages to using it, as confirmed in Miller's 2010 thesis.

After firing, only filters that passed the bubble test proceeded to the flow rate test, and only filters that passed the flow rate test (had flow rates below 3 L/hr) were tested for *E. coli* removal.

4.6 **Results**

This section summarizes the results of this research. More detailed data can be found in (Hester 2011). All box and whisker plots in this section show four quartiles and the mean values for each data set. The bottom and top of the thin, vertical lines represent the minimum and maximum values. Mean values are displayed as points connected by a thick, colored line.

4.6.1 Clay Characterization

4.6.1.1 Plasticity

The following tables and figures summarize the results from the Atterberg Limits tests described in Section 4.2.2.

Table 4-2: Average water contents of the three clay sources

Source	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)
Gbalahi	62.96	24.54	38.42
Wayamba	57.26	21.84	35.42
Taha	51.05	16.80	34.26

Recall that the plasticity index is the range of water contents over which the clay exhibits plastic behavior, and it is calculated by subtracting the plastic limit from the liquid limit. These results reveal that the Gbalahi clay is the most plastic of the three clays, as indicated by its plasticity index, but all of the clays could be characterized as highly plastic.

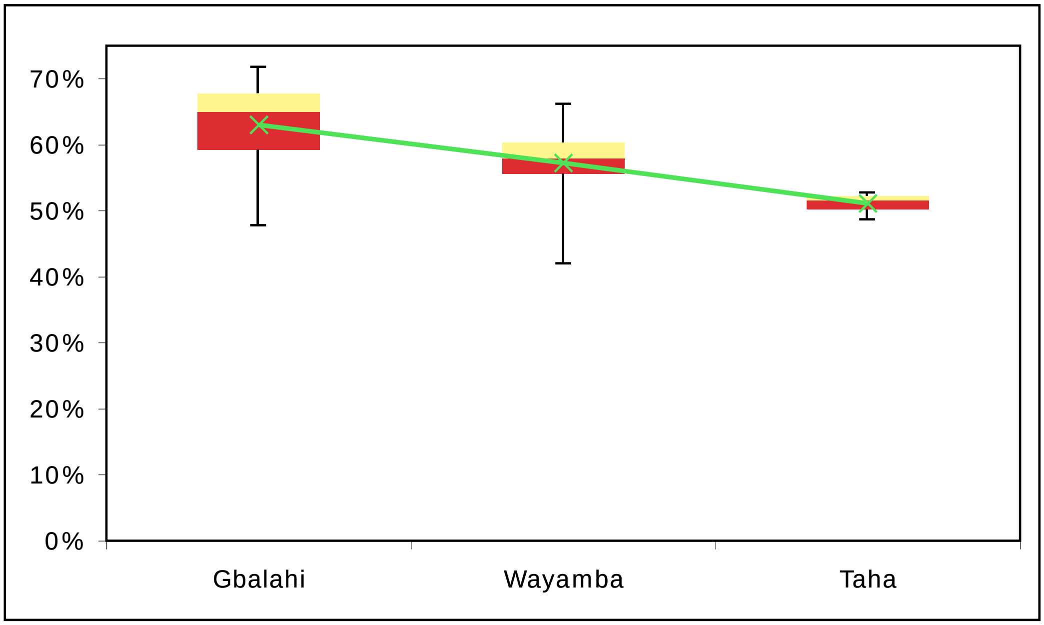

Figure 4-4: Liquid limit box plot

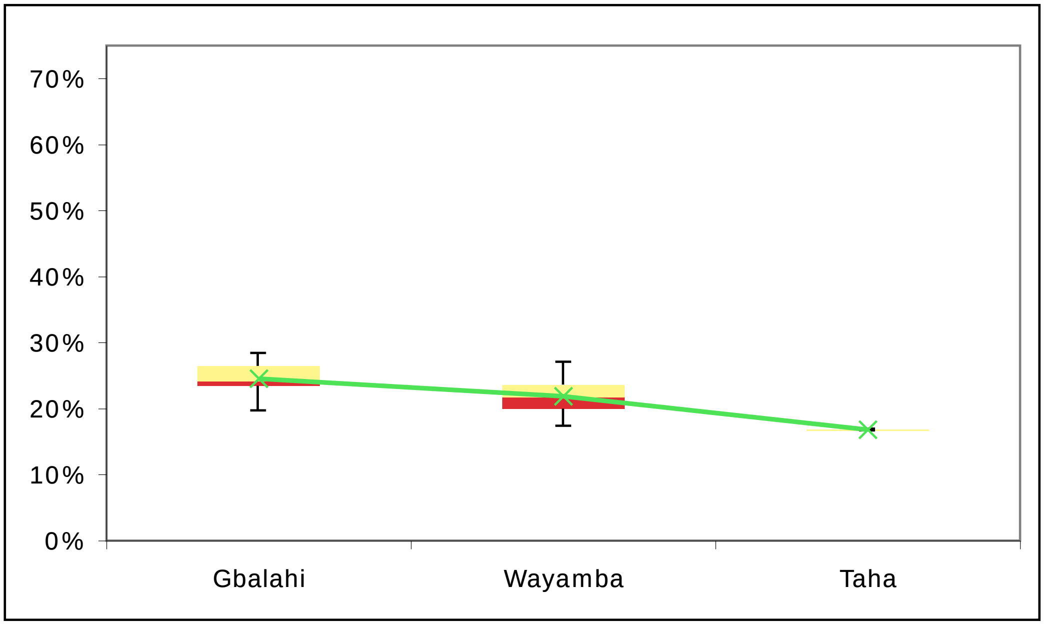

Figure 4-5: Plastic limit box plot

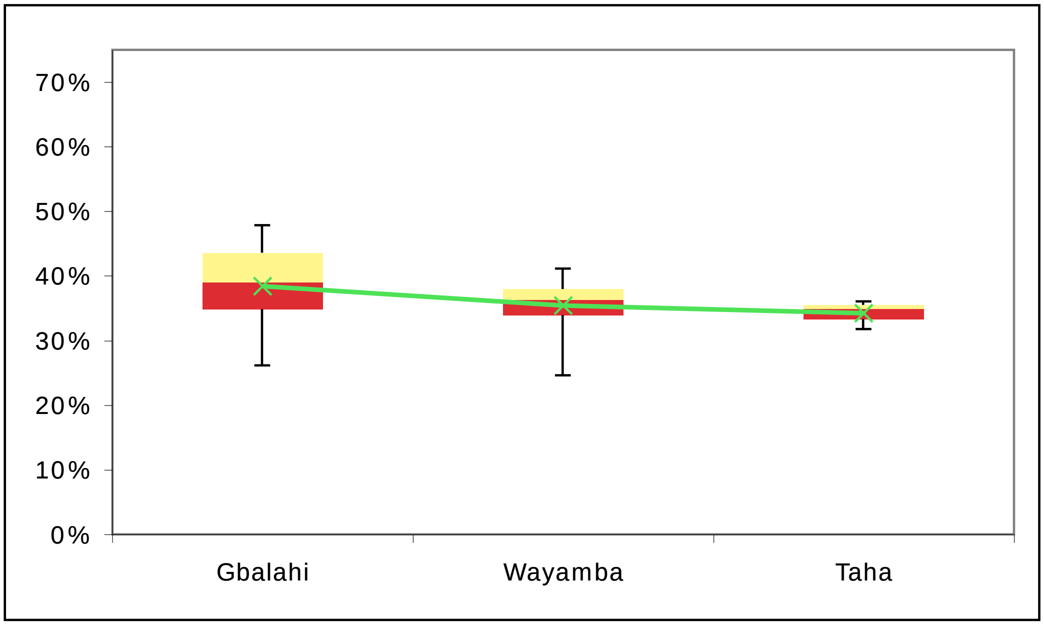

Figure 4-6: Plasticity index box plot

4.6.1.2 Percent Clay

Table 4-3, Figure 4-7 and Figure 4-8 are a summary of the data from the particle size analysis[11] described in Section 4.2.3.

Table 4-3: Particle size distribution summary (average percentage by weight)

Source	Sand (%)	Silt (%)	Clay (%)
Gbalahi	13.55	26.99	59.47
Wayamba	19.61	29.49	51.90
Taha	28.40	24.80	46.80

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11. [11] Testing and analysis done by the Savanna Agricultural Research Institute in Tamale, Ghana.

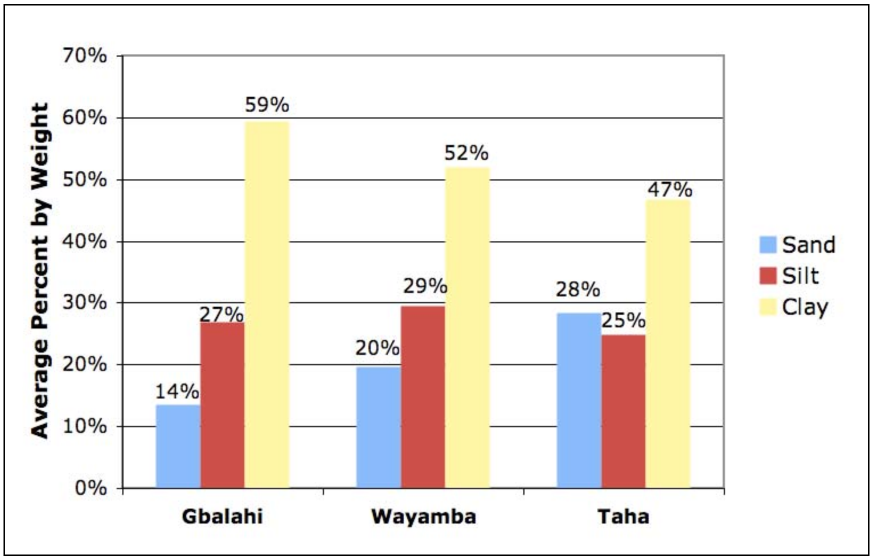


Figure 4-7: Particle size distribution, organized by source

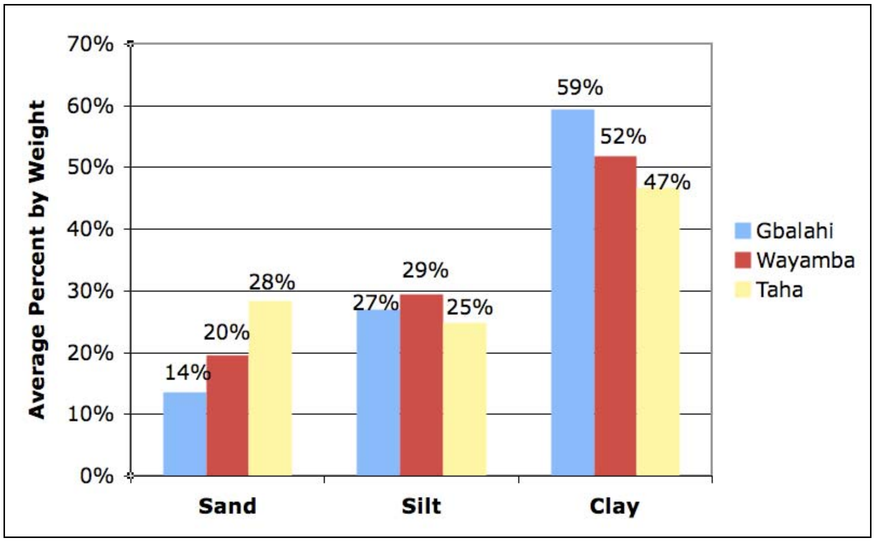


Figure 4-8: Particle size distribution, organized by size

The amount of silt is relatively constant for all three sources, but there is a marked decrease in percentage of clay and increase in that of sand from Gbalahi to Wayamba to Taha.

4.6.2 Filter Performance

4.6.2.1 Flow Rate

Table 4-4 is a summary of the data collected in the flow rate tests described in Section 4.4.1:

Table 4-4: Flow rate summary [L/hr]

Source	Average	Standard Deviation
Gbalahi	3.1	1.2
Wayamba	4.9	0.5
Taha	4.9	0.2

Although the filters made from the Gbalahi clay had the lowest average flow rate, they also had the highest standard deviation.

Figure 4-9: Flow rate box plot

4.6.2.2 Reduction of Turbidity

Table 4-5 is a summary of the turbidity percentage reduction from the unfiltered to filtered water, as described in Section 4.4.2. The Gbalahi clay filters had much higher removal of turbidity on average (70.4%, vs. 56.8% for Wayamba). The filters made with the Gbalahi clay and those made with the Wayamba clay had a similar standard deviation. The Taha filters performed the poorest in terms of turbidity reduction (49.4%).

Table 4-5: Turbidity reduction summary

Source	Average (%)	Standard Deviation (%)
Gbalahi	70.4	11.49
Wayamba	56.8	11.54
Taha	49.4	3.49

Figure 4-10: Turbidity reduction box plot

4.6.2.3 Reduction of Microbial Contamination

Table 4-6 is a summary of the results from the microbial tests described in Section 4.4.3. The filters made from Taha clay had the highest reduction in *E. coli* (90.6%), which is surprising since they performed least well in turbidity reduction (49.43%). It should be noted that the microbial contamination measurements were taken on two different days, and thus there were two different starting levels of *E. coli* contamination (most probable numbers of 2419.6 and 547.5), which might have biased the results.

