Ceramic Filter Manufacturing in Northern Ghana: Water Storage and Quality Control

By

Shanti Lisa Kleiman

B.A.Interdisciplinary Studies
New York University
New York, NY, 10003

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Author____
Department of Civil and Environmental Engineering Department of Urban Studies and Planning
May 6th 2011

Certified by ____
Susan Murcott
Senior Lecturer of Civil and Environmental Engineering
Thesis Supervisor

Accepted by____
Heidi M. Nepf
Chair, Departmental Committee for Graduate Students

Accepted by____
Professor Joseph Ferreira
Chair, MCP Committee
Department of Urban Studies and Planning

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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. By 2011, the factory had the molds, supplies, and kiln necessary for large-scale filter production, butneeded to both increase its own water storage capacity, and to implement quality control standards. This thesis documents 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 records work done between January and April 2011 to build water infrastructure for the PHW factoryand to improve quality control for CPF production. Detailed documentation of the design and construction of an underground water storage system, observations about the iterative process of establishing standardized quality control procedures, 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.

Thesis Supervisor: Susan Murcott
Title:Senior Lecturer of Civil and Environmental Engineering

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Abbreviations

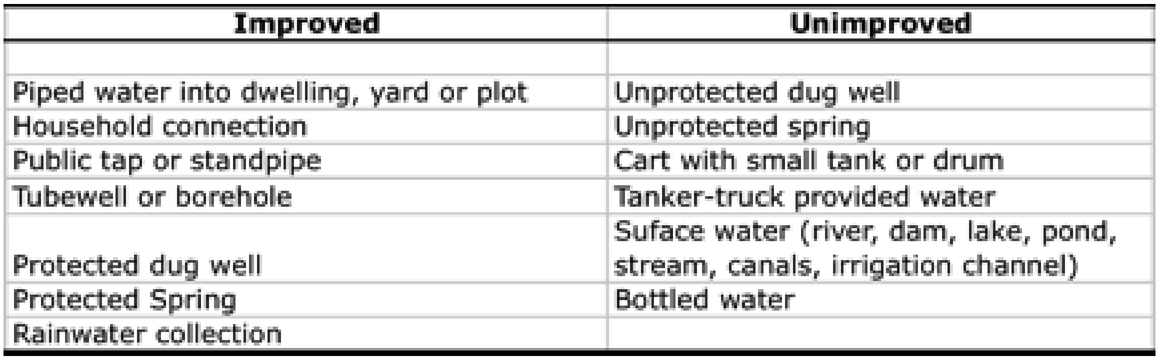
CMWG	Ceramic Manufacturing Working Group
CT	Ceramica Tamakloe Filtron Filters
CPF	Ceramic Pot Filters
ET	Evapotranspiration
HWTS	Household Water Treatment and Safe Storage
JMP	Joint Monitoring Programme
MEng	Master of Engineering
PHW	Pure Home Water
POU	Point of Use
RWHS	Rainwater Harvesting System
UN	United Nations
UNDP	United Nations Development Programme
UNICEF	United Nations Children’s Fund
WHO	World Health Organization

1 Project Background

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. By 2011, the factory had the molds, supplies, and kiln necessary for large-scale filter production, butneeded to both increase its own water storage capacity, and to implement quality control standards. This thesis documents 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 records work done between January and April 2011 to build water infrastructure for the PHW factoryand to improve quality control for CPF production. Detailed documentation of the design and construction of an underground water storage system, observations about the iterative process of establishing standardized quality control procedures, 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.

1.1 Household Water Treatment

The United Nations and the WHO use the terms "improved" and "unimproved" as standard metrics for determining water safety. "Improved" refers to protected water sources including household connections, public standpipes, boreholes, and protected dug wells, protected springs, and rain harvested water. "Unimproved" refers to any type of open surface water, uncovered, or unprotected well.



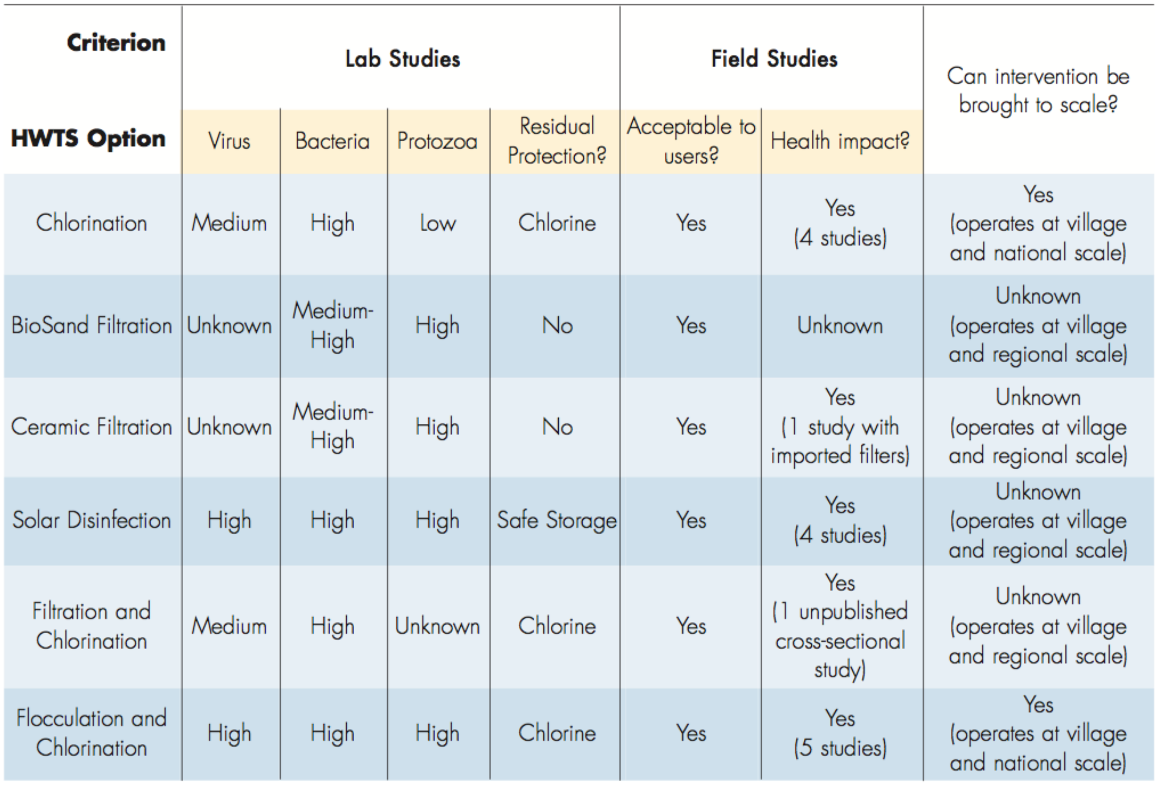
Improved	Unimproved
Piped water into dwelling, yard or plot	Unprotected dug well
Household connection	Unprotected spring
Public tap or standpipe	Cart with small tank or drum
Tubewell or borehole	Tanker-truck provided water
Protected dug well	Suface water (river, dam, lake, pond, stream, canals, irrigation channel)
Protected Spring	Bottled water
Rainwater collection	

Table 1: Improved and Unimproved Drinking Water Sources (Adapted from JMP WHO/UNICEF 2010)

These standards are used to define Millennium Development Goal Target to halve the population without sustainable access to safe drinking water by 2015 (UNDP 2011). However, while these metrics are indicators of infrastructure improvements that may correlate with safe water, they are not truly indicative of the quality of the water being consumed, because pathogens or other contaminants can even be transmitted via “improved” sources. The pathogens of concern include the bacteria, viruses, and protozoa responsible for causing cholera, typhoid, hepatitis, guinea worm, and other water-related diseases. Despite the international and national efforts to improve drinking water supply and sanitation in Ghana, diarrhea still accounts for 12 percent of all deaths of children under five, and Ghanaian children lose an average of 3.4 million school days annually because of diarrhea-related diseases (WHO 2006, WaterAid 2008).

In fact, Fewtrell and Colford published a ground-breaking World Bank study in 2004 suggesting that improvements in water quality, specifically point of use treatment (POU), and hygiene education have a greater impact on reducing diarrheal disease than increased access to sanitation and water supply (Fewtrell and Colford 2004). Adequate water supply and sanitation are very important for improving health, and reducing both the time spent and physical burden of carrying water from distant sources. However, this study showed that waterand sanitation “hardware” alone are not sufficient, and that other approaches to reduce diarrheal disease need to be explored, validated, and funded (WHO 2006).

In 2003 and 2004 Clasen, et. al., published two studies demonstrating that contamination often occurs during collection, transport, and storage of drinking water from improved sources and emphasized the importance of point of use interventions, such as household water treatment and safe storage (HWTS), to improved health. (Clasen et al 2003, Clasen et al 2004). Below,Table 2 shows performance comparisons of various household water treatment options.



Criterion	Lab Studies				Field Studies		Can intervention be brought to scale?
HWTS Option	Virus	Bacteria	Protozoa	Residual Protection?	Acceptable to users?	Health impact?	
Chlorination	Medium	High	Low	Chlorine	Yes	Yes (4 studies)	Yes (operates at village and national scale)
BioSand Filtration	Unknown	Medium-High	High	No	Yes	Unknown	Unknown (operates at village and regional scale)
Ceramic Filtration	Unknown	Medium-High	High	No	Yes	Yes (1 study with imported filters)	Unknown (operates at village and regional scale)
Solar Disinfection	High	High	High	Safe Storage	Yes	Yes (4 studies)	Unknown (operates at village and regional scale)
Filtration and Chlorination	Medium	High	Unknown	Chlorine	Yes	Yes (1 unpublished cross-sectional study)	Unknown (operates at village and regional scale)
Flocculation and Chlorination	High	High	High	Chlorine	Yes	Yes (5 studies)	Yes (operates at village and national scale)

Table 2: Household Water Treatment Comparison (Lantagne et al 2006)

A more recent meta-analysis by Waddington and Snilstveit challenges the research of Fewtrell & Collford and Clasen & Barnstable by highlighting the importance of sanitation "hardware" in reducing diarrheal disease and morbidity over time. According to their study, when long-term studies of 12 months or longer are compared, sanitation hardware has a significant impact advantage over point-of-use water treatment in reducing diarrheal morbidity. They found an inverse relationship between HWTS efficacy and the length of time from installation. However, they also find that household water supply and POU water supply interventions, such as household standpipes or piped water connections or, tend to be more effective than source water supply and source water treatment interventions. Waddington and Snilstveit emphasize that they are not advocating one intervention approach over another, and that local context best determines which intervention is most suitable in a given situation. However, they do challenge the dominant consensus that POU water treatment and hygiene interventions are more effective than sanitation hardware interventions (Waddington and Snilstveit 2009).

A further challenge comes from Schmidt and Cairncross, who argue that scale-up of HWTS may be premature given the lack of conclusive evidence on the effect of household water treatment on diarrheal reduction. They assert that current evidence that links HWTS to reductions in diarrheal disease does not take bias into account, and therefore, double-blinded studies are needed to definitively prove the efficacy of HWTS interventions (Schmidt and Cairncross 2009)

Other evaluation criterion not mentioned in Table 2 but with relevance to Northern Ghana include cost and effectiveness with highly turbid water.Cost is critical in determining the effectiveness of treatment becauseconsumer ability and willingness to pay will often dictate the scale a given intervention can reach. In rural parts of northern Ghana, the average annual income is estimated at US$442 or about US$1.2 per day (Greene 2009); cost is going to be of vital importance in determining feasibility. Additionally, it is not unusual to find extremely turbid water with1,000 to 2,000 NTUin Northern Ghana. Given this high level of turbidity, the effectiveness of a filtration system over time will determine whether it can compete with other methods in terms of sustained positive health impact.

Cost and accessibility can potentially be enhanced when products are made and supplied locally. Pure Home Water is committed to local manufacturing as a part of a strategy for producing and selling ceramic water filters at a low enough price point to achieve its mission of providing safe drinking water through HTWS.

1.2 Water Resources and Access in Ghana

The Volta basin, the largest river system in Ghana, is made up of the Black and White Volta sub basins, the Oti River, and the lower Volta, and drains 70% of the country's total land area (Figure 2). The remaining 30% of surface water resources are provided by the southwestern, and costal river systems (not depicted) .