Table 4-6: Percent *E. coli* reduction

Source	Average (%)	Standard Deviation (%)
Gbalahi	84.3	16.65
Wayamba	86.7	10.06
Taha	90.6	1.31

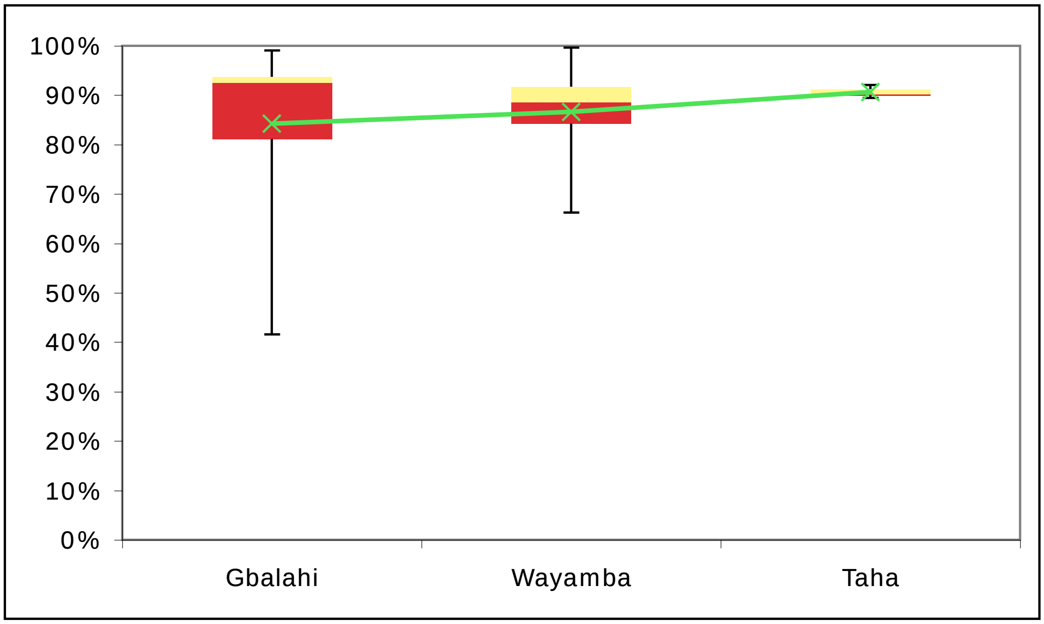


Figure 4-11 *E. coli* reduction box plot

Due to insufficient dilution of contaminated source water, total coliform colonies were too numerous to count both before and after filtration for many of the filters, so no conclusions about total coliform removal can be made.

4.7 Discussion

This section explores the statistical significance of the results from the research done in January 2011 by the author and research partner, Shanti Kleiman, who collaborated on the flow rate, turbidity, and coliform removal testing. Only the Gbalahi and Wayamba sites were considered in these analyses because of the dramatic difference in sample size, sampling methodology, and limited clay availability of the Taha clay (only a small quantity was found). Also, the statistical analysis is much more straightforward with only two samples and the conclusions can be more useful for the purposes of commercial filter production.

4.7.1 Testing for Statistical Significance

The goals of this thesis are to measure the differences in the clay from the two sites, establish the effects of the clay parameters on the filter performance, and determine which site, if either, is better for the factory to use. For questions about whether or not there was a significant difference in a parameter between the two clay sites (either in the clay sample or performance of the filters made from the samples), a Student's t-test was used to determine whether there was a statistically significant difference between the population means. In this method, the difference between the two sample means is normalized by the square root of the sum of the sample variances:

$$t = \frac{\overline{x}_1 - \overline{x}_2}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

$\overline{x} =$ sample average

$s^2 =$ sample variance

$n =$ sample size

The critical t-value is that which corresponds to a chosen threshold probability (5% is a typical value) that the means are, in fact, the same. For a two-tailed test, if the absolute value of the t-value is greater than 2.2, then there is a less-than-5% probability that the means are the same and the null hypothesis (that the two means are equal) can be rejected.

For questions about whether or not certain parameters were linked, regardless of what site they came from, linear regression was used to see if there was a statistically significant relationship between them. The R^2 value from the linear regression is a measure of how well the data points align with the best-fit line. A t-test related to the one described above can also be used to calculate the probability that there is a relationship between the two parameters. In this case, the null hypothesis is that the apparent relationship between the two parameters is due to random chance.

The Excel 2003 Data Analysis ToolPak was used for all of these tests.

4.7.2 Differences Between Clay Sites

Data for each parameter was organized into two groups according to clay source, and a t-test carried out to determine if there is a significant difference between the population mean of the two groups. Results are shown in Table 4-7.

For any given test, rejecting the null hypothesis that the two population means are equal indicates that there is a significant difference in the parameter between the two clay sources. The parameters that are significantly different are the percent clay in the sample, the flow rate of the filters, the turbidity reduction, and the percent of the sample passing the sieve during initial preparation of the clay (ie, how much gravel there was in the raw sample). It should be noted that failing to reject the null hypothesis does not prove that it is true. Rather, it just can't be proven with the given data that it is false. Therefore, it cannot be concluded that population mean of the other parameters are the same across both clay sources.

Table 4-7: T-test results for all parameters

Parameter	t Stat	Two-tail P-value	Statistically significant difference?
Depth of sample	-1.596	0.13	No
Plasticity index	1.270	0.22	No
Percent clay	3.448	0.0024	Yes
Flow rate	-4.792	0.00024	Yes
Trubidity reduction	2.885	0.0086	Yes
Percent gravel*	2.993	0.0072	Yes
E. coli reduction	-0.421	0.68	No
Coliform reduction	0.327	0.75	No

Yellow indicates statistical significance
***This refers to the percentage of the sample retained on the sieve during initial clay processing.**

4.7.3 Effect of Clay Parameters on Filter Performance

Figure 4-12 summarizes the results of the regression analyses for many combinations of parameters.

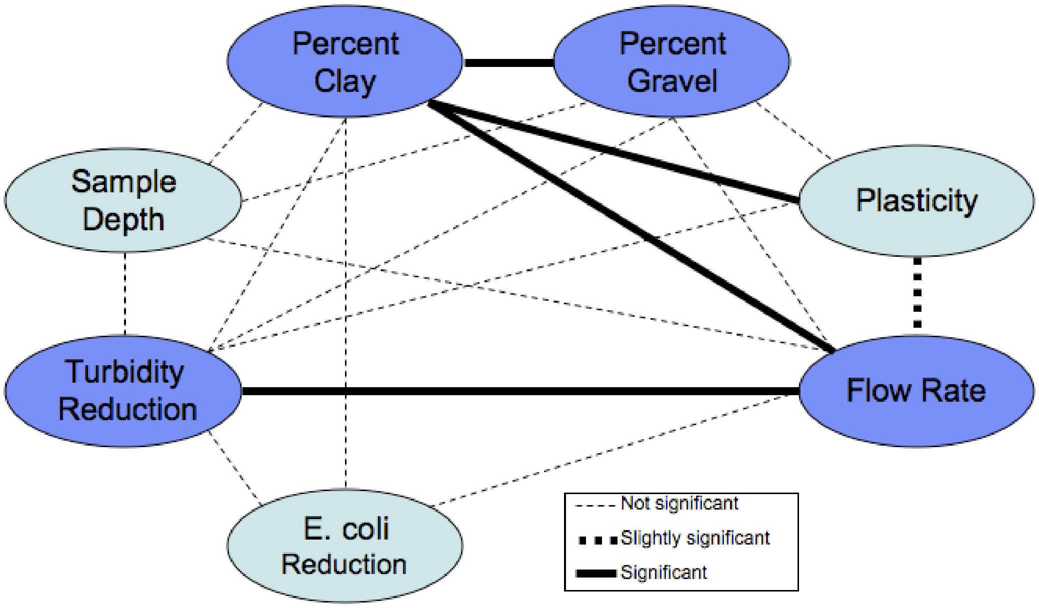


Figure 4-12: Summary of regression analyses

Of all the parameter combinations analyzed, there is only a statistically significant relationship between percent clay and percent gravel, percent clay and plasticity, percent clay and flow rate, and flow rate and turbidity reduction. These results suggest that the percentage of clay in the sample has an impact on the flow rate of the filter made with that sample. This makes sense, because the pore size should be related to the size of the particles that make up the clay. It is reassuring to see a highly significant relationship between flow rate and turbidity reduction, as flow rate is used as one of the principle quality control measures. It is a little worrying, on the other hand, that there is not a significant relationship between the flow rate and *E. coli* reduction, as slower flow rates should correspond to higher quality water filtration. The lack of a relationship between turbidity reduction and *E. coli* reduction is unexpected for the same reason. Finally, it is useful to know that there is a significant relationship between the percentage of the sample that passes the filter during preparation and the percentage of clay in the sample, because this confirms that the amount of gravel in a sample is one possible indicator of clay quality. This is something that local potters know either intuitively or from experience.

4.7.4 Analysis of Bradner Data

Table 4-8 provides a summary of the regression analyses of different combinations of Bradner's data. These analyses excluded any data point that did not have data for either of the two parameters being tested.

Table 4-8: Regression analysis of Bradner data

Parameter 1	Paramter 2	Adjusted R^2 value	t Stat	Two-tail P-value	Statistically significant relationship?
Clay ratio	Flow rate	1.0000	1.47E+16	0.000000	Yes
% rice husk	Flow rate	0.0546	1.722	0.0945	No
Clay ratio	E. coli reduction	0.0155	-0.486	0.6340	No
% rice husk	E. coli reduction	-0.0666	0.037	0.9709	No

Yellow indicates statistical significance

The most remarkable relationship is that of the clay ratio (weight of Wayamba clay over the weight of Gbalahi clay) to the flow rate. There was a perfect one-to-one relationship between the clay ratios and the flow rates recorded. This indicates a very strong relationship between the relative amount of each clay used and the flow rate of water through the resulting filter[12]. The rice husk had a somewhat significant relationship to the flow rate (a P-value below 10%) but not significant enough to reject the null hypothesis that the relationship between them is due mostly to chance, which requires a P-value of at most 5%.

---

12. [12] The perfect one-to-one relationship between flow rate and clay ratio is likely due to a lack in precision in flow rate measurements. Even without this perfect correlation, however, there would still be a strong relationship between these parameters.

Neither the clay ratio nor the percent weight of rice husk had a significant relationship to the *E. coli* reduction.

4.8 Conclusion and Recommendations

4.8.1 Clay Site Recommendation

The data presented in Section 4.6 indicates that the Gbalahi clay is more plastic, has a higher clay content, and yields filters with more appropriate flow rates and better turbidity removal. The analyses in Section 4.7.2 indicate that the differences between the clay contents, flow rates, and turbidity removals associated with the clays from the two sites is statistically significant. Since the differences are significant and the values of the Gbalahi clay parameters are more desirable, it is recommended that the Gbalahi site continue to be used if only one source is chosen. The analysis of Bradner's data in Section 4.7.4, however, indicate that the flow rate of the filters can be dramatically changed by mixing two clays together and/or adjusting the ratio of these clays. It is possible, therefore, that a mixture of clay from the two sites could be one way of achieving a better recipe, although such mixtures were beyond the scope of this thesis.

If new clay sites are considered in the future, it may be beneficial to perform clay tests similar to the ones performed by the author in order to establish how similar the clay is. If it is significantly different from either Gbalahi or Wayamba clay, it is recommended that several test batches be made and their performance measured before using the new site for commercial filters. Similar steps should be taken if it is suspected that a large region of different clay has been discovered within one of the existing sites. Otherwise, further clay tests are only recommended for research purposes and are not a necessary part of regular production.

4.9 Recommendations for Future Work

More work must be done to ensure that the filters being produced at the Pure Home Water factory perform at a consistently high level. Progress has been made, but the filters are still not ready for sales and distribution. Specifically, the filters are not achieving the log-2 *E. coli* reduction recommended in the Best Practices Manual (CMWG 2010) and achieved by CT filters from Accra (Johnson et al. 2008) and elsewhere (UNICEF 2007).

4.9.1 More Recipe Experimentation

The task most relevant to this thesis and arguably the most important in ensuring filter quality is to finalize the filter recipe. Bradner has continued the work of Miller, Watters, and the author, but an acceptable recipe is yet to be finally established. Bradner agrees that this research should continue:

> Our results are currently inconclusive but the staff understands our methods and intentions and will continue to help with this research. Meanwhile a mixture of 25% Wayamba and 75% Gbalhai clay at 10% rice husks is being used for production. This mixture was determined to be adequate for production though possibly not optimal. Determination was made based on a rather hasty assessment of flow-rates, bacteria removal, and filter strength. (Bradner 2011)

Since it is now thought that a mixture of clays from the two sites may be better than using clay from one site only, there are even more possible combinations that could be tested, though some may also be thrown out based on the results from Bradner's work. The amount of rice husk is also yet to be finalized. It is recommended that the systematic analysis of possible recipes continue, with duplicates or triplicates of each one, until a suitable recipe is found that leads to an appropriate flow rate and a log-2 reduction in *E. coli*.

4.9.2 Controlling Combustible Fineness

One concern shared by members of the MEng Ghana Team and consultants involved in the production process is that the fineness of the combustible material added to the clay is poorly controlled. On pages 59-61 of his thesis, Miller provides scanned images of sawdust and rice husk that has been processed in a hammermill before and after being sieved by hand (2010). The hammermill has been in the process of being repaired and upgraded and thus wasn't used for any of the research presented in this thesis, but it was used in the production of filters during Miller's research. Since the size of the milled and sieved combustible determines the size of the largest pores in the fired filter, it is recommended that more care be taken in making sure that the combustible is of the same fineness. The amount of combustible used by the MEng Ghana team to produce their batches of filters in 2011 was based on research done by Miller and Watters, but if the combustible is of a different size, then this may not have been appropriate.

Members of the MEng Ghana Team observed that when sieving the rice husk by hand, more and more of the larger pieces of husk fell through the sieve as the sieving time increased. This is due to the fact that most of the pieces are long and narrow, so it is only a matter of time before they are shaken just right so that their thinner dimension fits through the mesh.

> Currently, as the rice husks being purchased are already of fairly small particle size, only one screening is being done to the rice husks to remove the very fine particles along with a visual inspection to remove the occasional really large contaminants (stones, dirt, other grain pieces). It would be very beneficial to have a two-screen process – one for anything greater than the desired size and one for the fines. Some discussion was given to creating framed screens that could be suspended and then shaken – greatly reducing the amount of time currently required to run small amounts of rice husks through a hand-held sieve. (Bradner 2011)

It is the author's opinion that the hammermill is and even more efficient and effective tool to ensure consistent combustible particle size. Until it is returned to the factory, the two-screen process described by Bradner may be the best substitute. Meanhwile, two areas of research are indicated here:

1. Measuring the impact of combustible fineness on filter performance by making and testing filters with varying combustible particle sizes.
2. Determine the optimal "sieving time" that yields a maximum amount of fine combustible material and a minimum amount of coarse material.

5 Ceramic Filter Manufacturing in Northern Ghana: Quality Control

Shanti Kleiman and Travis Reed Miller (section 5.5)

Abstract

In 2009, Pure Home Water (PHW), a Ghana based non-profit organization working to provide affordable and safe drinking water to people in the Northern Region of Ghana, began the construction of a ceramic pot filter (CPF) factory near the city of Tamale. This section discusses elements of PHW's efforts to bring household water treatment and safe storage (HWTS) to scale through local manufacturing of ceramic pot filters. Specifically, it discusses work done between January and April 2011 to improve quality control for CPF production. A literature review, filter modeling and design comparisons, and recommendations for additional research are provided to serve as a practical guide for PHW management and others who may engage in similar work in the future.

5.1 Background

In 2009, Pure Home Water (PHW), a non-profit organization working to provide affordable and safe drinking water to people in the Northern Region of Ghana, began the construction of a ceramic pot filter (CPF) factory near the city of Tamale. By 2011, the factory had most of the molds, supplies, and kiln necessary for large-scale filter production, but needed to both increase its own water storage capacity, and to implement quality control standards.

From January-April 2011, substantial progress was made in moving the PHW factory closer to full-scale production. The progress made in the area of quality control (QC) included the construction of a filter saturation tank, flow test racks, and calibrated T-devices for flow testing filters. In addition, essential work was done in capacity building: staff are now trained in key quality control areas including flow rate testing, bacterial testing, and kiln firing procedures.

Due to the iterative work of testing and retesting filters using different filter compositions, the PHW factory is now closer to determining an optimal filter recipe given locally available clay and materials. However there are key research questions that will help PHW develop quality control procedures that are based on appropriate and standard metrics. The purpose of this document is to discuss these key research questions that will provide a good basis for PHW management and design decision making, as the factory moves towards its goal of reaching production capacity of up to 350 filters per month by the end of the 2011. This section will begin with an overview of the quality control issues related to ceramic filter manufacturing, followed by a review of relevant literature, and a discussion of testing results, and suggested research.

5.2 Ceramic Filter Manufacturing and Quality Control

The main areas of post firing quality control are (1) flow rate testing, (2) visual and auditory inspection, (3) pressure (crack) tests, and (4) bacteriological testing. The purpose of the CFP is to remove harmful bacteria and protozoa from drinking water. Bacteriological testing is the most direct way to measure a functioning filter, however it can be expensive and time consuming. Therefore other methods of quality control are typically used in CFP factories around the world to provide standardization of quality in the manufacturing process: flow rate testing, bubble/pressure testing, and auditory or visual testing. All four parameters are intended to identify filters that are damaged or otherwise will compromise the efficacy of the filter. This document focuses on two aspects of quality control, flow rate testing and removal efficacy.

5.3 Flow Rate Testing & Removal Efficacy Literature Summary

5.3.1 Flow Rate Procedure

In Rayner's 2009 study on the current practices in CPF manufacturing, of 18 respondents, 16 perform flow rate tests on 100 percent of their filters, and 15 soak their filters before flow rate tests. The soaking time varies from 2-24 hours. Measuring methods also vary with nine factories measuring effluent and eight factories use a calibrated T-device to measure the amount of water filtered (Rayner 2009). Maximum acceptable flow rates and volume of filter element of each factory that responded to this portion of the survey are shown in the Figure below. The flow rates range from 1-5 L/hr and the volume of the filled pot element ranges from 6-11 liters.

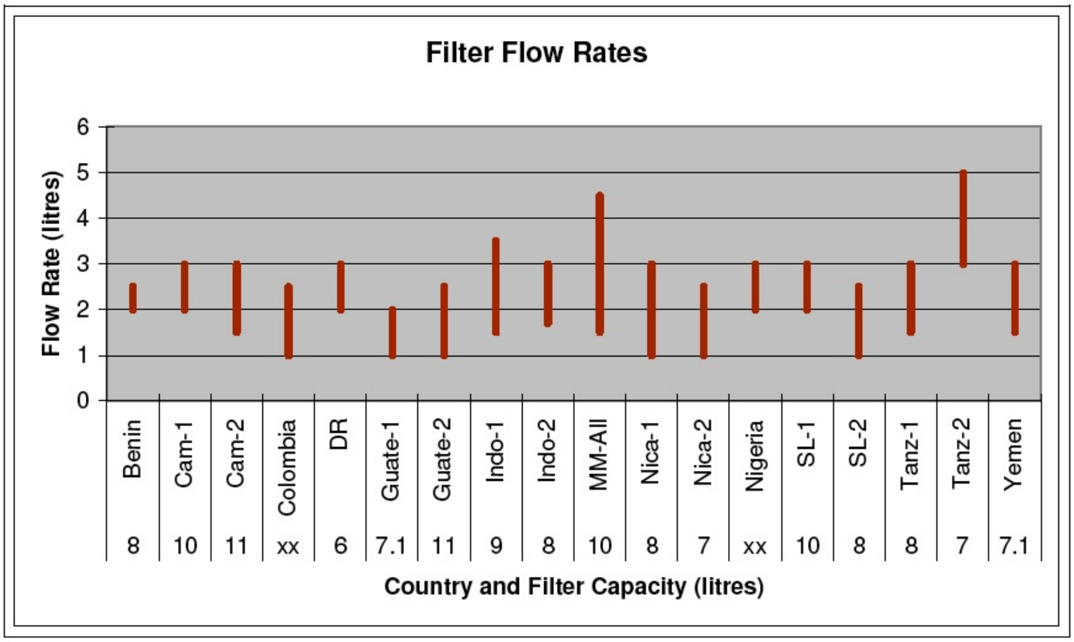


Figure 5-1: Maximum Flow Rates and Filter Element Capacity (Rayner 2009)

5.3.2 Filter Mechanism and Purpose of Flow Rate Test

Flow rate testing is the most commonly used quality control parameter to determine filter efficacy (Rayner 2009). While a more definitive quality control parameter is microbial testing of filter effluent, microbial testing is generally expensive and requires a certain level of technical experience. Therefore, other proxies for water quality, such as flow rate testing, are used to test each filter before it goes to market. Out of 18 factories surveyed, 16 flow test 100 percent of their filters (Rayner 2009). Flow rate is important both as a proxy for water quality, and to ensure that the filter can provide enough drinking water per household, estimated to be at least 4.5 liters per person, per day for a family of six (Howard and Bartram 2003). To ensure sufficient water, the minimum acceptable flow rate recommended by PFP for a new filter is 1.5 to 2.5 L/hr (PFP website retrieved 3/19/11). However, there is research suggesting that maximum flow rate could be increased without compromising effluent quality (Bloem et al. 2009).

Maximum flow rates vary depending on the holding capacity of the filter. Initially a flow rate range of 1-2 liters per hour was developed by PFP because the instructions for water disinfection on the 0.32 solution of silver Microdyn commonly sold in Nicaragua are to add one drop to 2 liters of water and wait 20 minutes. Ron Rivera, founder of PFP, determined that with a safety factor of three, 60 minutes for 2 liters of water, the minimum flow rate should be 1 liter/hour (Lantagne 2001a). Faster flow rates may indicate that there are cracks in the filter that compromise filter quality, the pore size is too large, and/or the water has not had sufficient time to interact with the colloidal silver. To achieve this flow rate, PFP set a target pore size of 1 micron. While the actual pore size of the filter was found to vary between 0.6-3 microns (Lantagne 2001a) and 33-52 microns (Halem 2006), filters with larger pore sizes are still effective at trapping all protozoa and a significant portion of bacteria because other filtering mechanisms are at work (Lantagne 2001a; Halem 2006). The filtering occurs not only through mechanical screening but also through sedimentation, adsorption, diffusion, inertia, turbulence, tortuosity, chemical activity, and biological activity (Halem 2006). This is supported by research that showed a 46 percent reduction in diarrheal diseases among filter users versus non-users (Brown and Sobsey 2006).

5.3.3 Flow Rate and Removal Efficacy

The studies that specifically investigate the relationship between flow rate and removal efficiency do not show strong consistency in testing conditions, methods, or results. Klarman, studying filters from the Filter Pure factory in the Dominican Republic, found that filter flow rates *increased* over the 5-week duration of the study. She also found that when filter flow rate increased above 1.7L/hr, TC removal dropped below 99% and that there was no clear correlation between flow rate and turbidity. Klarman's influent water, however, had a 5-week average turbidity of 3.0 NTU, which is very low in comparison to influent used in other studies. *E. coli* levels in Klarman's influent were also too low to measure reductions (Klarman 2009).

Bloem, on the other hand, testing new filters from the RDI factory in Cambodia, found that filter flow rate decreased rapidly over the 6 month duration of the study due to clogging. Although filters with a faster initial flow rate decreased more rapidly than those with a lower starting point, they still had a higher ending flow rate than the filters that started with a lower rate. Bloem also found that filters with initial flow rates of up to 7.2L/hr and filters with initial flow rates of 1.8 L/hr perform equally well in their removal efficiency for bacteria.

The filters in Bloem's study that were dipped in silver did better at removing *E. coli* than un-dipped filters (3.05 vs. 5.9 LRV). Based on these findings, Bloem recommends investigating the impact of increased flow rate on removal efficiency (Bloem et al. 2009).

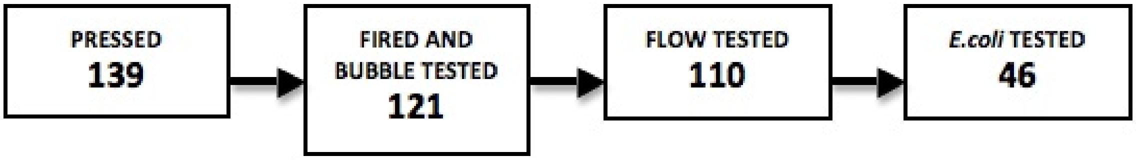
Lantagne studied n=4 PFP filters in Managua, Nicaragua in her flow rate and removal efficiency comparison, both before and after silver application in filters with flow rates ranging from 1-3L/hr. In pre-silver investigations, Lantagne found that 3 out of 4 filters remove *E. coli* and none of the filters removed total coliform or H2S producing organisms. In post silver tests, the *E. coli* in the influent water was not present, and therefore removal efficiency could not be tested. However, all 3 filters that advanced to this testing phase removed 100 percent of total and fecal coliform (Lantagne 2001b).