Most of Ghana’s central and southern regions have two rainy seasons from April to July and September to November while the north is a semi-arid region that has one rainy season per year (Obeng-Bekoe, 2010). Annual rainfall in Ghana varies regionally with the southernmost part of the country receiving an average of 2,100mm/yr and gradually declining to an average of 1,100 mm/yr in the north (Obeng-Bekoe, 2010). This is significant given that only an estimated0.2% of cropland in Ghana is irrigated under public or informal irrigation schemes (Earth Trends 2003). The problem of water scarcity in the north, therefore, has an impact on water availability for drinking and sanitation, as well as productive purposes, pressuring people to compete with plants and animals for this vital resource. Water vulnerability is compounded in the north by extreme variability as well as a gradual trend of an average annual decline in precipitation of about 1.37mm/yr (Amekudzi, 2010)

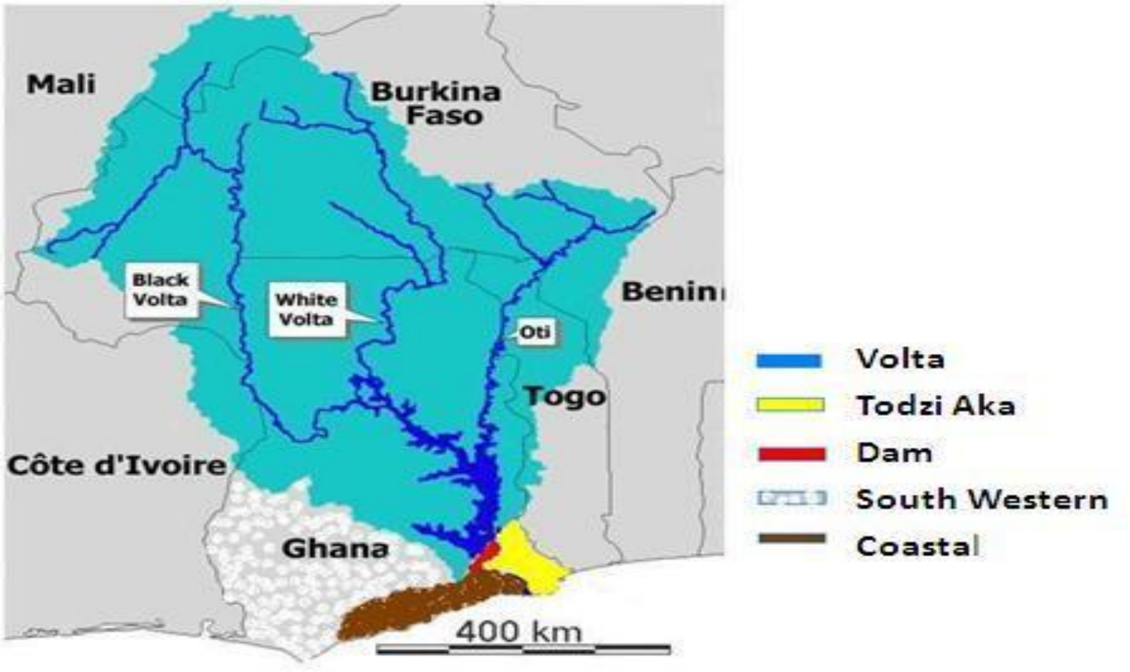


Figure 2: Major Basins and Sub-basins of Northern Ghana (Obeng -Bekoe, 2010)

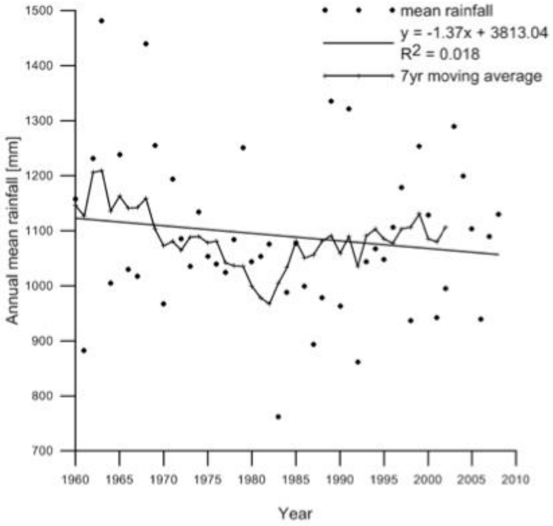


Figure 1: Annual Rainfall in Northern Region 1960-2010 (Amekudzi, 2010)

Water access in Ghana is provided primarily by surface and groundwater with little access to piped water supply. Twenty percent of the country’s population rely on unimproved water sources such as water from the river systems, in addition to open dams known as“dugouts” because they have been “dug out” of the earth in an effort to collect and store rainwater during the rainy season in orderto provide a daily water supply for washing, cooking, drinking and productive use (WHO 2010). In the Northern Region, this figure is much higher with 50% of the population relying on unimproved sources as the main water supply (Ghana Statistical Service 2004). The Ghana Water Resources Commission estimates that there are over 10,000 boreholes countrywide while Water-Aid, a UK-based NGO, estimates that NGOs have partnered with the government to implement 14,000 drilledboreholes with hand-pumps, 12,000 hand-dug wells withhand-pumps, and 800 small piped systems for rural water supply (WaterAid 2008). Piped water supply is limited with an estimated 30% of urban residents and 3% of rural residents connected to piped supply (WHO/UNICEF JMP 2010). An overview of 2010 countrywide statistics on urban and rural water supply is shown below.

	Improved	**Piped Connection**	**Other Improved**	**Unimproved**
Urban	90%	30%	60%	10%
Rural	74%	3%	71%	26%
Total	84%	13%	71%	16%

Table 3: Improved and unimproved water sources in Ghana (Adapted from WHO/UNICEF JMP 2010)

1.3 PHW Organizational History

Founded with local partners by MIT Senior Lecturer Susan Murcottin 2005, Pure Home Water (PHW) is a non-profit organization in Ghana whose mission is to provide safe drinking water to people in Northern Ghana. The organization's goal is to be a self-sustaining non-profit that is able to sell enough water treatment systems and related products to cover its costs. Early student teams from MIT conducted research onHWTS performance, consumer preferences in water treatment techniques, and willingness to pay in order to find the best systems for the region. After also considering bio-sand filters, ceramic candle filters, chlorination systems, and solar water disinfection(SODIS), PHW determined that ceramic pot filters (CPFs) with safe storage containers promised the simplest and cheapest method to effectively clean water in Northern Ghana at a household scale. From 2005-2009, PHW focused on distributing CPFs that were made in Accra, Ghana, teaching people how to use them, and monitoring how effectiveness and durability over time. PHW chose the *Kosim* water filter because it is effective in removing *E. coli* (Johnson et al 2008), has been shown to be linked to the reduction of cases of diarrhea(Johnson et al 2008), can be manufactured almost entirely out of local materials, and is culturally appropriate given that water in Northern Ghana is generally stored in large clay vessels (Watters, 2010).

1.4 PHW Factory

Reason to Build the Factory

As PHW grew, shipping filters from Accra became less efficient. Initially, many filters were broken on the trip from Accra to Tamale. Over time, PHW had trouble with the supplier providing pots behind schedule and with inconsistent quality. In order to eliminate these problems in the supply chain and to better serve Northern Ghana, PHW began constructing its own factory in Tamalein late 2009. While the construction of the building is still ongoing, the factory has the molds, supplies, and kiln necessary for production. In January of 2010, a four-person team of MIT students began work on developing a set of best practices in filter production for the factory. Reed Miller and Travis Watters recommended clay recipes based on the flow rate and durability of test filters made with different proportions of combustible material and clay. Preliminary pot production in the summer of 2010 resulted in pots that were too brittle to be sold. Further work and research has been carried out by the 2010-2011 MIT Ghana team, local management and staff, and Manny Hernandez. The factory currently has orders pending from NGO groups to supply filters for Northern Ghana. Before meeting these orders, quality controls are being established in order to ensure that quality production is achieved.

Rammed Earth Blocks and Factory Business Model

Early attempts to sell Kosim filters at their true production price were unsuccessful because the $18 price of the system was well above the willingness to pay of rural families, particularly the more vulnerable, rural households that PHW aims to serve. In order to meet its goal of being self-sustaining, PHW is testing out the financial feasibility of selling select construction materials-- earth blocks, concrete blocks, and fire-bricks-- as a revenue stream to subsidize Kosim filters for rural families. PHW currently owns standard rammed earth block molds and produces these earth blocks for its own factory construction, but has not yet developed a point of sale for the blocks or contracts with other vendors.

Key Areas of Support Needed

At this stage in the factory's development, PHW needs support in a few key areas: Development of new HWTS and/or water/sanitation/hygiene products to attract a larger consumer base; materials research to ensure standard clay composition and firing; water and wastewater recycling infrastructure; and a review of quality control protocols as part of the larger effort to standardize CPF production processes. In terms of quality control protocols, PHW has considerable experience in Ghana with HWTS and ceramic pot filters, and is an associate with the Ceramic Filter Manufacturing Working Group, which recently released*Best Practice Recommendations for Local Manufacturing of Ceramic Pot Filters for Water Treatment*(Ceramic Manufacturing Working Group 2011).

1.5 Ceramic Filter Manufacturing

Ceramic filters are available around the world in different forms: candle filters, disc filters, and ceramic pot filters.Many of these productsare enhanced with colloidal silver or silver nitrate. The type of filter that Pure Home Water manufactures is the colloidal enhanced ceramic pot filter. In total there are about 35 operational filter factories in 18 countries producing the colloidal silver enhanced pot filter (Rayner 2009).

The filter was originally developed by Dr. Fernando Mazariegos in Guatemala, and later, beginning in 1999, standardized and disseminated by Ron Rivera of Potters for Peace (PFP). In 2010, the Ceramics Manufacturing Working Group (CMWG) published a study on the Best Practices for Ceramic Filter Manufacturing, which surveyed 25 CPF factories on their production and quality control procedures. Based on an extensive literature review and survey results, they produced best practice protocol and standardization recommendations for existing and future factories.

Manufacturing the filter is a multi-stage process that requires quality checks and standardized procedures at each step. The production process can broadly be broken down into the areas listed below adapted from the CMWG manual. A more detailed flow chart from the CMWG manual can be found below in Figure 3.

- Sourcing material
- Mixing clay & burnout material
- Pressing clay into filter pots
- Trimming pressed filters
- Drying
- Firing
- Quality Control
    - Flow rate testing
    - Visual and auditory inspection
    - Pressure (crack) tests
    - Bacteriological testing
- Applying Silver
- Packaging

The goal of PHW is to get production capacity up to 350 filters per month by the end of the 2011, but actual production will be determined by retail customer demand and wholesale contracts. Maximum capacity is currently limited at 75 filters per day based on kiln capacity. However, reaching that level is dependent on having certain mechanized equipment (mixer, hammer-mill, pug-mill), which are currently not available and need to be build or procured (Getachew 2011). Two important factors in reaching this scale will be improvement and standardization of quality control procedures, as well as the construction of a water storage and recycling system for production and employee use. Implementing quality control procedures will enable PHW to produce quality filters, which will build the company's brand while saving both time and money. At the same time, the water storage and recycling system will help Pure Home Water conserve their water for reuse in the Kosim production process and improve the working environment for all employees.

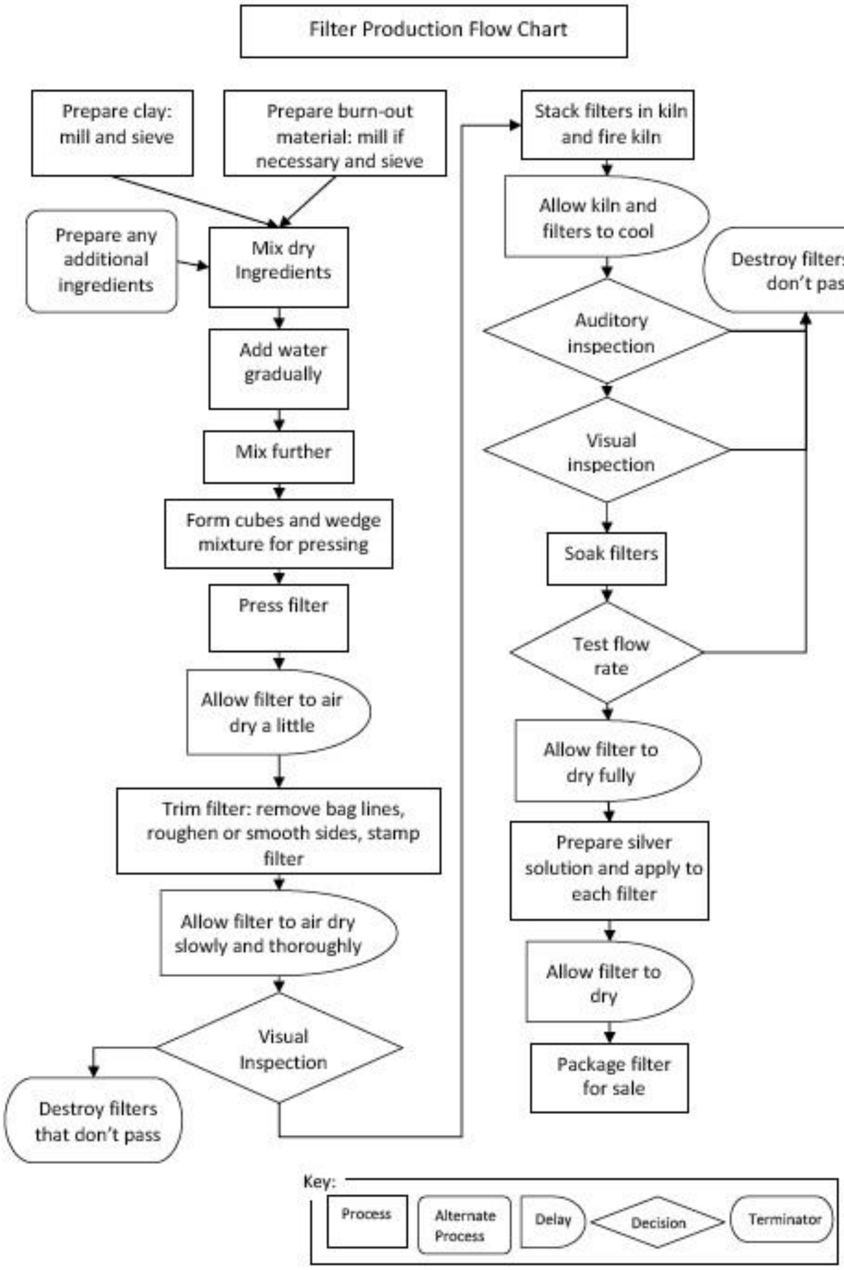


Figure 3: Ceramic Filter Production Chart (CMWG 2011)

1.6 Research Methodology, Structure, and Work Objectives

The main purpose of this work is to help Pure Home Water use their water resources as efficiently as possible and to improve flow rate testing procedures in the PHW factory. These goals were approached through application of the recommendations from the CMWG best practices manual and engagement with a team of experts, including PHW staff and PHW consultants, Manny Hernandez, and Curt and Cathy Bradner.