Van Halem tested filters from Nicaragua, Cambodia, and Ghana and used Delft canal water spiked with *E. coli* to obtain microbial reduction results. Van Halem recommends testing increased filter flow rates stating that the PFP recommended flow rate (1-2 L/hr at the time of Halem's analysis) is not enough for the water needs of a family and that filters with higher discharges (CT Ghana) perform as well as filters with low discharges (RDIC Cambodia) in the removal of micro-organisms. Van Halem questions the reliability of flow rate testing as an optimal quality control test because low discharge does not necessarily mean higher removal efficiencies, but it can indicate consistency of manufacturing procedures. She recommends a combination of the bubble-point test and audio check as an additional testing protocol. In addition, she states that the exact upper limit of flow rate must be determined *at the production location* in conjunction with standardization of the manufacturing procedure (Halem 2006, italics mine). Napotnik et al supports further field research on the relationship between flow rate and removal efficacy. All of the filters in Napotnik's study performed well at removing TC and *E. coli*, however the flow rates varied both between filter pair types and within each filter pair (Napotnik et al. n.d.). Filter flow rate depends on the quality of influent water, the hydraulics of the filtering element (size, shape, composition), the average pore size and consistency of pore size distribution achieved from the manufacturing process (due to the combustible type, sieve size, and method), the height of the water in the filtering element, and the frequency with which it is filled (Rayner 2009). Because quality of influent water (both turbidity and organisms present), filter hydraulics, input materials, and the fact that consistency of manufacturing practices will vary widely from factory to factory, it is important to take the best practices guidelines as starting points for factory specific investigations in filter performance under local conditions, while at the same time potentially moving towards greater standardization across manufacturing methods (Halem 2006; Ceramic Manufacturing Working Group 2011).

5.4 Summary of Key Quality Control Research March-April 2011

In March 2011, Curt and Cathy Bradner, founders and directors of Thirst-Aid, an NGO based in Burma that promotes safe drinking water and improved hygiene through education and appropriate technologies, traveled to Tamale, Ghana to consult on work begun at the PHW factory in January 2010 and 2011 to improve PHW filter production quality.

Bradner worked with PHW employees to press filters with different clay and rice husk ratios, in order to assess various clay and combustible proportions and to train PHW staff. During the month of March Bradner pressed 139 filters and of those filters, fired 121 filters. The fired filters were then tested using visual inspections, bubble tests, flow rate tests, and coliform tests. Of the fired filters, 110 passed visual and bubble tests and went on to be flow rate tested. Forty-six of the flow-tested filters had flow rates within an acceptable range and went on to be tested for *E.coli* removal.



Of n=25 filters tested on 3/31/11, none were within acceptable *E.coli* removal ranges (42-93% removal) for distribution. The Bradners believe, however, that they are honing in on a composition ratio that produces a strong filter with an appropriate flow rate and bacterial removal for the filter volume.

5.4.1 The Need for a Better Flow Metric

For most factories an appropriate flow rate target is close to the PFP recommended value of 2.5 L/hr. The PFP value is based on an assumption that this flow rate correlates with acceptable removal efficiencies. Bradner uses the rule of thumb that for every liter of capacity 0.35 L/hr is allowed. Filter users, however, prefer even higher flow rates, but not at the expense of a functioning filter.

Ultimately the standard for the viability of the filter should be the removal efficiency, for which flow rate testing is supposedly a proxy. In the testing conducted by the Bradners at the PHW factory during March and April there seems to be little correlation between flow rate and removal efficiency. It is important to emphasize that the sample size is small and there was no redundancy in tests conducted on each filter, therefore, these results are not statistically significant. In addition the filters tested during March and April were intentionally not soaked or painted in silver in order to get "without silver" results.

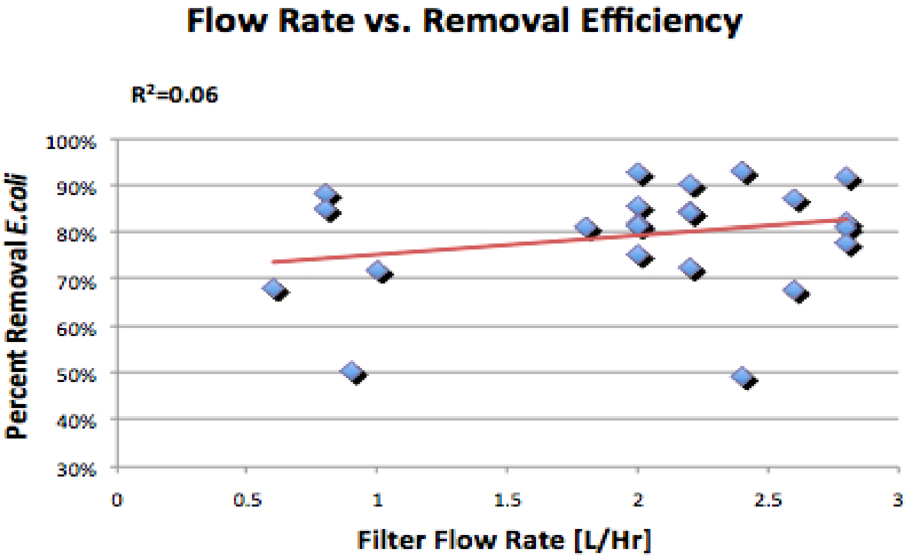


Figure 5-2: Scatter plot of flow rates vs. removal efficiencies for filters in Tables 9 and 10 showing a very weak correlation

However, the results do show that, at least in the initial stages of determining an appropriate filter composition using new materials from new locations, flow rates are not an accurate or reliable proxy for removal efficiencies. The linear regression shows a very weak correlation between flow rate and removal, but in the opposite direction expected, it shows a weak correlation between increased flow rate and increased removal efficiency (Figure 5-3).

A better design and quality control metric for determining the relationship between flow and removal efficiency may be surface loading rate. Flow rate is measured in [L/hr] while surface-loading rate is measured in volume/time/area or [L/hour/m^2]. While pots of different designs will have different flow rates because they have different surface areas they don't necessarily have to have different surface loading rates. If PHW wants to determine a relationship between removal and flow, it will be valuable to measure surface loading rates so that the results can be applied to different filter designs**.**

The PHW factory currently manufactures a paraboloid filter with a 5.75L/hr capacity in order to better serve larger family sizes with treated water. The factory is considering a new filter with 10L capacity, using a half-hemisphere design. To compare the two filter designs, Reed Miller modeled the surface loading rate for both the paraboloid filter and half hemisphere designs as well as a flower pot-shaped design using the equations from his 2010 thesis and flow equations derived for this report (Miller 2010, Miller 2011)

5.5 Modeling Flow through Hemispherical Ceramic Filter and Comparison with Flower Pot and Parabaloid [13] [14]

Several authors have modeled flow through ceramic filters utilizing Darcy's Law (7-1). Darcy's law considers flow through a cross-sectional area of a porous medium of a given thickness and hydraulic conductivity subject to a head of water (Miller, 2010).

$$Q = \frac{KAh}{t} \qquad (7\text{-}1)$$

where:

Q is the flow through the filter

K is hydraulic conductivity of the side walls and bottom

A is the cross-sectional area through which water flows

t is thickness of the filter

h is the head

---

[13] This section was written by Travis Reed Miller.

[14] The equation numbering cooresponds to Millers 2010 thesis

5.5.1 Flow through Flower Pot Filter

The original filter designed by Potters for Peace was in the style of a flower-pot planter. van Halem (2006) produced the Figure 1.9 below, demonstrating the cross-sectional shape of the flower pot filter. Note that "L" does not extend to the rim of the filter, instead it extends to the usable portion of the filter which is at the bottom of the lip of the filter. r1 is similarly measured from this vertical position. Alternative notation is also mentioned: $r1=r_T$, $r2=r_B$, and L=H.

In Table 5-1, van Halem (2006) compared the dimensions of sample filters produced by Flower Pot ceramic filter factories in three countries, including Ghana, where Pure Home Water (PHW) is located. The dimensions listed for Ghana are for filters produced in Peter Tamakloe's factory in Accra, the capital as well as for the newer ones produced by PHW, measured by Travis Watters (2010) were added.

Figure 5-3: Schematic drawing of filter dimensions

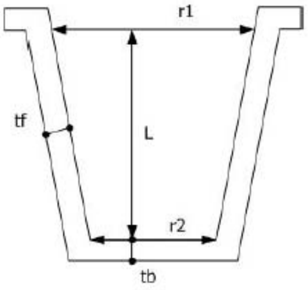


Table 5-1: Filter dimension comparison in three countries

Dimension	r1 (or r_T)	r2 (or r_B)	L (or H)	t_F	t_B	tanθ
Units	cm	cm	cm	cm	cm	
Cambodia	13.25	9.75	23.5	1.6	1.4	0.15
Ghana (Accra)	14	10	23.5	1.3	1.5	0.17
Ghana (PHW)	10.9	7.35	19.7	1.5	1.5	0.18
Nicaragua	13.25	11	22	1.3	1.7	0.10

The default thickness values for flowrate calculations are taken to be 1.5cm for t_f and t_b.

Leftwich et. al. (2009) derived an equation for flow through flower pot filter allowing for variation in the angle of the side wall with respect to the bottom; its corrected version is shown below (7-2). Note that only the height of the water, not the time, is necessary to calculate the flowrate; if a function determining height with time is available, though, it could be useful.

$$Q_T = K\pi H_W(t)\left[\frac{r_B{}^2}{t_B} + \frac{r_B H_W(t)}{t_F} + \frac{(H_W(t))^2}{3t_F}\tan\theta\right] \tag{7-2}$$

where:

Q_T	is total filter discharge
K	is hydraulic conductivity of the side walls and bottom
$H_W(t)$	is the height of the water at time t
r_B	is radius at the bottom of the filter
t_B	is thickness of the bottom
t_F	is thickness of the side walls
θ	is angle of deviation of the sidewall from the normal to the bottom

Note the relationship of the sidewall angle to the geometry (7-3):

$$\tan\theta = (r_T - r_B)/h \tag{7-3}$$

5.5.2 Modeling Flow through Paraboloid Filter

Miller (2010) derived the flow through a paraboloid filter based on Darcy's Law. The cross-section of the filter is shown in Figure 5-4.

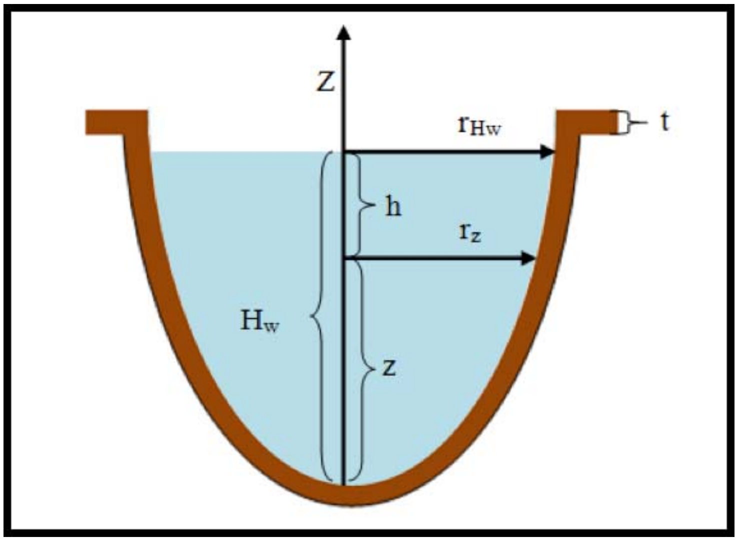


Figure 5-4*:* Paraboloid Filter and Relevant Dimensions

Quadratic surface of a paraboloid:

$$z = br_z^2 \tag{8-1}$$

$$r_z = \sqrt{z/b} \tag{8-2}$$

$$r_z = c\sqrt{z} \tag{8-3}$$

where:

z is the height from the vertex (or bottom most point of the inside of the filter)

b is a coefficient

r_z is the radius at height z

c is $\sqrt{1/b}$

Darcy’s Law for Paraboloid Filter with Constant Hydraulic Conductivity and Thickness

$$Q = \frac{K}{t}\int_{0}^{H_W} dA(z)\, h(z)\, dz$$

(8-4)

where:

Q is the flowrate

K is the hydraulic conductivity

t is the thickness

H_w is the height of the water

dA is the differential cross-sectional area through which water flows at height z

h(z) is the head above height z

dz is the differential change in height z

The head, h_z, above the height z is given simply by the difference between the height of water and height.

Head above Height Z

$$h_z = H_W - z \tag{8-5}$$

The differential cross-sectional area through which water flows at height z, A(z), is the circumference of the circle at that height multiplied by an infinitesimally small slant height, dl. However, it is useful to perform the integral in terms of a differential height, dz, shown below.