Participant observation was another significant element of the fieldwork conducted in Ghana. During January 2011, the author collaboratively designed, documented, and participated in water infrastructure construction at the PHW factory. We began the construction of one rainwater storage tank in January and it was completed in April 2011, with the plan to build multiple water storage units for harvested rainwater as finances permit. In addition, we constructed a saturation tank for soaking filters prior to flow rate testing. These two tanks will be connected so that it will be possible to recycle water used in the saturation tanks and the flow rate tests, thereby conserving water and reducing PHW'soperating costs.

Flow rate testing procedures were documented during January with further improvements and documentation by PHW consultants Curt and Cathy Bradner in March and April 2011. This thesis compiles the lessons learned from tank construction and flow rate procedure work in January, and incorporates the latest quality control improvements and recommendations for standardization from Curt and Cathy Bradner. Together these projects intend to contribute to the improved efficiency and quality of PHW Kosim Filter productionand to enable the organization to scale up for increased sales and distribution.Beyond the PHW factory, documentation of the process of building a large capacity (30m^3) underground water tank will be useful to other organizations or businesses with water storage needs.

The thesis can be divided into two main parts: chapters 2 and 3 cover water storage, including a review of the literature on storage tank construction and then a discussion of the construction undertaken at PHW; chapters 4, 5 and 6 cover one aspect of quality control, namely flow rate testing, with a discussion of the literature and then a detailed look at results from testing at PHW. Chapter 7 concludes the thesis with synthesis and discussion.

A central objective of this project was to create a practical document that both providesa record of the water storage design and construction process at the PHW factory, and that documents the iterative process of establishing a new filter factory committed to quality assurance. The author's observations and recommendations are provided as fuel for future areas of research and organizational advancement.

2 Literature Review: Water Storage

2.1 Tank Design: Material, Shape, Placement

Tank placement, shape, and materials are critical to constructing a water storage tank (cistern) that will be effective for a long period of time. More specifically, the following elements should be carefully considered:

- Materials efficiency
- Structural integrity
- Materials availability
- Local construction expertise.
- Aesthetics

(Ludwig 2005a, Gould and Nissen 1999)

Materials efficiency is the ratio of material used to construct the cistern to the volume of water enclosed, which is important in reducing both cost and consumption of natural resources. **Structural integrity** is calculated in order to avoid water leakage, safety hazards, and/or wasted investment from a poorly constructed tank. Designing a tank according to **materials availability** and **local construction expertise** can help avoid wasted materials and ensure a structurally sound tank. If the tank is not designed to withstand internal and external forces, varying weather, and inconsistent use conditions, the tank will have a high likelihood of failure, regardless of the skill or experience of the builders,(Ludwig 2005a). Tanks should be constructed using conservative calculations that include an appropriate safety factor for failure. In flood zone areas, a safety factor of about 1.25 can be used to protect against uplift (Gougen and Thronton 2010). In addition to practical usage considerations, tanks do not need to be ugly or obtrusive in their natural or urban environment. **Aesthetics** is a worthwhile factor in determining tank placement, size, and shape (Ludwig 2005a).

Tank Shape

From a structural and materials standpoint, a spherical or egg shaped tank is most efficient. However, depending on the tank size, available materials, and construction expertise, the most suitable tank shape for a given project may change (Ludwig 2005a). The Portland Cement Association recommends that beyond the bottom and top of the tank, joints should be avoided wherever possible, as this is where leaks are most likely to occur. Ludwig and Gould & Nissen recommend avoiding rectangular tanks and tanks with sharp corners because they are less effective in both materials efficiency and structural integrity, while USAID suggests that rectangular tanks are appropriate in some circumstances but should be avoided for tanks over 2 meters in width. All three authors recommend cylindrical tanks as the most practical shape for tanks holding water of over $10m^3$ holding capacity (Ludwig 2005, Gould and Nissen 1999, USAID 1982)

Building Materials

Water tanks can be built out of a number of materials including, ferro-cement, galvanized steel, stainless steel, rocks and mortar, concrete, bricks, low toxicity plastics, clay, and a combination of masonry in and over plastic (Ludwig 2005a). Concrete construction can be divided into three main methods; ferro-cement, cast concrete, and concrete block. Ludwig and Gould focus on ferro-cement tanks as their design of choice because of structural integrity, ease of construction, and low comparative materials cost. However, Ludwig, Gould, the University of Warwick, and USAID all accept masonry as a viable option when working with experienced builders. They caution that masonry has a tendency to leak and has trouble withstanding pressure forces, so these types of tanks must be reinforced and sealed with cement stucco or another type of water proof liner (Ludwig 2005, Gould and Nissen 1999, USAID 1982).

Placement

Water tanks can be built above or below ground. Advantages of in ground or partially buried tanks include cool water year round,improved taste and quality, little or no evaporative loss, structural support from the surrounding soil walls, preservation of above ground space, overall aesthetics, and reduction of the risk of accidental drainage.(USAID 1982, Ludwig 2005)Disadvantages of underground tanks include greater difficultywith repairs, inspection, and cleaning; they are more structurally challenging to build; and gravity feeding is not possible so water must be pumped out mechanically. Moreover, surface water and shallow ground water can contaminate a tank if seepage occurs (Ludwig 2005).

Ludwig recommends siting tanks with elevation, soil stability and ground slope, security, and aesthetics in mind. Elevated tanks can be an advantage because they allow water to be gravity fed. If elevation is an option, the tank placement should be designed with the spatial layout of water use in mind to avoid common design errors like pumping water downhill (Ludwig 2005). It is best to build tanks in or on “native” soil, meaning soil that is undisturbed and freshly excavated. Building on tilled soil or fill can be hazardous because the soil may not support the weight of the tank causing it to sink, slide or lift. Similarly building on sloped land requires extra analysis to ensure that the tank does not slide down the hill (Ludwig 2005). Security is comprised of both structural security and water quality. Placing tanks away from potential hazards like falling trees or other hazards such as chemical and microbial contamination sources is also necessary(Ludwig 2005a).

2.2 Tank Design: Common Tank Features

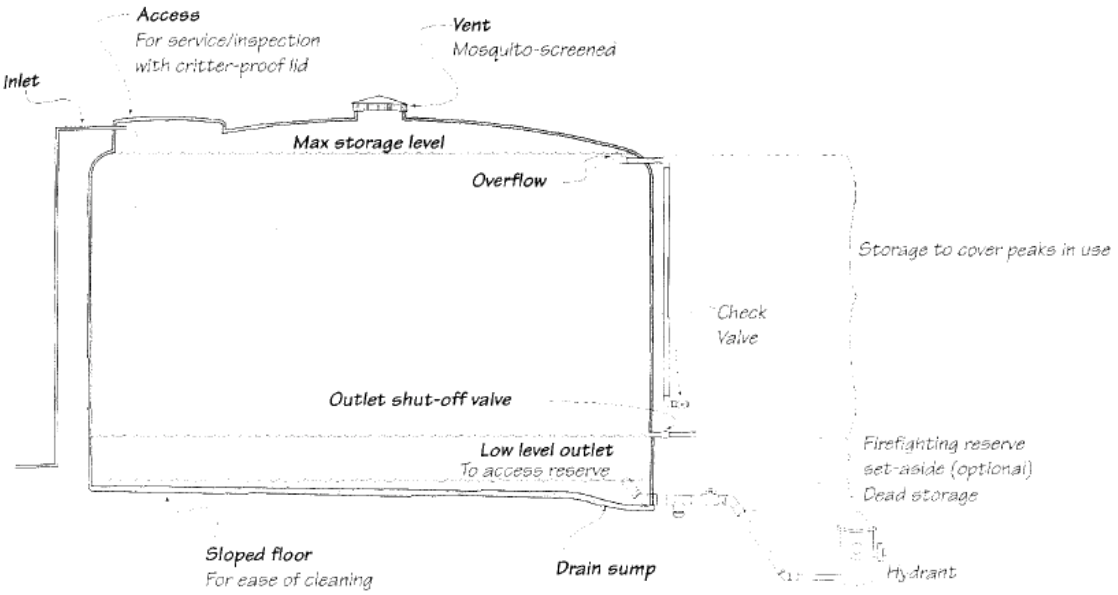


Figure 4: Common Tank Features (Ludwig 2005)

Ludwig (2005), Gould (1999), and USAID (1982) recommend the following tank features in order to avoid some of common problems with water storage.

- Inlet
- Outlet
- Drainage at base of tank
- Impermeable reinforced concrete cover
- Service access
- Overflow pipe
- Screen to keep out rodents and insects
- Air vent
- Protection from the sun

Inlet

Placement of the inlet depends on the location of the water source. If the water source is gravity fed to the tank, then it can be placed in the roof dome. In rainwater harvesting systems the inlet can be connected to a first-flush device, which flushes waters from the first rain in order to allow dirt and possible contaminants to be diverted from the storage unit (Ludwig 2005 and Figure 5). When the inflow is conveyed from the roof, it is important that there is a sufficient angle from the roof to the tank in order to prevent sagging (Ludwig 2005). Gould recommends excavations at least 3 meters below the eave of the roof.

Figure 5: Fixed Volume Device (Left), Sagging Conveyance (Right) (Barnes 2009)

Outlets and Drains

Outlets are where water is extracted from the tank, and drains are where water is drained from the tank for maintenance and cleaning. The outlet and drain can be in two different locations or, if it is designed correctly, they can be one unit. It is important, however, whether one unit or two, that the outlet is placed close enough to the base of the tank to avoid significant amounts of "dead storage" space, but not so low that settled sediment and sludge get into the clean water (Figure 6). The drain, on the other hand, must be placed low enough so that the sludge can be extracted from the tank for cleaning (Figure 7). One-way to do this is to connect a pipe extender to the outlet on the inside of the tank. During regular use the extender ensures that water is extracted from above any potential sediment layer. During maintenance, the extender can be removed so that the sludge flows out the pipe to make cleaning the tank easier (Ludwig 2005). If possible, on the interior wall of the tank, the exit where the outflow pipe is placed should have rounded rather than sharp corners; this reduces turbulence and increases flow rate (Ludwig 2005). For an underground tank, it is necessary to dig an access hole with steps and a cover to the outlet and drain since the bottom of the tank is buried.