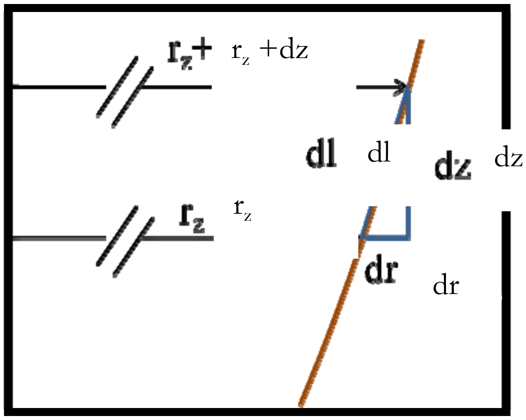


Figure 5-5: Close-Up View of Filter Side Wall

Differential Cross-Sectional Area

$$dA = 2\pi r_z dl \tag{8-6}$$

Slant Height

$$dl = \sqrt{\left(\frac{dr}{dz}\right)^2 + 1}\, dz \tag{8-7}$$

First Derivative of Radius (Equation 8-4) with Respect to Height

$$\frac{dr}{dz} = \frac{c/2}{\sqrt{z}} \tag{8-8}$$

Differential Cross-Sectional Area, Expanded

$$dA = 2\pi c\sqrt{c^2/4 + z}\, dz$$
(8-9)

Darcy's Law for Paraboloid Filter with Constant Hydraulic Conductivity and Thickness, Expanded

$$Q = \frac{2\pi ck}{t}\int_0^{H_w} \sqrt{c^2/4 + z}\,(H_w - z)dz \tag{8-10}$$

The integral was solved using integration by parts.

$$Q = \frac{4\pi ck}{3t}\left[\frac{2}{5}\left(\left(c^2/4 + H_w\right)^{\frac{5}{2}} - H_w\left(c^2/4\right)^{\frac{3}{2}} - \left(c^2/4\right)^{\frac{5}{2}}\right)\right] \qquad (8\text{-}11)$$

5.5.3 Modeling Flow through a Hemispheric Filter

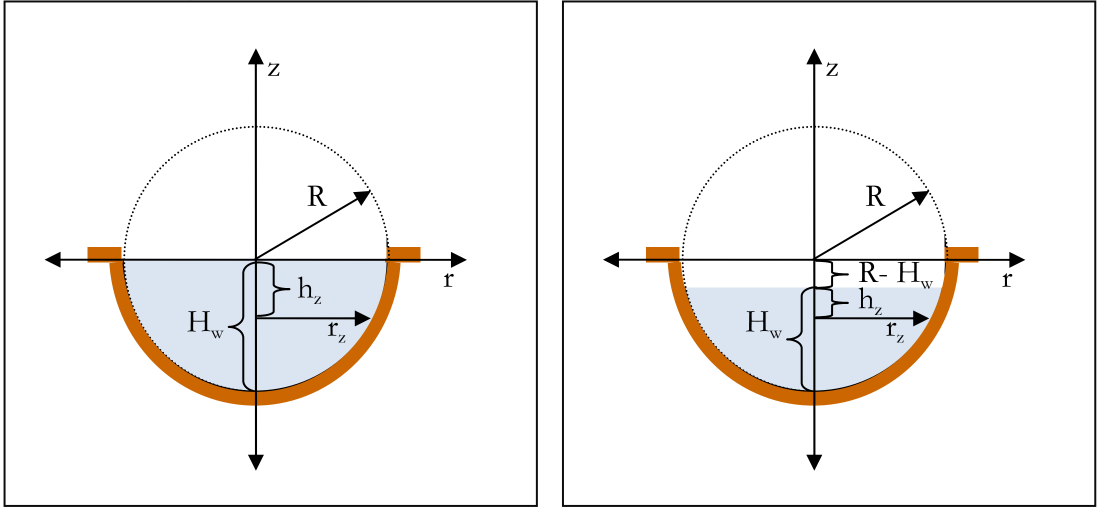


Figure 5-6*:* Model of Hemispheric Filter and Relevant Dimensions, Full and Partly Full

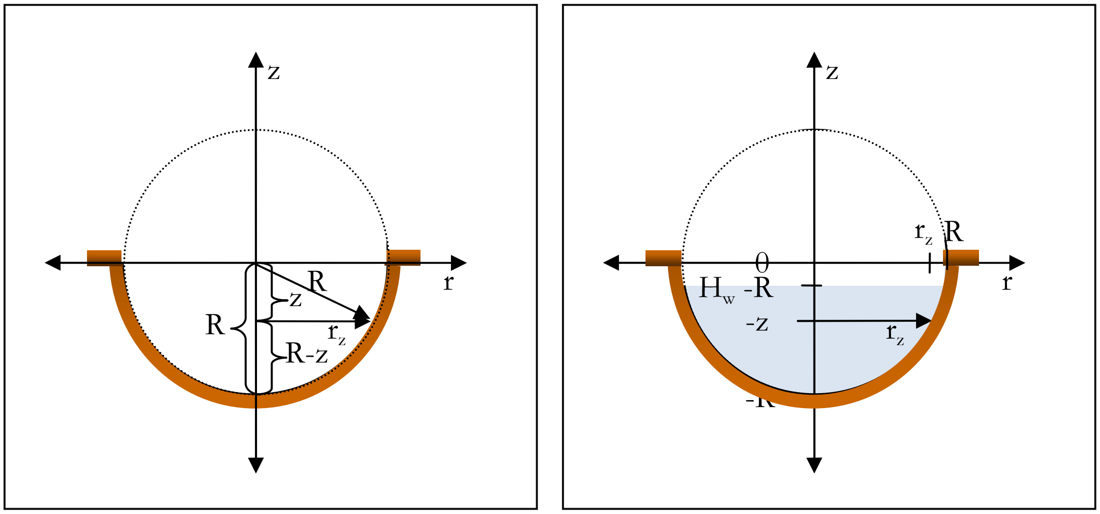


Figure 5-7*:* Model of Hemispheric Filter and Relevant Dimensions, Geometry and Coordinates

For ease of calculations, the cross-section of the filter is modeled as a half-circle centered on the origin. The radius, R, is equal to the height of the filter, R (9-1), in the simple circle formula. The height of the water, H_w, is only equal to R when the filter is full.

$$r_z^2 + z^2 = R^2 \tag{9-1}$$

Equations 9-4 through 9-7 which were used to develop the flow model through the paraboloid filter are general enough to be applicable to the hemispheric case as well. The main difference in the geometries is how radius changes with height, dr/dz. Therefore, dr/dz is found for the hemispheric case, and substituted into 9-7, which is then combined with the other equations to arrive at the flow model.

$$r_z = \sqrt{R^2 - z^2} \tag{9-2}$$

$$\frac{dr}{dz} = \frac{-z}{\sqrt{R^2-z^2}} \tag{9-3}$$

$$dl = \sqrt{\left(\frac{-z}{\sqrt{R^2-z^2}}\right)^2 + 1}\, dz \tag{9-4}$$

$$dl = \frac{R}{\sqrt{R^2-z^2}}\, dz \tag{9-5}$$

$$dA = 2\pi R dz \tag{9-6}$$

$$Q = \frac{K}{L}\int_{z_{low}}^{z_{high}} dA(z)\, h(z)\, dz \tag{9-7}$$

$$Q = \frac{2\pi KR}{L}\int_{-R}^{H_w-R} H_w - z\, dz \tag{9-8}$$

$$Q = \frac{2\pi KR}{L}\left|H_w z - \frac{z^2}{2}\right|_{-R}^{H_w-R} \tag{9-9}$$

$$Q = \frac{2\pi KR}{L}\left[\left|H_w(H_w - R) - \frac{(H_w-R)^2}{2}\right| - \left|(-R)H_w - \frac{(-R)^2}{2}\right|\right] \tag{9-10}$$

$$Q = \frac{2\pi KR}{L}\left[\left|H_w{}^2 - RH_w - \frac{(H_w-R)^2}{2}\right| - \left|-RH_w - \frac{R^2}{2}\right|\right] \tag{9-11}$$

$$Q = \frac{2\pi KR}{L}\left|H_w{}^2 - RH_w - \frac{(H_w-R)^2}{2} + RH_w + \frac{R^2}{2}\right| \tag{9-12}$$

$$Q = \frac{2\pi KR}{L}\left|H_w{}^2 - \frac{(H_w-R)^2}{2} + \frac{R^2}{2}\right| \tag{9-13}$$

$$Q = \frac{2\pi KR}{L}\left|H_w{}^2 - \frac{H_w{}^2 - 2RH_w - R^2}{2} + \frac{R^2}{2}\right| \tag{9-14}$$

$$Q = \frac{\pi K R}{t}\left|2{H_w}^2 - {H_w}^2 + 2RH_w - R^2 + R^2\right| \qquad (9\text{-}15)$$

$$\boldsymbol{Q = \frac{\pi K R}{t}\left[{H_w}^2 + 2RH_w\right]} \qquad (9\text{-}16)$$

When the filter is full, H_w=R, so 9-16 simplifies to:

$$\boldsymbol{Q_{full} = \frac{3\pi K R^3}{t}} \qquad \mathbf{(9\text{-}17)}$$

5.5.4 Surface Loading Rate (SLR)

In addition to flowrate, the SLR of each filter was also calculated. The SLR was calculated as flowrate per surface area. Volume equations are also shown below because they are utilized in setting equivalent volumes across the filters for hypothetical comparisons.

Flower Pot

Surface Area, $SA_F = \pi {r_B}^2 + \pi(r_B + r_T)\sqrt{(r_T - r_B)^2 + H^2}$ (9-18)

Paraboloid

Surface Area$SA_P = \frac{\pi r}{6h^2}\left[\left(r^2 + 4h^2\right)^{3/2} - r^3\right]$, (9-19)

Hemispheric

Surface Area, $SA_H = 2\pi R^2$ (9-20)

5.5.5 Comparing Flowrates

PHW would like to have filters with 10L capacity, but there is a constraint on the upper radius of the filters because of the size of the buckets which have been purchased. The new "wiggle room" was determined by considering the desired location of the bucket to interact with the bottom of the filter lip. Based on Curt Bradner's mold design, there should be a fillet with 0.17" radius where the filter wall meets the bottom of the filter lip. It would be best for the bucket lip not to touch the fillet, so an additional 0.08" of wiggle room was added to allow for differences in filter shrinkage. Therefore, two sets of filters were compared:

1. Current designs used by PHW in Ghana (not applicable for hemispheric),
2. Filters designed to fit inside the bucket with 0.25” (0.635cm) of wiggle room on all sides.

The new Qualiplast buckets purchased by PHW have at 14.6” inner diameter.

The hydraulic conductivity, k, was set at 0.234 cm/hr (Miller, 2010), while the thicknesses of all the sides were set to be 1.67cm for all filters, based on Curt Bradner’s Myanmar filter mold design. Fortunately for modeling purposes, the position of the height of the water in a full filter coincides with the top of the bucket. Therefore, the maximum inner radius of a filter at the height of the water when full for given a bucket size is:

$$r_{H_w max} = r_{bucket} - t - 0.635cm \tag{9-21}$$

To model the new Flower Pot filter, the r_T was set based on the bucket diameter, and the r_B was found by holding the angle, θ, and height roughly constant from the original design.

Flower Pot

Volume, $V_F = \frac{\pi h}{3}(r_T{}^2 + r_T r_B + r_B{}^2)$ (9-22)

Recalling that: $\tan\theta = (r_T - r_B)/h$ (9-23)

To model the new paraboloid and hemispheric filters, the r_T was set based on the bucket diameter, and the shapes were scaled from the original design.

Paraboloid

Volume, $V_P = \frac{1}{2}\pi r^2 h = \frac{1}{2c^2}\pi r^4$ (9-24)

Radius with respect to Volume, $r = \left(\frac{2c^2 V_P}{\pi}\right)^{1/4}$ (9-25)

Hemispheric

Volume, $V_H = 2/3\pi R^3$ (9-26)

Radius with respect to Volume, $R = \left(\frac{3V_H}{2\pi}\right)^{1/3}$ (9-27)

5.5.6 Modeling Results and Synthesis

Figure 5-8: Modeling Results

Shape	Bucket, ID (in)	r_T (cm)	r_B (cm)	H (cm)	V (L)	t (cm)	Q (L/hr)	SLR (L/hr/m^2)
Flower Pot: Current Design	11.7	10.90	7.35	19.7	5.2	1.5	2.14	16.28
Paraboloid: Current Design	12.8	12.30	-	21.0	5.0	1.5	1.65	13.78
Flower Pot: New Design	14.6	16.24	12.64	20.0	13.2	1.67	3.84	16.38
Paraboloid: New Design	14.6	16.24	-	36.6	15.1	1.67	5.61	21.19
Hemispheric: New Design	14.6	16.24	-	16.2	9.0	1.67	5.65	34.13

The new bucket diameter is considerably larger than the current bucket diameter, therefore the volume and flowrate of all of the new designs are considerably larger than the current designs. The flowrate of the paraboloid and hemispheric new designs are comparably larger than the flower pot design as well as the "industry"-wide standard of 1-2 L/hr. Still, because the larger flowrate is mostly due to geometry and not a change in the composition of the clay, the performance can be expected to be similar. Additionally , these filters were modeled with a hydraulic conductivity, k, of 0.234 cm/hr which may not accurately reflect the k of new filters; the flowrate and SLR values will change with a new k.