Figure 6: 30m^3 Cement Block Tank, Tamale Ghana. Red area is the approximate height of dead storage due to tap/outlet location. (Barnes 2009)

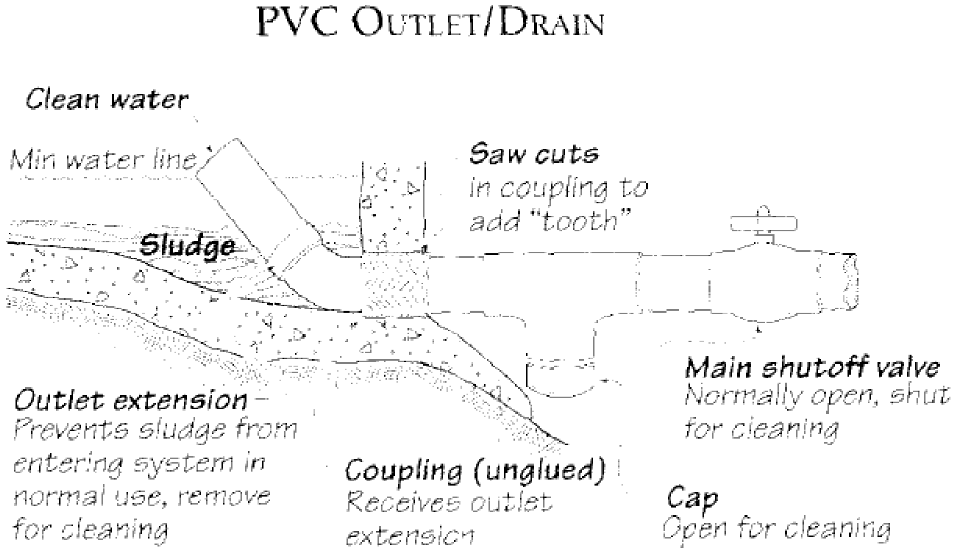


Figure 7: Outlet/Drain as one location. The removable outlet extension lets clean water in when in use and when removed allows sludge to drain out. (Ludwig 2005)

Overflow Pipe and Rodent Proofing

The overflow pipe for the tank is a way to divert excess water and to prevent the tank from pressurizing if water is flowing in but can't get out easily. It can also divert debris and contaminants that float as a film on the surface. The overflow pipe should be placed at the maximum storage line. To maximize water storage this should be as high as possible while also leaving space for air between the inlet and outlet. To design the inlet so that it clears surface water without dumping clean water from the mid or deeper sections of the tank, the outlet spout should sit on the same plane as the maximum water level (Ludwig 2005).

The overflow pipe should also be made rodent and mosquito proof by installing a check valve that allows water out but nothing in. In lieu of a check valve, a wire mesh and screen may be installed to prevent entry (Ludwig 2005).Similarly *all* openings to the tanks including air vents, service access, inflow and outflow pipes, overflow pipes and drains should be properly screened to prevent rodent entry. Valves also help prevent mosquito larvae from being laid inside the piping. Ball valves are fine on most of the access points to the tank. The reason a check valve is recommended for the overflow pipe is so that water is not prevented from exiting the tank if the water level exceeds the maximum (Ludwig 2005).

Concrete Cover and Service Access

While domed roofs are more structurally efficient, flat roofs may be easier to build and support. Ludwig recommends domed roofs with a rise ratio of 0.1 meaning that from the top of the walls, the center point of the roof rises an additional height equivalent to 1/10th of the tank diameter. In large tanks, a central support column should be built and rebar should be installed radially for support. When building the roof service entry, a hatch should be installed. The service entry should be as close to the edge as possible so that a service ladder can be installed in the wall. A service ladder in the wall is better than a portable ladder because it reduces the exposure of the inside of the tank to contaminants.

Figure 9: Service Access (Barnes 2009)

Figure 8: Access ladder (Barnes 2009)

3 Rainwater Tank Construction

3.1 Rainwater Tank Initial Designs and Adaptations

Figure 10: Manny Hernandez discusses tank designs with PHW staff and masons

The tank design was a collaborative effort that benefited from the input of many people including Mary Kay Jackson, Managing Director of PHW, Susan Murcott, founder of PHW, Manny Hernandez, professor and ceramic filter expert, Frank Kuma, a Ghanaian contractor with experience building large capacity concrete block tanks, Joanna Cummings, a fellow MEng classmate, and the author.

Tank construction materials and methods were based on local expertise and availability of materials. Two design decisions made early in the process were, first, to build the tank out of concrete block and, second, to build two storage tanks with 60 m^3 capacity each, one in January and another as soon as financially and logistically possible.

Tank Capacity

Water needs were calculated based on a projected production of 50 filters/day by the end of 2011, and 100 filters/day in 2012. We used the long-term production goal of 100 filters/day to calculate factory water demand. Filter production requires about 2 liters per filter; employee needs were estimated at about 400 L/day (8 employees); flow rate test water was projected at 1000L/day; and saturation tank water was estimated at 9,936 L per month. Water recapture for recycling and reuse from flow rate test water was estimated at 90% while recapture from the saturation tank was estimated at 50%-- bothare conservative estimates. Based on water balance calculations for water extraction and

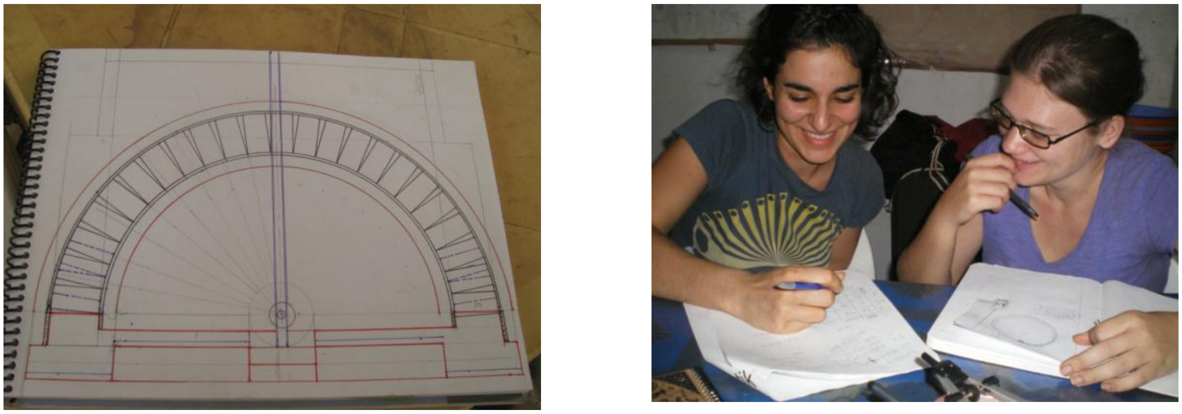


Figure 11: Sketch of foundation cross-section[Hernandez] (Left), Shanti Kleiman and Joanna Cummings sketch tank measurements (Right)

water inputs for a 20-day work month and 9 months of operation per year, (not including production during the 3 month rainy season), we calculated the PHW yearly water demand to be about 160m^3. (See Appendix D for the full calculation). Rainwater supply (S) was determined using the following equation, which did not initially take evaporationinto account.

Yearly water demand estimate

160m^3

S=R*A*C

Where
S is Mean Rainwater Supply (m^3),
R is Mean Annual Rainfall (m/yr),
A is Catchment Area (m^2) and
C is a dimensionless Runoff Coefficient (Volume Collected/Total Runoff Volume)
(Gould and Nissen 1999)

Evapo-transpiration (ET) is an important factor to consider in calculating water balances. However, it is difficult to provide a general calculation for the water loss due to ET because the data available for Tamale and Northern Ghana varies by region, by calculation method, and by season. In addition, calculations for ET also vary with the vegetation that is considered. One study done in the Tamale region compared various methods of ET calculations using NASA Landstat data, daily air temperatures collected over 40 years, and 10 years of daily sunshine and wind-speed data collected at 5 ground stations upstream of the Volta Lake. The average evaporation values found by the study ranged from 1.21-3.90 mm/ day (Opoku-Duah, Donoghue, and Burt 2007). These averages are calculated for ET over a large open water source and could be used for very rough estimates for the PHW water storage units, however, the author does not know what the ET would be for a partly underground, *covered* concrete water storage unit in Taha, Ghana without empirical data.

The PHW factory roof is a corrugated metal roof, which corresponds to a runoff coefficient value of 0.85 (Gould and Nissen 1999). The portion of the roof used for conveyance to the rainwater-harvesting unit is 117 m^2 for half the existing roof, therefore the yearly mean rainwater supply is:

Yearly water supply estimate

104m^3

$S= R*A *0.85= 1.044m*117 \text{ m}^2 *0.85= 103.8 \text{ m}^3$

Based on the demand side need for 160 m^3 to run the factory, and the supply side contribution of 104 m^3 of water, we designed a first tank with 60m^3 capacity. However, this was modified during construction, as will be discussed in the rainwater tank construction section.

If a rough estimate of 2mm/day of evaporation losses is taken into account, the water balance reduces rainwater capture by about 70% to:

$S= R*A*0.85 = (1.044m-.73m)*117 \text{ m}^2 *0.85= 31.2 \text{ m}^3$

If these losses are accurate, a tank of 60m^3 is too large, unless extra capacity for the storage of tanker water is desired. After design adaptations and modifications, we built a tank with a capacity of about 27 m^3. Currently, there is no production of CPFs during the rainy season and consequently, no water withdrawals from the tank during the three-month rainy season. PHW should therefore be able to assess if the rough estimate of 2mm/day of evaporation is an over or under estimate based on whether the tank fills to capacity during that time.

Construction Method and Costs

In his 2009 survey of rainwater harvesting systems in Tamale Ghana, Barnes did a cost comparison of tanks built in the area, finding examples of plastic storage tanks, ferro-cement tanks, concrete block tanks, as well as informal storage systems. The plastic storage option had the highest costs at USD$100-125/m^3, whereas most of the storage options surveyed had a *construction* cost of between USD$71-$167/m^3 of storage capacity (Barnes 2009). While storage costs for a large capacity RWHS are high, it will allow PHW to reduce the amount of money spent on purchased of water. Currently PHW is paying USD$28-35/m^3 for the purchase of trucked water.

The three most viable storage options available locally included plastic tanks, ferro-cement tanks, and concrete block tanks. Plastic tanks were excluded because of the prohibitive cost for the large 60 m^3 (15,850 gallon), storage capacity needed for the PHW water factory. The examples of concrete block tanks constructed in the vicinity cost $3,500 for 75 m^3 (USD$46.6/m^3) including conveyance, hardware, and labor. However, these $3,500 tanks were subsidized by the NGO, World Vision, and the amount of subsidy is unknown. Therefore, it is difficult to assess the actual price/m^3 of water. The Presbyterian Church of Tamale builds 10m^3 capacity ferro-cement tanks which cost $708 (USD$70.8/m^3), including conveyance, but excluding labor costs, which in their case, is often provided by the community in which the tanks are installed (Barnes 2009). Ludwig (2005b) estimates the cost of a 56,000 L tank to be about USD$38/m^3, although his estimates are approximate, excluding labor and not calculated using Ghanaian material prices (see Appendix B), while Gould and Nissen (1999) estimated large capacity underground ferro-cement tanks to cost approximately USD$21/m^3.

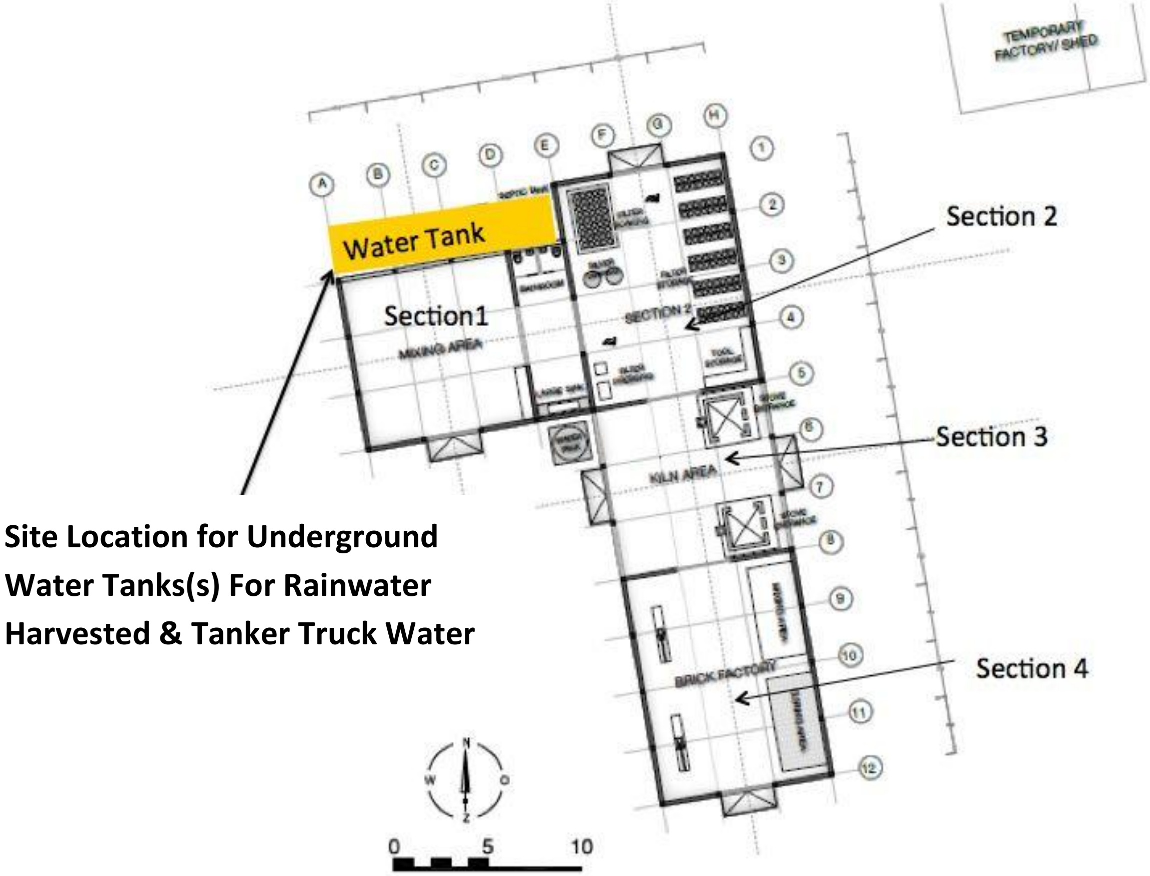
Despite lower cost estimates for larger ferro-cement tanks, the choice was made to use concrete block construction because we knew of no local contractors with experience building large ferro-cement storage units (above 10m^3), and so both the ferro-cement tank construction method and cost savings were only theoretical, whereas there was tangible local knowledge in working with concrete block for tanks over 10m^3. We also considered using poured concrete and forms instead of blocks to build the walls, but again, while poured concrete is a commonly used method to build water tanks in many parts of the world, there were no local resources that we were aware of in and around Tamale. Concrete block, on the other hand, is readily available in Tamale, and the local masons are familiar with concrete block construction.