Comparing the paraboloid and hemispheric designs, the paraboloid offers a very large volume of 15.1L, while the hemispheric still has a substantial capacity of 9.0L. However, the paraboloid design has a much larger H, meaning that the filter will extend farther down into the bucket and result in there being less storage available in the bucket for filtered water. Therefore, if it has acceptable removal, the hemispheric design is recommended as it has sufficient volume, comparable flow, and offers more bucket space for water storage.

5.6 Research Recommendations

Once the optimal filter composition is selected, the next step is to compare flow rate, surface loading rate, and coliform removal efficiency to determine if there is a correlation among these parameters in filters with and without colloidal silver applied, and also to determine within what flow rate range the relationship is valid. The faster SLR for the hemispheric filter may be ideal from the user perspective but must be tested to determine the performance from a user efficacy perspective.

In addition, the relationship between flow rate, surface loading rate, and removal may be different for filters with and without colloidal silver – especially if increased contact time with colloidal silver leads to increased removal efficiencies. The need for additional research to explore the relationship between flow rate and removal efficiencies is supported by Halem 2006 and Bloem 2009.

Regardless of removal efficiencies and surface loading rates, flow rate is an important quality control parameter in that it tests for the standardization of filter performance from the "user's" perspective and ensures that filters are producing acceptable volumes of purified water daily. However, if the correlation between flow rate and removal is not strong the necessity for regular and low cost microbial testing as a quality control parameter increases. It is possible that surface loading rate could replace flow rate as a quality control parameter once the relationship between the flow rate and the surface overflow rate for the PHW CPF design is determined.

Another essential area to research is the relationship between the extent of firing and filter performance. The tests performed in March 2011 at the PHW factory suggest that there is no relationship between extent of firing and filter performance. This hypothesis should be verified by research that investigates the relationship of extent of firing to filter flow rate, bacterial removal, and strength. This information will help PHW, and potentially other ceramic filter factories, standardize kiln firing times for new filters.

The author's recommendations to PHW for top *research* priorities (which are compatible but not synonymous with top *production* priorities) are:

- Determine the relationship between flow rate, surface loading rate, and bacterial removal efficacy on filters *with and without* silver applied.
- Establish the maximum flow rate allowable for the PHW filter based on acceptable removal efficiencies (assuming flow rate testing is the most viable 1st quality control parameter).
- Determine the relationship between the extent of firing and filter flow rate, surface loading rate, strength, and bacterial removal efficiency.
- Prioritize design criteria based on Miller's analysis and removal data to determine which factor (volume, bucket size, flowrate, or surface loading rate) is most important in deciding on future filter design shape.
- For more on the research completed in January–March 2011 please see http://web.mit.edu/watsan/docs_theses_ghana.html

6 Evaluating the Technical Performance and Social Acceptability of Keg-Shaped Ceramic Water Filters in Northern Ghana

6.1 Project Abstract

The Kosim Water Keg (KWK) is a new ceramic water filter designed to be easier for households to use and maintain. The design seals together two ceramic pot filters (CPFs) to form a keg shape. The keg is submerged in raw water stored in any water vessel, and water is cleaned as it filters to the keg interior. A siphon mechanism extracts the purified water for the user. The research project reported on here is constructing prototype KWKs and testing them for bacterial removal, turbidity removal, filtration rate, and siphoning rate. A preliminary consumer study is also included.

Eight KWKs were constructed and tested in Tamale, Ghana in January 2011 (photos of selected KWKs can be seen in Figure 5-1 below). From January 18th to 25th, the KWKs were tested using dugout water, a turbid surface water source commonly used in Northern Ghana. The KWKs constructed from Ceramica Tamakloe (CT) filters were able to remove 91.6% of total coliforms and 96.0% of *E. coli* colonies. The control CT CPFs were able to remove 97.8% of total coliforms and 99.3% of *E. coli* colonies. KWK turbidity removal averaged 58%, which was lower than the 78% removal achieved by the CPFs. Filtration rates of the KWKs were 9 to 11 liters in the first hour compared to only 2 to 3 liters per hour for the CPFs. Siphoning the first three liters of water out of the KWKs averaged 0.59 liters per minute which was slower than the than the 1.42 liters per minute that flowed out of the CPFs' spigot.

Figure 6-1 (left) Two KWK Installed in Water Vessels
(Right) Two KWKs In Front of Their Water Vessels

Five KWKs were provided to five households to collect more detailed user feedback on the design. Responses were positive, with households particularly liking that the KWK provided clean water, kept the filtered water cool, and could be used with their existing water vessels. However, they found the siphon water removal mechanism to be too slow.

The KWK is a promising product that merits further research. Longer term testing is still needed to 1) refine the design; 2) evaluate product durability; 3) develop a filter cleaning regime; and 4) conduct a more thorough household study. The construction design works, but further improvements could be made to the sealant method between the two pot filters, the siphon removal mechanism, and the restraint system that keeps the KWK submerged.

6.2 Project Background

Pure Home Water includes in its mission a goal of being financially self-sustaining through the sale of household water treatment and safe storage (HWTS) systems. Originally, they did not promote any single treatment technique as being preferable. They wanted to educate consumers about the importance of HWTS, the pros and cons of available methods, and provide consumers with a range of products from which they could choose to purchase the system which best met their individual needs

6.2.1 Early Product Diversity

Murcott hired two Ghanaian engineers to promote and sell water treatment products in 2005. During this first year, PHW promoted safe water storage, ceramic pot filters, candle filters, biosand filters, and SODIS. However, in 2006, a joint team of MIT Masters of Engineering and Sloan MBA students traveled to Pure Home Water to evaluate the suite of products being promoted and devise a business plan. They determined that selling a variety of products was not very effective because it: 1) added complexity to the education and marketing campaign beyond the ability of a 2 to 3 person organization; 2) added overhead costs for PHW because PHW had to store all the additional merchandise; and 3) confused customers. The assessment team determined that not all solutions were equally appropriate for the area, particularly biosand filters and SODIS, due to the water turbidity. Other filters, such as the candle filters, did not perform as well as advertised when tested by MIT Masters students. The assessment team recommended reducing the product line down to safe storage systems and the CT filters (Gordon et. Al 2006). PHW decided not to promote biosand filters and safe water storage systems because biosand filters still needed modifications before they could be sold, and the safe water storage containers were not selling. Instead, Pure Home Water would focus their efforts, at least initially, on the CT Filters, the ceramic pot filters with safe storage containers produced by Ceramica Tamakloe.

6.2.2 Experience with Ceramic Pot Filters

When selling the Kosim filters, the brand name PHW sold CT filters under, full cost recovery proved elusive. Rural households were only willing to pay GHS 6 (US$3.95) for the system, when a sustainable price would be about GHS 18 (US$11.90). As a result, filter sales were primarily through large NGOs, which could afford to pay full price for the filters. NGOs typically distributed them either for free or at highly subsidized price, further eroding the willingness to pay for the system.

In 2010, PHW began construction on their own ceramic filter factory. Now that PHW has their own factory, they are interested in expanding the product line that they produce at the factory in order to meet the varied needs of their customers. PHW wants to maintain their mission to bring water to the people who are most in need, but financially, this alone will not be a sustainable model. A model factory is one in Guatemala which is able to profitably sell ceramic water filters. Their business strategy has focused on creating a variety of products around the ceramic filter. For example, they offer hand-painted ceramic safe storage containers as an upscale alternative to the plastic receptacles. All filters provide the same level of bacterial performance, but the higher margin, more elegant storage containers bring in enough revenue to stay financially sound.

To this end, PHW is particularly interested in new products that can be made with their existing capacity, so that overhead costs stay low, and that can target a more up-scale consumer, so that profit margins can be higher to subsidize rural sales. Direct sales suffer when NGOs give away the same product to villagers for free. By having a variety of products, PHW can limit NGO sales to only one part of the product line in order to protect the selling price of the other products. This should allow PHW to meet its goal of financial sustainability while still bringing clean water to poor communities.

6.2.3 Consumer Preference Study

In 2008, MIT Masters student Vanessa Green conducted a user preference study regarding water purification methods for PHW. She found that urban and rural households considered the degree of health improvements to be the most important factor when selecting a treatment technique. Both groups also preferred traditional durable treatments to consumables or modern designs, and they emphasized that they want products that will last a long time without needing continual financial inputs. Most households did not consider the length of treatment, but a few households considered this to be the most important feature. Urban households generally placed a greater emphasis on quick treatment methods. Respondents did not emphasize water taste when selecting concepts and did not mind the taste of chlorine, since this indicated to them that the water was treated. Rural users as well as urban users selected options without a major emphasis on cost, even though willingness to pay is usually lower in rural areas. Urban users sometimes preferred higher priced solutions because they associated the higher price with better quality (Green 2008).

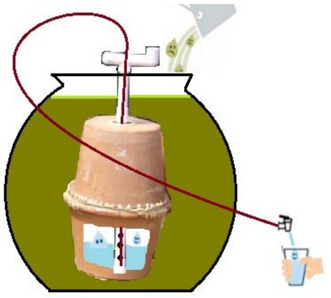
6.2.4 New Filter Design: Kosim Water Keg

The Kosim Water Keg (KWK) is a potential new product that Pure Home Water is considering as a future addition to their product line. The KWK, developed by Chris Schulz, a Senior Vice President at CDM, is designed to ameliorate the traditional drawbacks of ceramic pot filters: slow filtration

Figure 6-2 An Assembled KWK (without the siphon) in Front of the Ceramic Water Storage Vessel

B) Standard Kosim Water Filter (a CPF)
Source: IDEASS
<http://www.ideassonline.org/innovations/brochTesti.php?id=116&brId=28>

A) Kosim Water Keg
Source: Joanna Cummings



rates and the high recontamination risk.

To make the KWK easy to produce with the existing capacity of PHW, it is made from a composite of two ceramic pot filters. The top openings of the two filters are sealed together to form the keg body. A siphon extracts the clean water.

6.3 Research Goals

The KWK was originally field tested by Claudia Espinoza in Tamale, Ghana in Summer 2010. Since then, Mr. Schulz has made design changes to the seal around the keg, the KWK restraint system, and the mechanism to extract the filtered water out of the keg.

The goal of this field-based project was to construct prototype KWKs using the new design and test them for bacterial and turbidity removal, filtration rate, and siphoning (to remove the filtered water) rate. Additionally, consumer feedback would be gathered on the KWK design to determine what improvements potential customers would be interested in.

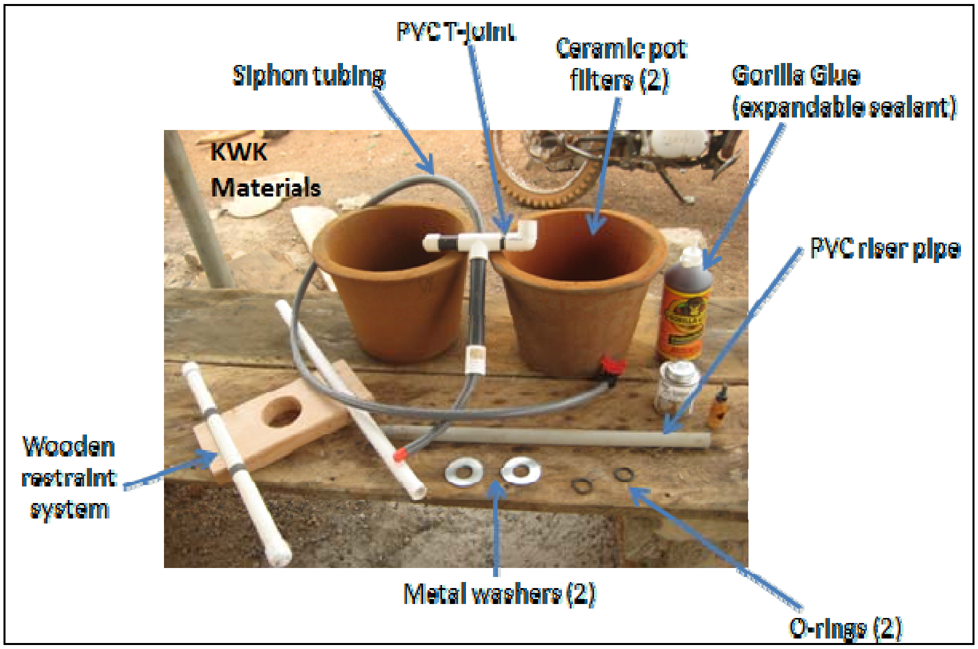
6.4 KWK Construction

Eight KWKs were constructed and tested during January 2011 in Tamale, Ghana at the PHW factory. Six KWKs were made from Ceramica Tamakloe (CT) filters and two were made from PHW filters.

6.4.1 KWK Construction Steps

Figure 5-3 (below) shows all the materials necessary for producing a KWK filter.

Figure 6-3 Photo of KWK Materials



To make a KWK, first, two traditional ceramic filters with flat rims are selected (Figure 5-4 left). A one-inch hole is drilled into the center of each of their bases (Figure 5-4 center) and a one-inch steel washer is glued around each hole (Figure 5-4 right).