Type of storage	Storage Capacity for System [m³]	Cost of System [US$]	Cost of Construction per m³ [US$/m³]	Notes
Ferro-cement	90	1900	21	*Gould and Nissen Estimate*
Ferro-cement	56.8	2169	38	*Ludwig Estimate* Materials Only - Storage Only
Ferro-cement	37.8	1641	43	*Ludwig Estimate* Materials Only - Storage Only
Concrete Block	75	3500	47	*Subsidized by World Vision* Subsidy amount unknown
Ferro-cement	18.9	1102	58	*Ludwig Estimate* Materials Only - Storage Only
Ferro-cement	10	708	71	*Presbyterian Church Tank* Includes conveyance – not labor
Plastic (5 units)	50	8333	167	*World Vision Tamale Offices*

Figure 12: Cost comparisons of different tank types common in Tamale, Ghana (Barnes 2009; Ludwig 2005b; Gould and Nissen 1999)

Tank Design and Adaptation

The tank was initially designed to be a rectangular concrete tank, however, after discussion and basic force calculations on uplift using the “Tank calculations” tool from (Ludwig 2005b) on tank design, we found that the cylindrical tank had a slightly better safety factor against uplift (1.17 vs. 1.35)(see Appendix A). Based on the literature review for this thesis, the author did rough designs for the inlets and outlets, but most of the tank design for the foundation and reinforcement happened on the ground and in the sketchbook of PHW factory consultant Manny Hernandez. Tank design was a collaborative process. The foundation and the initial design for reinforcement was the work of Manny Hernandez and the author, with the input of other engineers on site: Mary Kay Jackson, Joanna Cummings, Mitchell Westwood, Susan Murcott, and Chris Shultz. As Manny's other factory construction responsibilities took precedence, the decision was made to contract a local RWHS expert, Frank Kuma, who assumed project management responsibility for completion of the RWH tank after the initial design and during foundation construction. Frank Kuma contributed design evaluations, modifications, as well as construction oversight and management based on his experience as a contractor for water infrastructure projects and his previous work building concrete block tanks. To increase the safety and stability of the tank, we decided on a 1ft deep reinforced footing under the wall, and a 6-inch overhang, which would extend beyond the wall. In addition, Frank Kuma and Manny Hernandez recommended that the blocks be turned to sit on the 9 inch x 18 inch surface for the underground portion of the tank to increase stability. After the site excavation, we also discovered that the soil strata was predominantly clay towards the base of the excavation on the corner farthest from the factory, and predominantly laterite on the corner of the excavation closest to the factory. Frank suggested that we place the cylindrical tank towards the factory side closer to the laterite soil and away from the clay to protect against leakage into the tank from the cracked clay layer, which is likely to hold water around the tank and prevent drainage during the rainy season.



Site Location for Underground Water Tanks(s) For Rainwater Harvested & Tanker Truck Water

Figure 13: Factory layout schematic (Courtesy of Chris DeVries 2010)

The Shrinking Tank – A Cautionary Tale

While the initial tank was designed to accommodate 60 m^3 of water, the final tank can hold about 27 m^3, less than half of that the original calculations.

The 1st reduction: The tank began as 15 x 20 x 8 feet; the first reduction resulted from the excavation of the rectangular hole in advance of the design, which set certain constraints. The difficulty of hand digging though laterite and clay and the 3-week schedule in Ghana meant that whatever shape the tank was, it would be confined to fit within 15 x 20 feet.

The 2nd reduction: When the team decided that, for structural reasons, the tank should be cylindrical, this meant that the maximum possible tank outer radius was 7-feet 6-inches. To compensate for the loss in cubic feet of storage, we increased the tank height to 10-feet. Still, this change reduced the capacity by 33%, from 60,258L to 43,568L.

The 3rd reduction: The next decision was that a 6-inch footing (a reinforced foundation that extends beyond the outer radius of the wall) would provide extra stability and security against uplift forces, as well as space for masons to work on the outside of the tank from inside of the hole. The original rectangular design allowed for a 6-inch footing while still achieving 60,000L capacity. The footing on the cylindrical tank, however, reduced the outer radius of the tank to 7-feet and the holding capacity a further 14%, to 37,565L.

The 4th Reduction: The decision to turn the blocks on the long edge, so that the space from the exterior to the interior of the wall was 18-inches, resulted in another large reduction. While we originally allotted for 6-inches of the radius to be taken by block thickness, now blocks occupy an additional 12-inches of space. This was the correct decision for sound tank design, but reduced the inner radius to 5-feet 6-inches and storage capacity by 28%, to 26,897L.

In total, the tank capacity was reduced to 55% of the original design. Because this was a process that was unfolding on the ground with workers already hired, materials already purchased, and a time frame of 3 weeks to get the project underway, it's difficult to imagine that any of the decisions would have been made differently. They were the correct decisions in the moment and the logical next steps in a process that was already initiated, but, because these decisions were determined on the ground, we didn't have time to analyze their impact on our larger goal of providing storage for half of PHW factory's productive needs. The implications of this are that we ended up with a tank that was smaller than it otherwise would have been if we had anticipated some of these choices in advance. On the other hand, we ended up with a tank that was designed based on the best decisions taken under the pressure of time.

Construction Schedule

The construction of the rainwater tank is complete as of April 2011. The following is the construction schedule:
Nov/Dec 2010 - Excavation: Workers at PHW excavated the pit for the rainwater tank. The excavators used pick-axes and head pans to dig and clear the material from the pit. It took 3 people 12 days to dig the pit

January 2011 - Foundation
February 2011 - Walls and Roof
March and April 2011 - Inlets, Outlets

3.2 Building the rainwater harvesting tank foundation: Picture Log

Figure 14: Hernandez and Kleiman measuring radius of tank inside of excavated pit

Figure 15: Using pic-axes to break up the ground and dig the tank footing

Figure 16: Footing and center hole dug and ready for 2-inch base layercenter pole hole.

Figure 17: The mason applies a 2-inch base layer (1:3 cement to sand ratio) to the bottom of the footing, tank base

Figure 18: 2-inch base layer applied

Figure 19: This layer was kept moist with wet burlap bags for two days while it dried

Figure 20: The steel bender bending1/2 inch rebar

Figure 21: Close up of rectangular pieces that binds concentric circles of rebartogether for the footing

Figure 22: Close up of the jig used by the steel bender to bend rebar rod

Figure 23: Frank Kuma explains the design for reinforcement

Figure 24: Rebar reinforcement lifted down into excavated area for the footing

Figure 25: The steel bender links reinforcement for tank floor with reinforcement for footing

Figure 26: The steel bender begins radial reinforcement

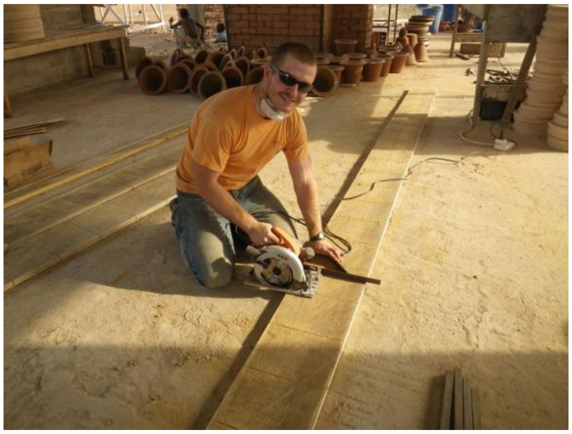


Figure 27: Mitch Westwood kerfs planks of wood for the formwork

Figure 28: Shanti Kleiman and Zachary nail plywood to the kerfed boards

Figure 29: Shanti Kleiman and Mitch Westwood patch up the circular forms after bending the wood into a circle

Figure 30: Finished forms

Figure 31: Carrying the outer form over to the excavated site

Figure 32: Lowering the outer form over the center-pole and around the rebar reinforcement

Figure 33: Carrying the inner form

Figure 34: Lowering the inner form

Figure 35: Raising center pole

Figure 36: Securing and positioning pole exactly at tank center using a level and 4 cables

Figure 37: Using rotating arm on the center pole to ensure accurate placement of the inner form. Cutting a hole in the outer form for the placement of a 4 inch PVC outlet and drainage pipe

Figure 38: Roof support pole raised and centered. The steel bender continues work on rebar reinforcement

Figure 39: Stone chips are delivered for use in the foundation cement mixture

Figure 40: Water is delivered for mixing the cement for the foundation

Figure 41: Pile of cement, sand, and aggregate (1:2:4 ratio) ready for manual mixing

Figure 42: Foundation pouring happens one head-pan at a time. Westwood stands on the stairs ready to pass down another head-pan full of cement to Sadat, who passes to Mr. Kuma, to pour into the foundation

Figure 43: The team works from 9am until 9:30 pm, using the head lamps of Mr. Kuma's truck as work lighting

Figure 44: The forms are removed the next day

Figure 45: Finished Foundation

Figure 46: Finished foundation is covered with wet burlap sacks to keep it moist while concrete dries

Figure 47: Post-January work: Wooden roof supports inside of tank

Figure 48: Post-January work: Tank walls are plastered with stucco

3.3 Building the tank: Results

After tank completion we ended with a tank of 26,897L capacity with a cost of GHC $6108.46 (USD$4183.80, or a cost of USD $155/m^3. The cost per cubic meter is approximately the same as the plastic storage option and higher than other local options. However, the concrete block tank should have a design life of 20-30 years, whereas a plastic storage tank has a design life of only about 10 years due to UV and weather degradation. Therefore, there may be a clear advantage in the long term of investing in concrete tank storage rather than plastic storage. The decision matrix below is based on the cost of construction of the PHW concrete block tank during January-April and the costs of known alternative options to concrete block tanks in Tamale. Note that it is possible that a lower cost could be secured for the construction of the concrete block tank depending on contractor and materials procurement. A next step for PHW will be toinquire with World Vision about their concrete block tank costs, whether they include labor, and to whom they contracted the construction work.

Tank Type Options	Cost	Product Life	Supports Local Economy	Total
Plastic (10m^3 x 3)	*	*	*	3
Concrete Block (30m^3)	*	**	***	6
Ferro-cement (10m^3 x 3)	***	**	***	8

Table 4: Decision Matrix for Future PHW storage tanks -ranked *Fair, **Good, and ***Best.

Based on existing information, the author recommends that for the construction of additional tanks, PHW should consider contracting the Presbyterian Church to build ferro-cement tanks on the PHW factory site. It is possible that the Presbyterian Church can build tanks with greater than 10m^3 capacity, which would have greater materials efficiency and be lower cost than three 10m^3 tanks. However, even if they cannot build large capacity tanks, the cost per m^3 of the 10m^3 tank is 54% less than the current 30m^3 concrete block tank. If a concrete block tank is desired, the author recommends hiring a local contractor to see the project through from start to finish with a pre-drafted budget for materials and labor.

4 Literature Review: Flow Rate Testing& Removal Efficacy

4.1 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 3 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).

The Kosim and other CPF enhanced with colloidal silver remove harmful pathogens from water in two main ways. The filter acts as a sieve to remove protozoa and bacteria that are too large to pass through to the safe storage receptacle, while the colloidal silver acts as a bactericide that limits bio-film growth. The filter has not demonstrated efficacy at removing viruses (D. Van Halem 2009). See Table 5for the size ranges of bacteria, helminthes, protozoa, and viruses.

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).