Figure 6-5 (left) Center Marked on CPFs; (center) Hole Drilled Into Center of CPF; (right) Metal Washer Sealed Around Hole

Figure 6-4 (left) Best Alignment Found to Match Up the CPFs (right) Gorilla Glue Applied to Rim

Next, the pot filters are stacked on top of each other and rotated to find their best alignment with the fewest gaps between the two rims (Figure 5-5 left). This position is marked with a pen. Glue is applied to one rim (Figure 5-5 right), and the two pots are glued together and allowed to dry with a PVC pipe placed through the pots to maintain a straight alignment.

The interior PVC riser pipe is made from drilling a series of holes in 3/4 inch schedule 80 PVC pipe. A hole in the top of the PVC pipe (inside the assembled keg) prevents a vacuum from forming inside the pipe during filtering. A PVC cap is glued onto the bottom end of the PVC pipe (Figure 5-7 top left), and the other end of the pipe is threaded to be the

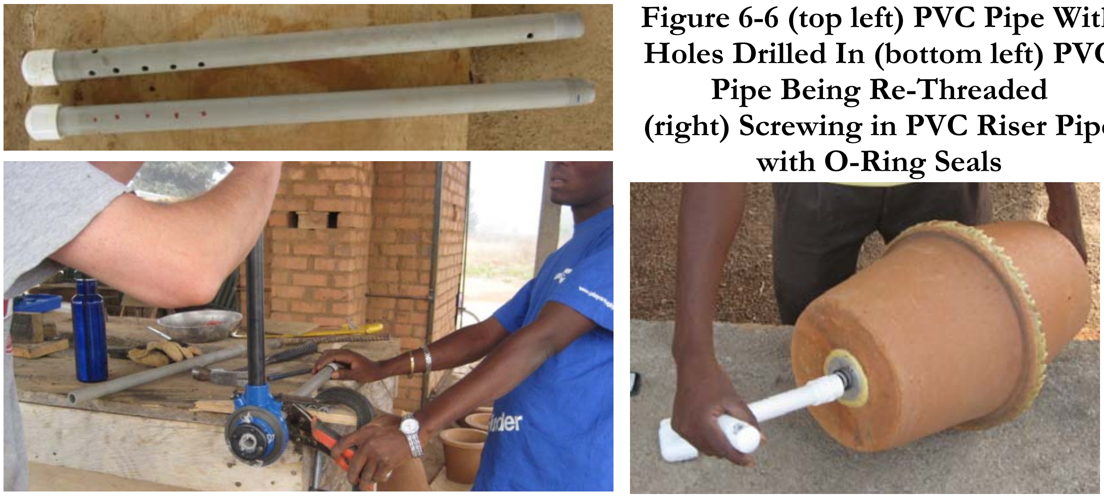


Figure 6-6 (top left) PVC Pipe With Holes Drilled In (bottom left) PVC Pipe Being Re-Threaded (right) Screwing in PVC Riser Pipe with O-Ring Seals

appropriate height (Figure 5-7 bottom left).

An o-ring is added to the pipe, which is then put through the keg and topped with another o-ring and a T-joint. The T-joint is screwed on the top of the keg top to form a compression seal with the PVC cap at the keg bottom (Figure 5-7 right). A 3/8 inch flexible tube is inserted through a hole in the top of the T-joint and water is siphoned out.

Prior to use, the KWK is tested for leaks by screwing flexible tubing onto the top of the keg, submerging the keg underwater, and manually blowing into the tube (Figure 5-6). Places where air bubbles escape the filter are marked, the glue there is filed down, and new glue is applied. The KWKs were not used in this field study until they were able to exhibit acceptably small bubble streams in the leak test.

Figure 6-7 Leak Testing Completed KWK

6.4.2 Lessons Learned from KWK Construction

The KWK construction process went smoothly overall. The three areas that still need improvement are 1) the glue sealant, where in this testing, the glue did not fully expand; 2) the restraint system to keep the KWK submerged and stabilized; and 3) the siphon removal mechanism.

6.4.2.1 Glue Sealant

The glue used as the sealant in the current design was Gorilla Glue, an American expanding water-proof glue. The biggest concern with Gorilla Glue during this trip was its uneven expansion. The glue was not expanding to its expected capacity in the ceramic to ceramic bonding between the two CPF. As the glue dried, some pots had much larger air bubbles in the glue, and these pots, when fully dry, had glue with virtually no expansion. Another problem with Gorilla Glue was that it did not provide a complete seal on its first application. None of the KWKs made with Gorilla Glue passed the leak test after their initial gluing. Even with reapplying the glue two or three times to a leaking site, kegs would still have a leak in the same spot. Sanding down the glue first before glue reapplication helped some, but this was still not enough to consistently completely seal a leak.

Figure 6-8 Holes in the Seal Due to Lack of Gorilla Glue

6.4.2.2 Restraint System

The restraint system serves two functions: 1) it keeps the KWK submerged even when it's empty; and 2) it keeps the KWK centered to prevent it from knocking into the vessel walls and damaging itself or the vessel. The KWK is quite buoyant when empty and is naturally unstable in the water. The current restraint system places the PVC riser pipe through a hole in a wooden block. Grooves in the block hold short pieces of PVC pipe arms. The PVC pipe is cut to catch against the curves of the top of the ceramic water vessel.

The problem encountered with this restraint system was that if the PVC pipes were cut slightly too long, there was a tendency to press down too hard on the KWKs to make the PVC arms fit. This caused the bottoms of the KWKs to crack; two of the four failed KWKs broke this way. While this was due to user error (pressing down too hard on the KWK) the fact that the author made this error twice indicates that inexperienced home users are likely to make the same mistake. Sizing the PVC piping is an iterative process, and longer PVC pipes make the installed KWK more stable inside the vessel. The KWK sinks as it fills with water, and the vessel diameter widens towards the middle, and so the longer the PVC pipes are, the more centered the KWK stays when full of filtered water.

6.4.2.3 Siphon Mechanisms

The siphon mechanism works best for extracting the clean water out of the KWK when the KWK is elevated on a table or stand above the water glass. However, because the KWK was being used in the large, traditional clay vessels, elevating the containers was not feasible. This resulted in the siphon mechanism being unreliable (nearly half of the time, the siphon would not start after the KWKs had filtered all night) and being slow (only 0.59 liters per minute).

6.5 Bacterial Removal Results

Bacteria and turbidity tests were performed from January 18th through January 25th on the Kosim Water Kegs and the ceramic pot filters (manufactured by both CT and PHW). The goal was to compare the bacterial performance of the KWK[15]s to CPFs. While bacterial results would never be better than the ceramic pots that form the KWK, the design goal is to have the KWKs well enough sealed to be able to match the bacterial removal of CPFs. Table 5-1 below shows the bacterial removal of the KWKs made from PHW filters and CT filters compared to the bacterial removal of the PHW and CT pot filters. Results shown were measured using IDEXX Quanti-Tray™.

Table 6-1 Summary of Bacterial Removal for the KWKs and CPFs

	# Filters	N (# of samples)	Coliforms Removal		*E. coli* Removal	
			%	Log	%	Log
CPF-CT Avg	2	2	99.95%	3.3	99.0%	2.0
KWK-CT Avg	***6*** / 4[16]	*20* / 15	*90.8%* / 97.8%	*1.0* / 1.6	*95.5%* / 97.7%	*1.3* / 1.6
CPF-PHW Avg	4	8	65.9%	0.5	90.5%	1.0
KWK-PHW Avg	2	5	10.7%	0.0	70.4%	0.5

This data is preliminary due to the limited number of samples taken (N is 2 to 20). However, the KWK was not able to achieve the same log removal of total coliforms or *E.*

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[15] To name the filters, the type of filter (ceramic pot filter – CPF vs Kosim Water Keg – KWK) comes first followed by the source filter manufacturer (Ceramica-Tamakloe – CT vs Pure Home Water – PHW). When speaking of individual filters, last comes the filter's identifying number (for KWKs) or letter (for CPFs).

[16] Two CT KWKs performed worse than the other four. The first number is the bacterial removal using all six KWKs, and the second number only uses the four best KWKs.

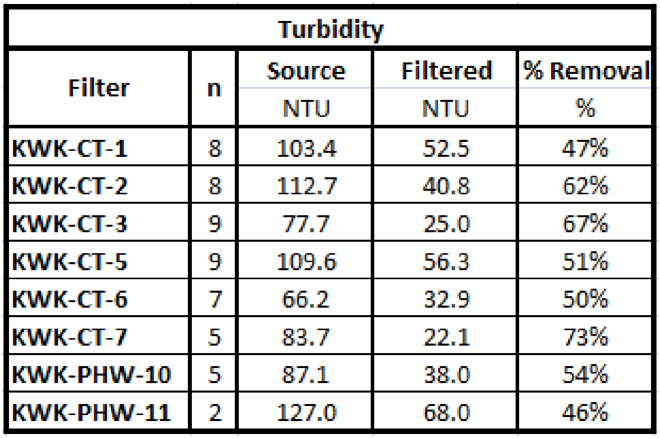
coli as the CPF. The KWK-CTs performed better than the KWK-PHWs. When looking at the KWK-CTs, two of the KWKs performed worse than the other four. Of these two, one failed on the last day of testing, and so likely had smaller cracks forming earlier. The other had trouble forming a good seal with the o-rings. To show how this affected the average performance for KWK-CT filters, on Table 5-1 for the KWK-CT, the first number (in italics) uses all six KWKs, and the second represents only the four better performing KWKS to show how well functioning KWKs perform.

The PHW filters, which were only research filters as the factory was not yet in production, performed poorly as both CPFs and KWKs. These filters were not lined with silver due to time constraints and turned out to be under fired, which is one variable among several that is still being refined at the factory. The KWK-PHWs did particularly poorly with total coliforms removal. During the leak test, no bubbles were visible at the seals, but bubbles were coming out of the ceramic pots themselves, even with very little air being blown into the kegs. The author suspects that the more porous PHW filters allowed the extra hydraulic pressure to push additional coliforms into the KWK.

6.6 Turbidity Removal Results

On average, the KWK filters were able to remove half of the turbidity in water. The table below shows average turbidity for the source water and the filtered water for each keg. All of the source water was dugout water, but not always newly collected dugout water. The variability in the average source water turbidity is because when the filtered water was taken out of the KWK during filtration rate testing, it was poured back into the ceramic water storage vessels. Each evening, additional raw water was poured into the ceramic water vessels until they were full to replace water lost to evaporation. The raw water in the vessels was not regularly mixed, and over the two week period, some particles likely settled out. While this difference in raw water is not ideal, it was not feasible to fully change the water in the water storage vessels each day due to the distance of the raw water source from the testing site and the lack of drainage to remove the existing water in the storage vessels.

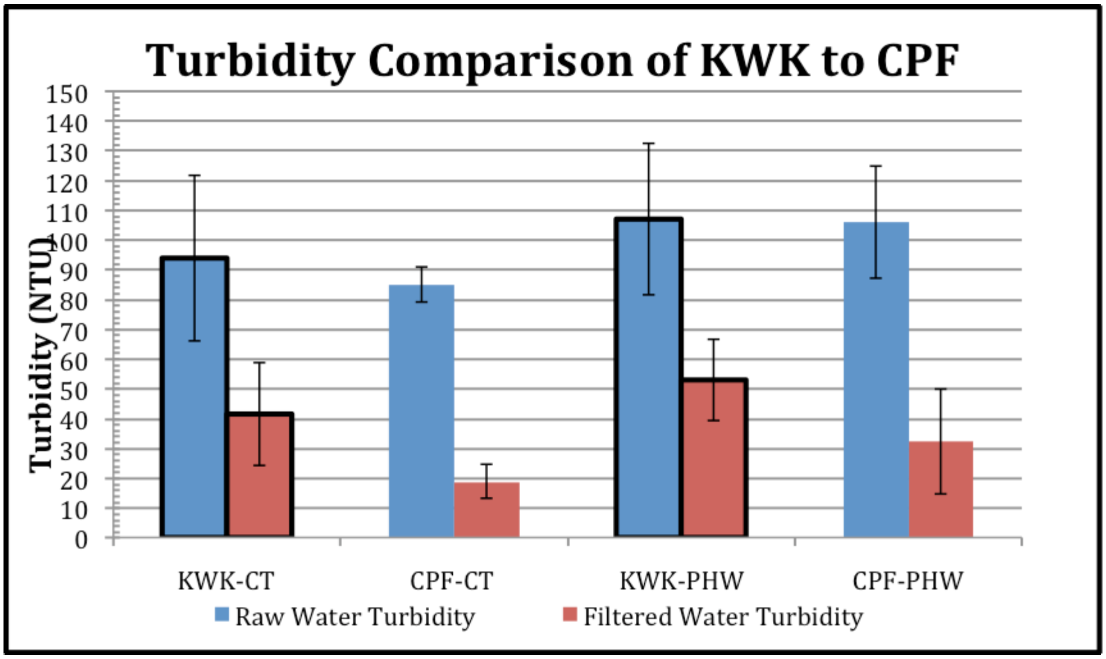
Table 6-2 Average Turbidity Removal For Each KWK



Filter	n	Turbidity		
		Source	Filtered	% Removal
		NTU	NTU	%
KWK-CT-1	8	103.4	52.5	47%
KWK-CT-2	8	112.7	40.8	62%
KWK-CT-3	9	77.7	25.0	67%
KWK-CT-5	9	109.6	56.3	51%
KWK-CT-6	7	66.2	32.9	50%
KWK-CT-7	5	83.7	22.1	73%
KWK-PHW-10	5	87.1	38.0	54%
KWK-PHW-11	2	127.0	68.0	46%

The KWKs were not able to remove as much turbidity as the ceramic pot filters as shown in the Figure 5-9 below.