Organism	Disease	Remarks	Size Range
Bacteria			0.3-100 µm
Escherichia coli	Gastroenteritis	Diarrhea	
Salmonella typhi	Typhoid Fever	Fever, diarrhea	
Salmonella	Salmonellosis	Food poisoning	
Vibrio cholerae	Typhoid Fever	Heavy diarrhea, dehydration	
Viruses			0.02-0.2 µm
Enteroviruses (67 types including polio & echo)	Gastroenteritis, heart anomalies, meningitis		
Hepatitis A	Infectious hepatitis	Jaundice, fever	
Rotavirus	Gastroenteritis		
Protozoa			8-100 µm
Cryptosporidium	Cryptosporidiosis	Diarrhea	
Entamoeba histolytica	Amebiasis	Diarrhea, bleeding	
Giardia lamblia	Giardiasis	Diarrhea, nausea, indigestion	

Table 5: Commonly Known Waterborne Disease-Causing Organisms (Metcalf and Eddy, 1991)

4.2 Flow rate and removal efficacy

Performance studies of the filter element range widely in methodology. Of thirteen studies surveyed for this literature review, five studies were of new filters, twelve studies were of filters no older than 2-years, and one study, a longevity study, sampled filters of varying age. Studies range from n=1 filter to n=72 filters and vary from one time sampling to sampling over 6 months. About half of the filters studies tested the Potters For Peace "Filtron" filter from Nicaragua, while two studies tested RDIC's filter (Cambodia), one study tested Filter Pure's filter (Dominican Republic), four studies tested Tamakloe filters (Ghana) distributed by PHW, and one study tested the PHW filter manufactured in Tamale (Ghana). Five of the thirteen explicitly explore the relationship between flow rate and efficiency, while the others investigate areas such as filter longevity, hydraulic modeling, comparison with other water treatment methods, performance of filters under field conditions, silver application, optimal ceramic filter composition, and knowledge of physical characteristics of the filters such as pore size distribution (Bloem et al. 2009; Duke, Nordin, and Mazumder 2006; Campbell 2005; Fahlin 2003; Klarman 2009; Lantagne 2001b; Lantagne 2001a; Miller 2010; Napotnik et al. n.d.; Halem 2006).

The performance of CPF in removing pathogens is generally measured by log(10) reduction values (LRV) for indicator organisms (Brown and Sobsey 2006). Log(10) reductions below 1 are unacceptable for treatment system performance (Brown and Sobsey 2011). The most common indicator organism measured is the bacteria Escherichia coli, although two studies have also measured the removal efficiency of protozoan oocysts and MS2 bacteriophages (D. Van Halem 2009). LRV is calculated as a function of the influent and the effluent concentration of indicator organisms. Therefore, if the effluent has a non-detectable level of indicator organisms, the maximum log 10 reduction cannot be found (Brown and Sobsey 2006). Brown and Sobsey recommend taking log reduction value to be minima, while Van Halem and Bloem spiked the influent water with high levels of *E.coli* to ensure that there would be detectable levels in the effluent (Brown and Sobsey 2006; D. Van Halem 2009; Bloem et al. 2009). Despite the absence of the maximum log(10) reduction for most of these studies, the majority show a log (10) reduction between 2-3 and Van Halem achieves a log(10) reduction of 7 (D. Van Halem 2009).

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 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 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 filters 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 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.).

In a 2009 paper, Halem argues that factories should consider eliminating the practice of silver dipping to reduce filter cost because the removal of sulfite removing Clostridium spores was equally effective with and without silver, retention of MS2 bacteriophages was better in filters without silver application, and the removal of E. coli K12 was found to be very high without silver application (D. Van Halem 2009). Filter flow rate depends on the quality of influent water, the hydraulics of the filtering element (shape, size, composition), the average pore size and consistency of pore size distribution achieved from the manufacturing process, the height of the water in the filtering element, and the frequency with which it is filled (Rayner 2009). Lantagne found that silver application does not affect flow rate (Lantagne 2001a). 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 (Halem 2006; Ceramic Manufacturing Working Group 2011).

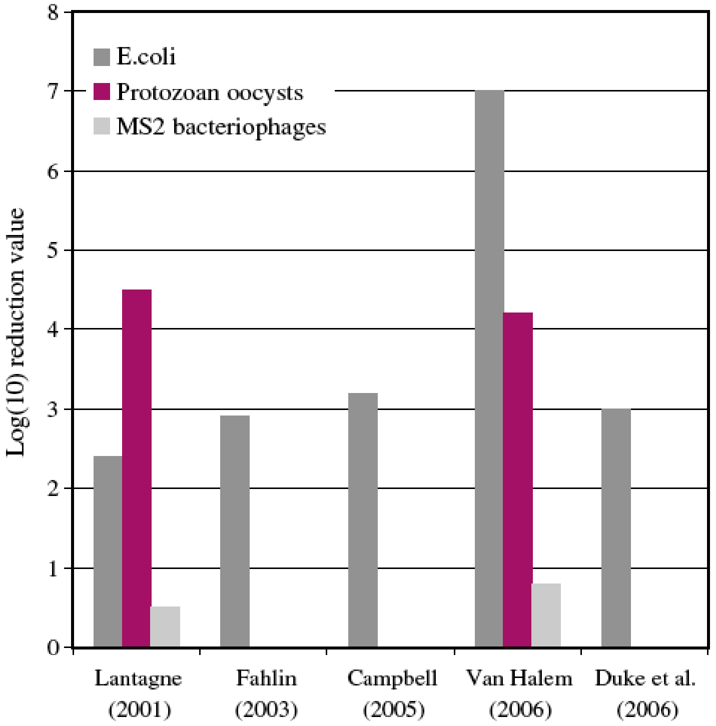


Figure 49: Removal Efficiencies in Nicaraguan Ceramic Pot Filter (Van Halem,2009)

4.3 Flow Rate Procedure

In Rayner's2009study 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.

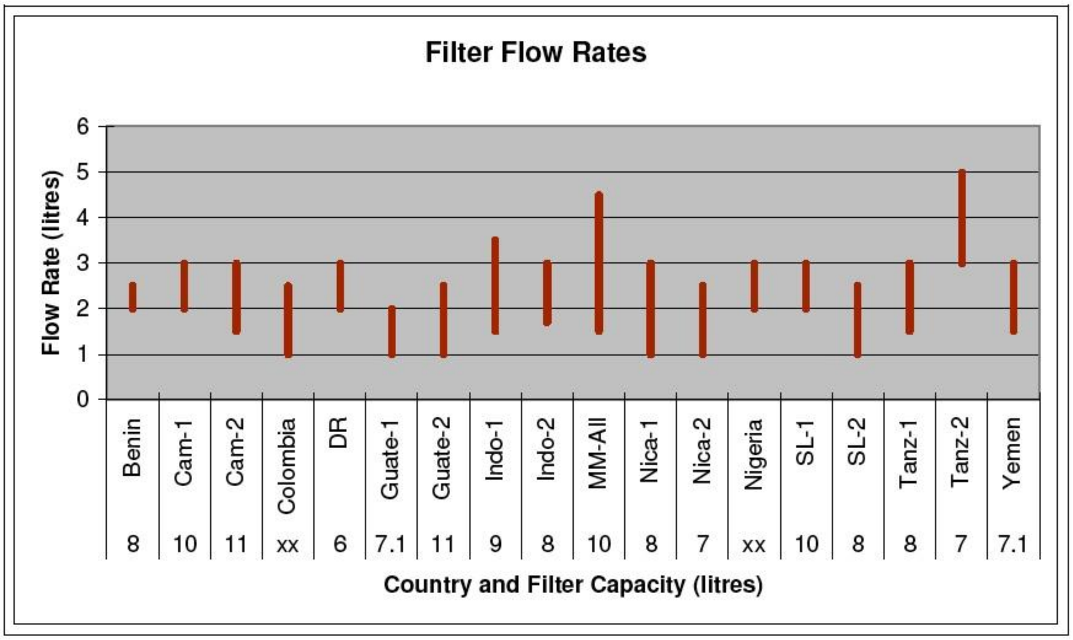


Figure 50: Maximum Flow Rates and Filter Element Capacity (Rayner, 2009)

Recommended practice is to soak filers for 12-24 hours in order to ensure both *consistent* and *maximum* flow rates (Halem 2006; Hagan. J. M. 2008; Rayner 2009; Ceramic Manufacturing Working Group 2011). While both measuring effluent and using a T-device work, the T-device allows measurement without removal of the filter element from the bucket while partially full. In addition, it ensures that for testing purposes, the filter is being filled to the same level each time, which provides more consistent testing conditions. Nardo suggests that maximum flow rate can be measured in the first 15 minutes and multiplied by 4 to get the maximum flow rate per hour (Nardo 2005). This method would be representative of a maximum flow rate for a household that tops their filter up with water every fifteen minutes, but not of the flow rate in the first hour as the rate of filtration decreases as the filter empties. Rayner, RDI-C, and CMWG recommend taking measurements after an hour of filtration. The flow rate for all filters destined for distribution should be tested and recorded in a log that corresponds with the filter's unique identification method. After the filter elements are measured, the filters should be set out on racks to dry in preparation for silver application (Halem 2006; Hagan. J. M. 2008; Rayner 2009; Ceramic Manufacturing Working Group 2011).

5 January Results: Flow Rate Testing

5.1 Building the Saturation Tank

An effective way to soak filters is to construct a saturation tank where filters can be stacked and soaked overnight. As discussed in the previous chapter, most factories soak their filters prior to flow rate testing in order to establish conditions for standard results (Rayner 2009). The RDIC and CMWG manuals recommend soaking filters for 12-24 hours, while RDIC notes that a minimum of 5 hours is acceptable (Hagan. J. M. 2008; Ceramic Manufacturing Working Group 2011). The RDIC Cambodia factory has a tank that fits 120 filters when filters are stacked 3 high, enabling production of 2880 filters per month (Hagan. J. M. 2008; Rayner 2009). For the PHW saturation tank, we designed the size based on a short-term projection of the production of 50 filters per day by June of 2011. The PHW tank can hold 90 filters when stacked 3 high.

The PHW saturation tank was constructed by Ghanaian masons using concrete block, which is commonly used in Tamale for tank construction, and therefore, was inexpensive and readily available. The tank took two days to construct and cost approximately US$144. See table below for a cost breakdown.

Item	**Unit Cost (GHC)**	**Number**	**Total (GHC)**	**Total Cost (GHC) (USD)**
Cement Block	1/block	46 blocks	46	
Cement	14/bag	1.5 bags	21	
Sand	150/truckload	1/20 of a truckload (approx 5 wheelbarrows)	7.5	
Water	0.05/liter	30 liters	1.5	
Tank Water Sealant	750/container	1/10 of container	75	
Skilled Labor	10/day	2 masons, 2days	40	
Other Labor	5/day	1 person, 2 days	10	
Exchange Rate 1/11/10: 1 USD to 1.46 GHC				201 **(US$143.6)**

Table 6: Saturation Tank Construction Costs

It is recommended that flow rate water be < 5 NTU to ensure that flow rates are accurately testing maximum values (CMWG 2011). The PHW Factory saturation tank was designed to allow for the water to be flocculated and recycled to the adjacent rainwater-harvesting tank. The outlet to the tank is fitted with a 45-degree angle elbow set into the floor of the tank. A detachable foot long length of 1.5-inch PVC pipe is attached to the elbow and fitted with a removable cap. When the saturation tank water needs to be changed, water is flocculated and clear water recycled into the rainwater tank while the sediment stays at the bottom of the tank. The PVC extension is removed in order to clean the sludge at the very bottom of the tank. See figures below.

Figure 51: The mason lays the first row of bricks

Figure 52: Manny Hernandez measures trench for the outlet pipe

Figure 53: The mason slopes the floor of the tank towards the drain

Figure 54: Sadat, Alhassan, and Shani stand inside of the completed tank

Figure 55: Filters soaking in the saturation tank

Figure 56: Outlet Detail – Drainage pipe with removable cap for draining recyclable water

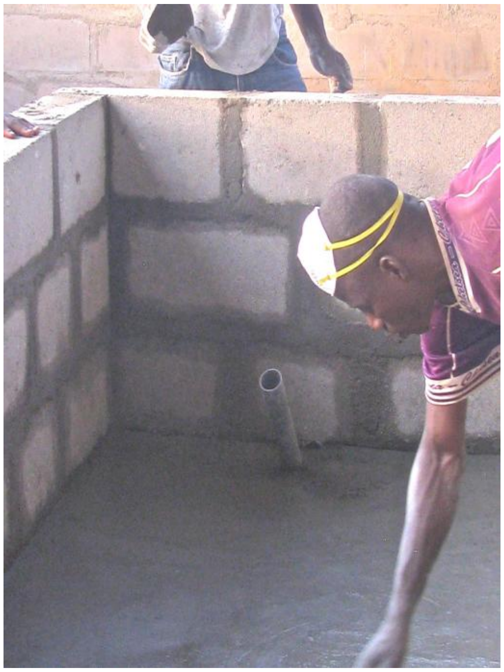


Figure 57: Outlet Detail – Grey drainage pipe (cap off) is also removable so that sludge from very bottom of tank can be cleaned out.