Figure 6-9 Graph Comparison of Turbidity Removal For KWK and CPF



6.7 Filtration Rates

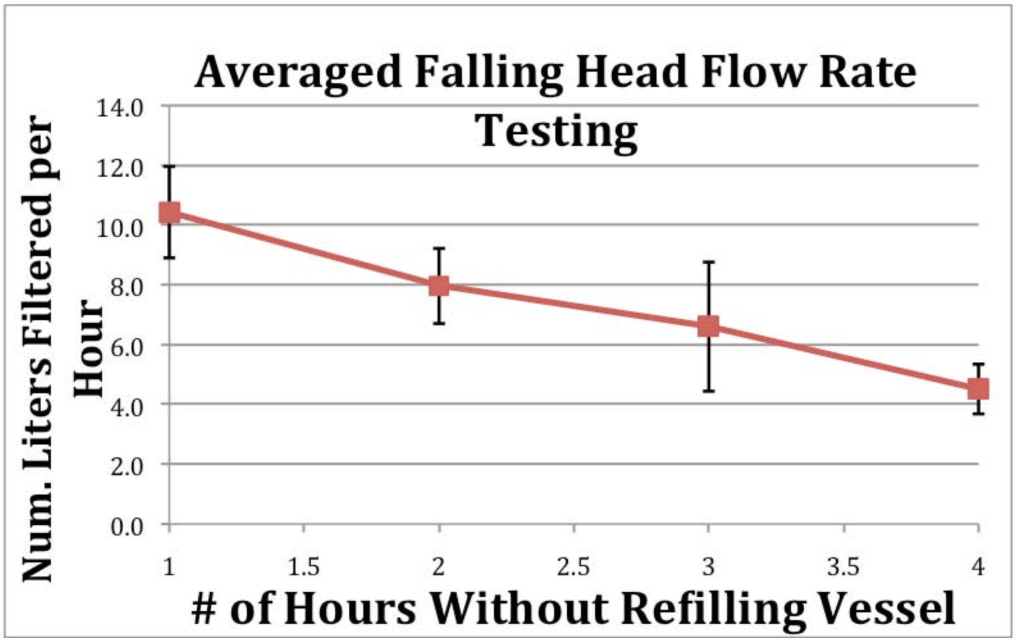
The KWKs were able to filter water much faster than their component ceramic pot filters(ie. the two CPFs that were used to make each individual KWK) as seen in Table 5-3 below (whether a pot is designated as One or Two has no meaning – both pots formed that KWK's body).

Table 6-3 Comparison of 1 Hour Filtration Rate of KWKs vs Component CPFs

	Pot One 1 hr Filtration Rate	Pot Two 1 hr Filtration	Sum of Pot Filters' Filtration Rate	KWK 1 hr Filtration Rate
	L/Hr	L/Hr	L/Hr	L/Hr
KWK-CT-1	2.20	2.85	5.05	11.80
KWK-CT-3	3.30	2.65	5.95	11.23
KWK-CT-5	2.85	3.30	6.15	10.40
KWK-CT-6	1.77	3.00	4.77	11.04

KWK filtration rates were also measured over a four hour period where the raw water was now refilled but the filtered water was removed from the KWK each hour (Figure 5-10). The filtration rates slow down over time due to the reduction in the raw water depth, which powers the filtration, but even four hours later, filtration rates are still well above the fastest filtration rates of the ceramic pot filters.

Figure 6-10 Falling Head Average KWK Filtration Rate



6.8 Siphoning Rate Out of the KWK

The flow rate out of the siphon varied widely during each run, even with the same KWK holding around the same volume of filtered water. Table 5-4 below shows the liters per minute flowing out of the siphon for each liter. This table shows the decline in siphoning rates as the keg drains lower. All of these siphoning rates start with a keg that has filtered overnight, and so they should each have about the same amount of filtered water (15 to 17 liters) in the kegs to start.

Table 6-4 Speed of Siphon (liters/min) for Each Liter Siphoned from KWKs

Liter #	Average	CT-1	CT-2	CT-3		CT-5		CT-7		PHW-10	PHW-11
1	0.69	0.58	0.34	2.00	0.50	0.47	0.57	0.52	0.62	0.74	0.52
2	0.59	0.41	0.50	1.82	0.36	0.40	0.36	0.67	0.57	0.38	0.44
3	0.53	0.38	0.44	1.67	0.44	0.39	0.35	0.44	0.44	0.33	0.41
4	0.55	0.37	0.43	1.71	0.50	0.37	0.34	0.68	0.36	0.32	0.40
5	0.51	0.34	0.40	1.50	0.50	0.33	0.38	0.73	0.34	0.24	0.37
6	0.47	0.32	0.37	1.46	0.49	0.30	0.22	0.70	0.22	0.26	0.33

Quick siphoning times during one test did not predict equally good results the next time that water was siphoned out of that KWK. The best siphoning rate was 2 liters per minute, which occurred once with KWK-CT-3, but the next time siphoning was successful with this keg, the siphoning rate was slightly below average.

Overall, the siphon does not perform well enough to be the permanent water extraction solution. While the siphon mechanism is cheap and easy to make, the siphon performance is too uneven. The first problem is how unreliable the siphon is to start. Even when the KWK filters were full, over 40% of the time, the siphon couldn't last long enough to siphon a full liter out of the keg. When the KWKs aren't full, such as when users are attempting to empty the kegs throughout the day, the siphon is even less reliable. The second problem is that the siphon flow rates aren't as fast as the traditional pot filters gravity powered spigots.

The final problem with the siphon is that it can remove all of the filtered water. At its best, the siphon left behind around four liters clean water. The majority of the time, however, it was leaving ten liters in the keg. This dramatically reduces the functional volume of the KWK and decreases filtering rates

6.9 **Consumer Survey**

Five households tried out KWKs for ten weeks. Amuda Abdul-Rashid, a Pure Home Water employee, followed up with each household weekly to fill out a survey asking how the KWK had performed.

The households reported that the KWK usually provided enough drinking water to meet their needs. Each week, they reported wanting water but not being able to get any out of the KWK only one to three times per week (household sizes varied from 5 to 13 members). The top four characteristics that households like about the KWK are that 1) it purifies the water; 2) the treated water is cooler; 3) the KWK looks nice; and 4) the pumping mechanism. In regard to the fourth point, while people were using the siphon tubing, no one reported actually siphoning out water. Instead they would continually pump the tubing up and down. However, when Mr. Abdul-Rashid checked if the KWKs could siphon, he consistently found that they could, although siphoning one liter of water took between two and three minutes.

In comparison to the traditional pot filter:

- All households thought the KWK filtered faster.
- Opinion was divided on whether the KWK was easier or the same difficulty to use as CPFs.
- Three of the five families thought the KWK was harder to clean.
- Households though that the clarity of the water out of the KWK and the CPF was the same.
- Three of the five households thought KWK water tasted better than the traditional filter's water, and the other two households thought it was the same.

People had no serious critiques of the KWK itself in the middle of the study, but by the end, households did not like having to pump the siphon to extract water, and they found that process to be too slow. All households wanted to be able to cover the storage vessel, and this would require a lid to be designed to accommodate the KWK stem that sticks up above the vessel. The ceramic water vessels produced for KWK testing were of a very poor quality, and users primarily commented on the quality of the ceramic water storage vessel, which is not actually part of the KWK.

6.10 **Conclusions and Recommendations**

The Kosim Water Keg has the potential to be a valuable product for Household HWTS, and it is worth continued research investment. In this small-scale testing, the KWK (using CT filters) could consistently achieve a 1 log reduction in total coliforms and over 1 log reduction in *E. coli*. The best performing KWKs could remove 98% of total coliforms and *E. coli*, and all of the KWKs made from CT filters had at least one filtration test where the filtered water had fewer than 10 colonies per 100 mL, the WHO guideline for "low risk" water (WHO *Guidelines* 2008). However, the bacterial tests done so far have only looked at the KWK performance in the short term. Longer-term testing needs to be conducted on the

KWK to determine what cleaning regime and schedule will preserve the optimal performance of the KWK.

In turbidity removal, the KWKs did not perform as well as their CPF counterparts (KWK removed 55% of turbidity and CPFs removed 83%), but more research needs to be done on the correlation between filtration rates and turbidity removal.

Regarding filtration speed, the KWK distinctly outperforms the CPFs. The KWKs consistently filtered over 10 liters per hour when the raw water vessels were completely full. The KWK could fill its entire volume (up to 17 liters) without needing the user to refill the raw water vessel. This compares favorably to the 2 to 3 liters per hour that the CPF could filter. Overnight, CPFs could only filter 5 to 7 liters in total due to their smaller raw water storage volume. As for accessing the filtered water, the KWK does not do as well as CPFs. The siphoning rate out of the keg was very slow (at 0.55 liters per minute), which compares poorly to the CPFs, which could release over 2 liters per minute out of its gravity fed tap. The siphon could be pumped up and down to remove water, and households who tried the KWK found this to be an acceptable method for removing water. However, the next design iteration should consider new ways to remove the filtered water from the keg.

The KWK does not require any special machinery, and, once the design is fully developed, it should be able to be produced by existing CPF factories after a few days of training. The three areas where the KWK design still needs work is in the sealant between the ceramic pots, the mechanism to remove filtered water from the keg, and the restraint system that keeps the KWK submerged in raw water. The seal between the two pots forming the KWK still needs further development to use materials that will be readily locally available and materials that are more reliable and controllable than Gorilla Glue proved to be. As mentioned before, the siphon removal system from the KWK, while it does work, works very slowly, and other mechanisms, such as hand pumps, that can remove water from the keg cheaply and without electricity should be researched. Chris Shultz, from CDM, has already identified a promising plastic hand pump after the results of this Ghana trip. Finally, the restraint system used to keep the KWK submerged in the raw water also needs improvement to: 1) reduce the stress that it puts on the raw water vessel; 2) improve the stability of the KWK when the keg has filled with water and is sunken lower in the raw water vessel; and 3) be more standardized across different size and shaped water vessels so that each restraint does not need to be custom cut for an individual vessel.

The design of the KWK itself appears to be popular with the target consumers. The households in the survey were positive about the KWK, but more surveys will be needed to determine how much users would actually be willing to pay for the KWK. Several families qualified their interest in the KWK to hedge on price, and families around the PHW factory are likely expecting any water product to be heavily subsidized based on their past experience with NGOs. In order to command a price relative to the cost of producing the KWK, it may be best to emphasize the KWK performance in regard to its ability to cool water down, since this is a property in high demand and easily observable.

7 Conclusions and Recommendations

Five individual projects were conducted as part of the Bilikpin Consulting Team. Background, methodology, recommendations and conclusions are presented in each of the project chapters. The five projects, ranging from developing and improving ceramic filter design, to pilot water sampling and sanitation technologies, all serve to contribute to the progress of Pure Home Water's work.

The water and sanitation realities as shown by the statistics presented in the introduction chapter are sobering and as seen through the five projects, a variety of technical, social and political challenges remain. Recommendations for Pure Home Water are summarized as follows:

- Perform additional research on H2S, detailed in Chapter 2, in order to determine viability. Chapter 2 suggests that H2S and Easygel are potentially applicable for use in Northern Ghana for presence/absence and enumerative testing purposes respectively.

- Continue piloting EcoSan latrines in rural Northern Ghana and explore alternative designs (such as the Bin-Bin and Sanergy latrines). Follow-up with the PHW latrine near the factory and continue sanitation and hygiene education with the PHW staff.

- Continue using the Gbalahi site as a clay source for ceramic filter manufacturing. However, it is possible that a mixture of clay from different sites could improve performance. Finalizing the filter recipe should be a priority for PHW.

- Improve PHW quality control procedures through the following research:
  - Determine the relationship between flow rate, surface loading rate, and bacterial removal efficacy on filters *with and without* silver applied.
  - Establish the maximum flow rate allowable for the PHW filter based on acceptable removal efficiencies (assuming flow rate testing is the most viable 1st quality control parameter).
  - Determine the relationship between the extent of firing and filter flow rate, surface loading rate, strength, and bacterial removal efficiency.

- Invest in further research for The Kosim Water Keg as it has good potential to be a valuable HWTS product.

The Bilikpin Team sincerely hopes that this project report will enable PHW to thrive and excel in the years to come.

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