5.2 Making Calibrated T-Devices

Figure 58: Completed T-devices on rack

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 allows rapid measurement of 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. Making an accurate T-device for the parabolic filter owes in large part to the work done by Travis Reed Miller on modeling the geometry and hydraulics of the parabolic filter (Figure 60). In his thesis, Miller determined the change in height that corresponds with the filter's water holding capacity in 0.1L increments. He also determined change in radii. These measurements can be found in Appendix E (Miller 2010).

Figure 59: T-device close-up (Bradner 2011)

To make the T-devices, ½-inch PVC pipe was cut in to 9-inch lengths and fit into a T joint. The handles of the T-devices were also made out of ½-inch pipe with the last 4 inches sliced in half to provide a flat surface for the devices to rest on the filter. Once the T-devices were assembled, measurements were marked with a sharpie from the 5L mark at the bottom of the T-devices up to the 0L mark at the top. The measurements should be done from top to bottom to maintain consistency of the 0L maximum water line mark. The accuracy of the T-devices were tested by using a graduated cylinder to pour water into the filter and checking if the amount poured in corresponded with the marking on the device. Once they were checked for accuracy, holes were drilled through the 1L, 2L, 3L, 4L, 5L marks with an electric drill, and 0.2L increments were marked with waterproof ink. The welder, Malik Abdul Aziz, made a T-device rack to store the T-devices near the testing area. The T-devices can be made without the T-joint, but would require an electric drill and power. Because the drill and power from the generator was in high demand during January, using the T-joints made it possible to do most of the T-device making work without electricity. RDIC makes their T-joints by using a larger diameter piece of PVC pipe for the vertical portion of the T-device and drilling a hole where a smaller diameter PVC pipe is fit through for the handles.

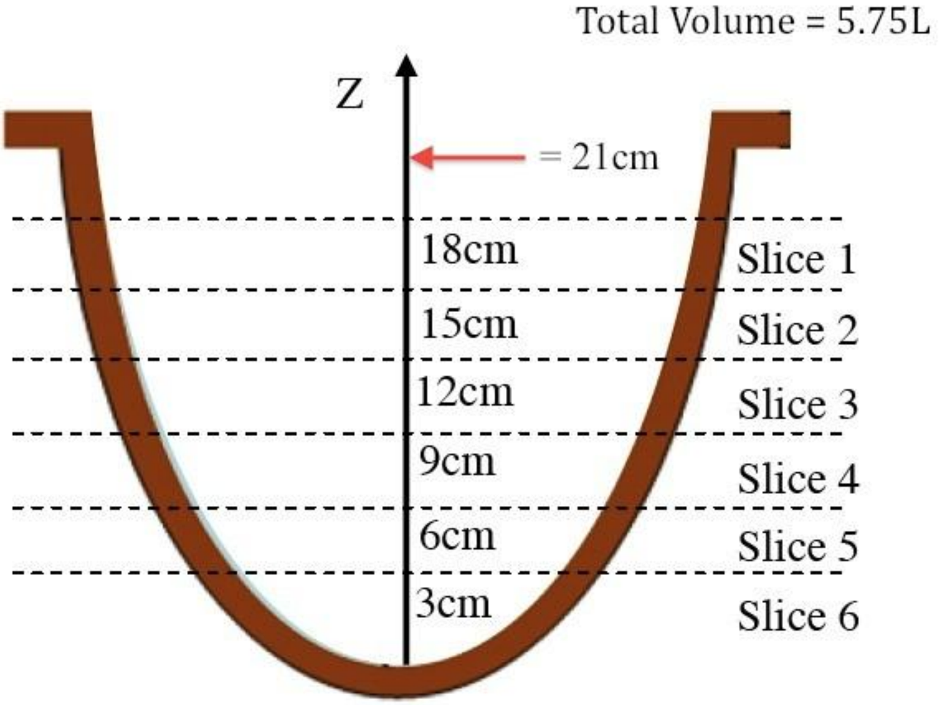


Figure 60: Filter schematic with height and total volume of filter (Adapted from Miller 2010)

5.3 Filter Flow Rate Test Method and Results: January

Figure 61: Filter flow rate tests

One of the top priorities when the MEng 2011 team was in Ghana for fieldwork in January was getting the factory up and running for production. This meant clearing the factory floor, pressing earth blocks to continue raising the walls for the building, constructing the saturation tank, starting on a rainwater tank, building metal shelves for the filter, fixing the filter presses, and setting up the kilns for firing. Joshua Hester, who is preparing a Master of Engineering thesis on the use of clay composition and filter performance spent the first two weeks out in in the field every day gathering clay from different locations in order to produce 27 filters with clay from 3 sites: Gbalahi, Wayamba, and Taha. The clay had to be dried, ground, and mixed in the correct proportions for filter making, then pressed, labeled with a unique identification number, dried out in preparation for firing, and fired.

Figure 62: T-device in filter element for flow test

The work that went into preparing both the factory and the ingredients for Hester's filters meant that firing happened during the last week of the team's stay in Tamale. Therefore, flow rate testing began a few days before we departed. Given these circumstances, the filter flow testing area is still being improved upon, as is the flow rate test procedure. Part of the work in preparing the flow testing area will be to complete a partition that separates the flow rate testing area from the rest of the factory to prevent dust, bits of metal, and other contamination from entering the flow test area. Having a permanent place for buckets or a flow testing rack will also be helpful to improve the efficiency of flow rate testing.

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 (see Figures 60 and 61). 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 (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 are shown in Figure 63.

Filters from Taha (n=3) and Wayamba (n=12) had the highest average flow rates, 4.9 L/hr and 4.86 L/hr respectively, with standard deviations of 0.2 (Taha) and 0.54 (Wayamba). The average flow rate for Gbalahi (n=12) was 3.07 with a standard deviation of 1.18.

If one were to follow the current PFP guidelines of destroying filters that exceed 2.5 L/hr, 50% of the Gbalahi filters and all of the Taha and Wayamba filters would be destroyed.

The next section will discuss the microbial results and flow rate test procedural improvements made by Curt and Cathy Bradner, PHW consultants and filter factory experts.

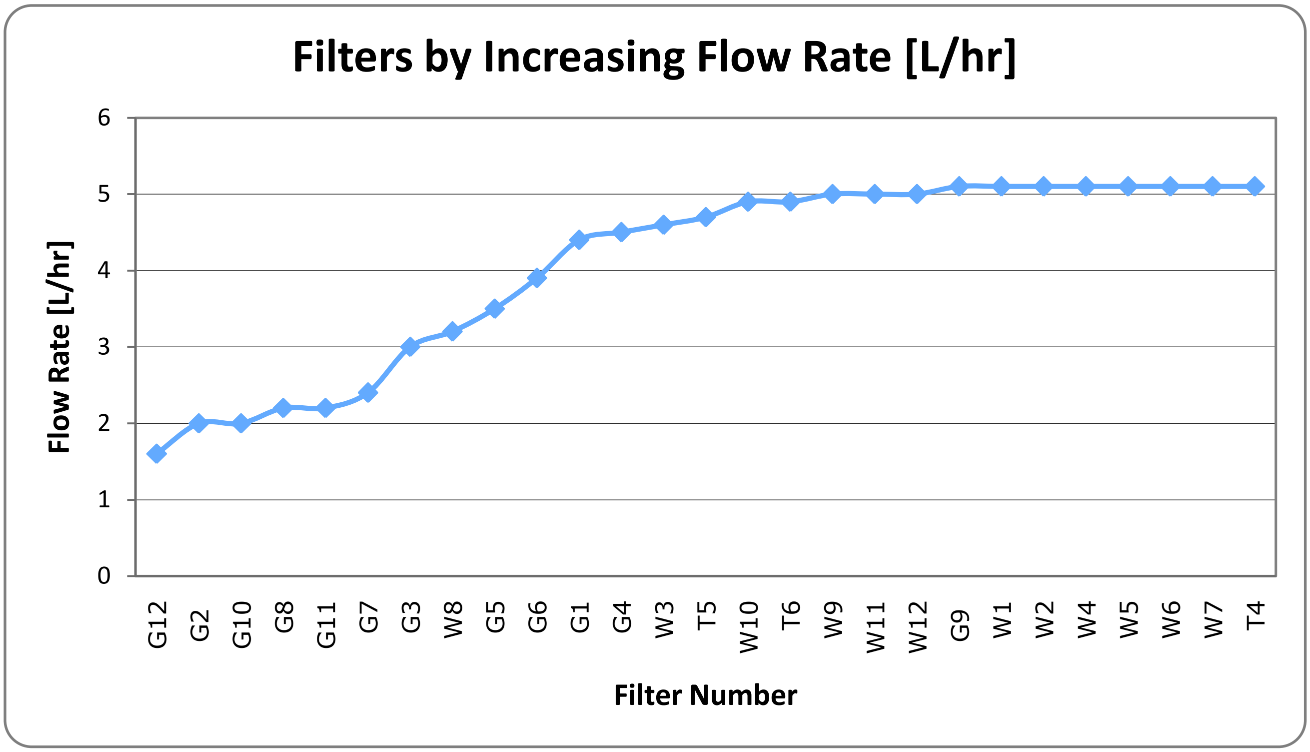


Figure 63: Filter flow rate results

6 March Results: Flow Rate, Bubble Testing, and Microbial Testing

In March 2011, Curt and Cathy Bradner, founders and Directors of Thirst-Aid, an NGO based in Burma thatpromotes safe drinking water and improved hygiene through educationand appropriate technologies, traveled to Tamale to follow up on work begun in January 2010 and 2011 to improve PHW filter production quality. Through their work with Thirst-Aid, the Bradners have trained producers to set up eight privately owned factories in Burma, which, in 2010 alone, manufactured and distributed over 90,000 filters (Thirst Aid, 2011). The methods and results from their testing between March 8 and April 6, 2011, detailed below, were obtained from emails and phone correspondence with Susan Murcott and the MEng team.

The results described below are not statistically significant because there was neither sufficient sampling size nor redundancy in the tests performed on each filter. Rather, the results describe a process of trial and error. Although the tests cannot provide results that can be generalized to other CPF factories, they *do* provide a basis for decision making for the PHW factory as they go forward in the their effort to standardize the composition and quality of the Kosim filter and meet early production targets. Therefore, what follows is intended to be an account of that process of trial and error involved in establishing a filter factory and of the Bradners' methods to find the ideal filter composition given local materials and conditions.

The methods and results are organized by date of testing.

6.1 Flow Rate Testing: 3/10/11

On March 10th 2011, Curt and Cathy Bradner, who will be referred to as "Bradner", re-tested Hester's parabolic filters. Flow testing took place at the PHW factory adjacent to the saturation tank (as was the case with the earlier flow testing conducted by Kleiman and reported in section 5.3). Before testing, they removed the filters from storage on the elevated metal drying rack on the factory floor and washed them.

Bradner's rule of thumb for appropriate flow rate is that for every liter of capacity,0.35 L/hr flow rate can be allowed. The parabolic filters have a 5.75 L capacity and therefore, by that standard, should not exceed 2.01 L/hr.

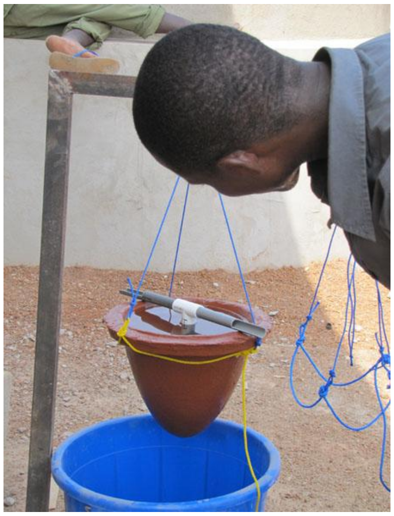


Figure 64: Flow rate testing (Source: Bradner)

The filters "soaked"until 1 liter of effluent passed through the filter. If it took less than 15 minutes or longer than 1 hour for 1 liter of effluent to pass through the filter, it was marked as defective. Filters that were out of range were thrown out and the rest of the filters were then re-filled to the brim with water and allowed to filter for 30 minutes. After 30 minutes Bradner measured the amount that had filtered by filling the filters to the brim and measuring how much water it took to re-fill the filters. This amount was doubled to obtain an estimate of the liter per hour filtration rate. Filters that were above 5.75 L/hr were eliminated, while the remaining filters were allowed to drain for one full hour before again checking how much water was required to fill them to obtain the liter per hour flow rates below.

The chart below shows Bradner's results. Some of the filters were recorded as exceeding 5.75 L/hr, which is not possible because the maximum filter capacity is 5.75L. This is because for this round of flow tests, filters with a very high flow rate were tested for 30 minutes and the flow rate was doubled, resulting in flow rates that are higher than the actual filter capacity.

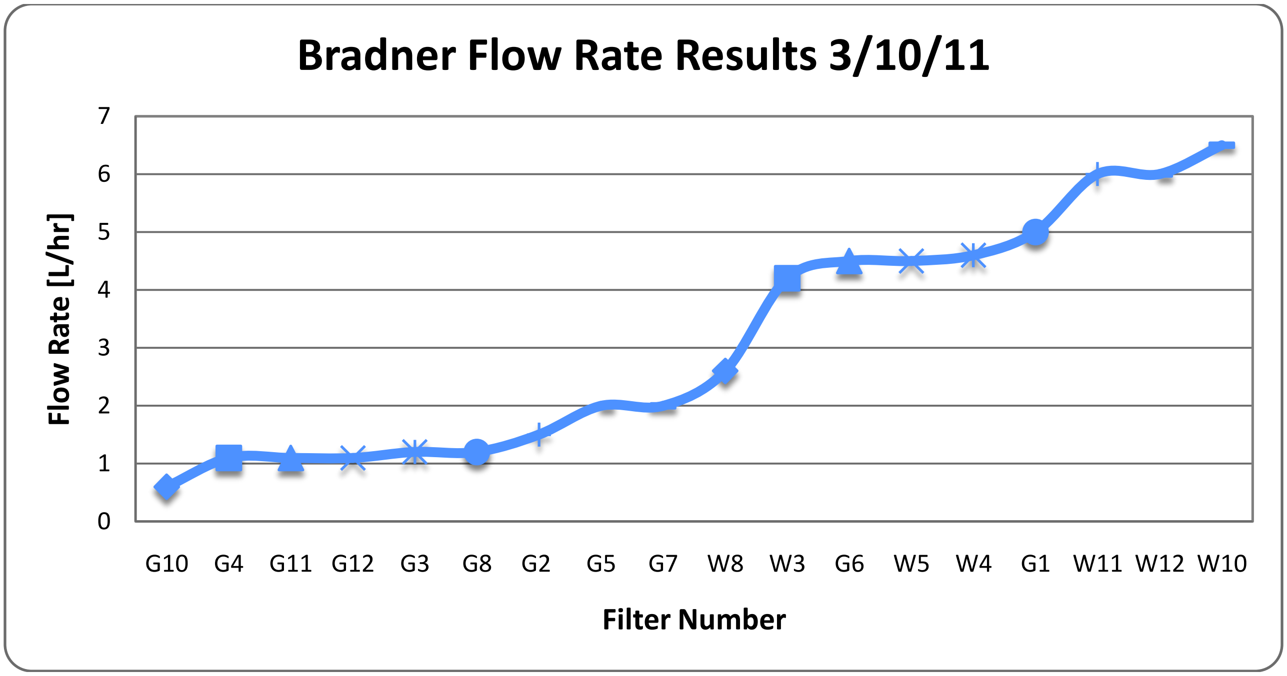


Figure 65: Flow rate test results

6.2 Removal Efficacy of Selected Filters: 3/12/11

Figure 66: Pure Home Water lab, inside of the Kalpohine office (Source: Bradner)

Figure 67: Collecting water samples directly from filter into Whirl-Pak® bag outside of Kalpohine office (Source: Bradner)

Of the filters flow tested above, only those with flow rates of 4.6 L/hr or less were kept for removal efficiency testing. Removal efficiency testing took place in the backyard of the PHW Kalpohine office compound, and in the PHW lab, which is located inside of the PHW Kalpohine office (Figures 66 and 67). A total of 27 samples were taken for coliform testing, 9 samples were of the source water (influent), 2 samples were blanks, 2 samples were of the house tap water, one sample was from Ceramica Tamakloe (CT) filter, and 13 samples were from the 13 PHW filters made by Hester, with flow rates of 4.6 L/hr or less. The samples were tested using m-Coli: Blue® 24 media and only *E. coli* colonies were counted.

Source Water

The source water was a dilution made from the dug-out at Kalpohine Village at 6 to 1 ratio with Tamale municipal water (22.7 liters of Tamale tap water to 3.7liters of Kalpohine Village dugout water). The source water was diluted with municipal water so that an accurate colony count could be obtained, (an ideal range of *E. coli* colonies of between 20-60 colonies per petri plate and an acceptable range of up to 200 colonies per plate).In addition Bradner wanted to reduce turbidity and focus on *E. coli* removal, with the intention to test representative high turbidity water (>100 NTU) once the filters demonstrate successful removal of bacteria. The diluted raw watersamples tested at an average of 130*E. coli* colonies per 100 ml.

Collection

All samples were collected directly from the filters (see Figure 67). Each filter was allowed to filter until 1 liter of effluent passed through the filter, as previously described. Samples were collected in sterile sample bags and labeled according to filter number.

Incubation

Samples were brought inside into the PHW lab to be processed immediately and incubated in a Millipore Portable Single Chamber incubator (Model Number XX631K203) for 24 hours at 35 degrees C (+/- 1 degree). Although the power shut off from 6:45am-7pm, the ambient room temperature throughout the testing period was, fortunately, verified by thermometer to be between 34 and 36 degrees.

Results and Next Steps

The majority of Hester's batch of filters were not removing bacteria adequately (see Table 7). With that knowledge,Bradner started looking for reasons why. Their first attempt at understanding why was to slice open 7 filters, including 2 filters that had good flow rates and good bacterial removal. They found that all of the filters were under-fired and, notably, there seemed to be no relation between the extent of firing and filter performance.

The next day, Bradner and the PHW factory staff made new filters from various combinations of Wayamba clay and Gbalahi clay.Based on the 13 filters of each type provided by Hester's work, Bradner hypothesized that the clay from Gbalahi is stronger than Wayamba clay, while the Wayamba clay is more porous. Bradner thought that the Gbalahi clay was "too good" meaning that there were not enough impurities and non-clay material mixed in with the clay.This observation is critical for sustained use, as one main cause of discontinued use for the Kosim filter is filter breakage (Desmyster 2009). The validity of this hypothesis is being assessed in Hester's Masters of Engineering thesis, which examines filter composition using clay from Gbalahi, Wayamba, and Taha (Hester, 2011).

Figure 68: Under-fired filter (Source: Bradner)

Bradner sought to reduce the amount of rice husks being used in the filters by relying on Wayamba clay to add porosity to the mixture without weakening the filters as much as adding excess rice husks does. Bradner's experience in Myanmar also led them to believe that a combination of two clays gave a better performing and more durable filter than those produced with only one clay.

With one exception (G6), Bradner flow rates are considerably lower than the flow rates found by Kleiman and Hester, which is consistent with the soaking methods used as well as with the lower ratio of rice husk used (11% versus 13%) . Kleiman and Hester soaked the filters for 24 hours, while Bradner "soaked" them by allowing 1 liter of effluent to pass through the filter. Regardingthis soaking method Cathy Bradner commented that she finds this method useful when there is limited testing time, as was the case at the PHW factory during the month of March, but also because in her opinion it is more representative of the flow rates that users will experience: "People in households are not going to soak their filters for 12 hours before they begin using them, so it's important to see what they see"- (Bradner 2011). Bradner emphasized, however, that for the training of quality control staff, filters are always soaked for a minimum of 12 hours.

Filter	**Hester & Kleiman Flow Rate [L/hr]**	**Bradner Flow Rate [L/hr]**	**Bradner *E.coli* Count [CFU/100ml]**	**Bradner Percent Removal *E. coli***
G2	2	1.5	4	96.9%
G3	3	1.2	2	98.5%
G4	4.5	1.1	11	91.5%
G5	3.5	2	1	99.2%
G7	2.4	2	1	99.2%
G10	2	0.6	69	46.9%
G11	2.2	1.1	28	78.5%
G6*	3.9	4.5	TNTC	N/A
G8	2.2	1.2	TNTC	N/A
G12	1.6	1.1	TNTC	N/A
W3	4.6	4.2	TNTC	N/A
W4	5.1	4.6	TNTC	N/A
W6	5.1	N/A (Lost more than 1 L in first 5 min)	TNTC	N/A
W8	3.2	2.6	TNTC	N/A
Bradner Source Water			130	

Table 7: Bradner and Kleiman & Hester flow test results comparison as well as Bradner percent*E.coli* removal results.

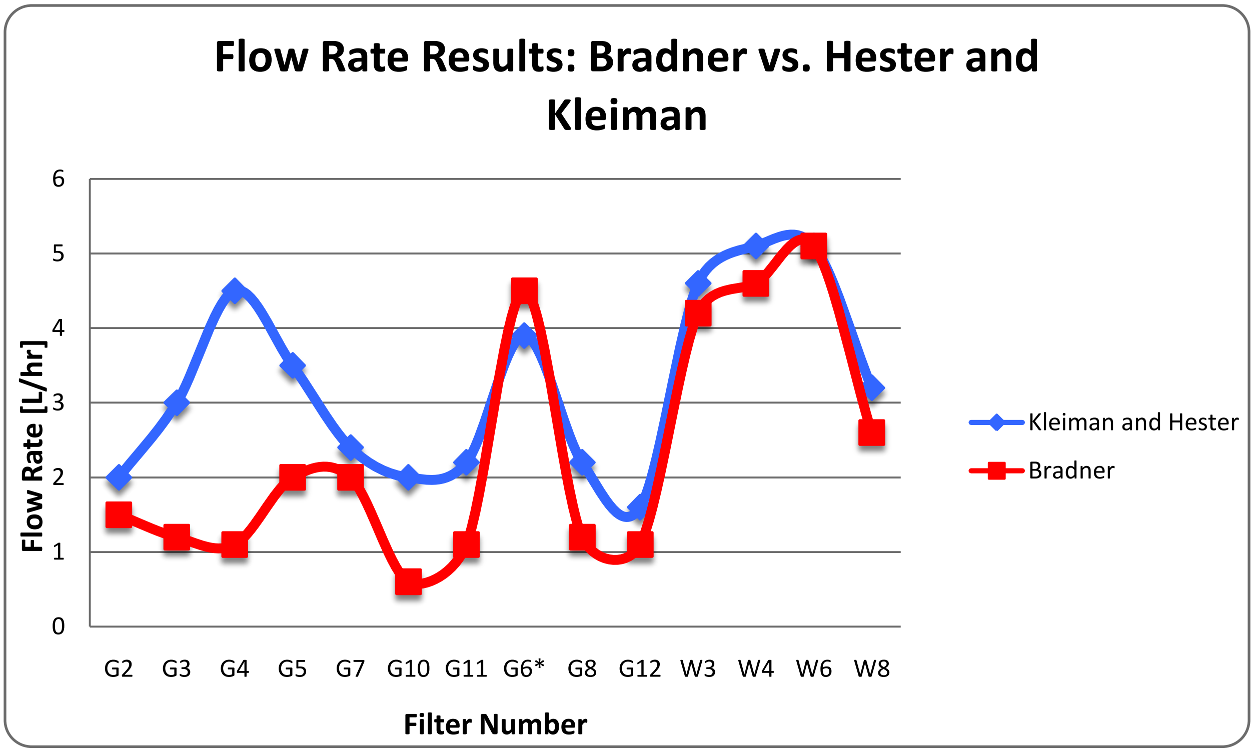
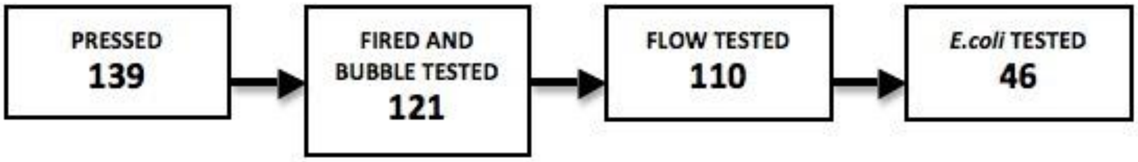


Figure 69: Flow rate test results comparison

6.3 Bubble Test, Removal and Flow Rate Results for New Filters with Varying Compositions: 3/25/11-3/31/11

To assess various clay and combustible proportions and to train PHW staff, Bradner worked with PHW employees to press filterswith different clayand rice husk ratios. Bradner notes that, “this mix usually gives a very clear indication of what’s going to produce the strongest filters with the best flow rates and can be fine-tuned from there” (Bradner 2011). 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.



Filters were soaked for 12 hours prior to testing. Filters that failed the flow test had flow rates of above 4L/hr or below 1L/hr. Some filters that “failed”, meaning they fell out of this range,were still intentionally passed on to the *E.coli*testing stage. Normally these filters would not pass inspection for bacterial testing or distribution. Hester has analyzed the significance of the varying compositions further in his Master’s thesis (Hester 2011). The analysis in this section focuses on Bradner’s use of bubble tests, flow rate tests, and coliform tests in their process of eliminating sub-optimal compositions and choosing the best composition for PHW factory production.

Bubble/Pressure Test

The bubble test, also known as a pressure or crack test, is performed on filters before they enter the flow-testing stage. The purpose of the test is to eliminate filters that have cracks or large pores in them (caused by improperly mixed ingredients or combustible particle sizes that are too large), or to alert staff to filters that may need special attention, such as those with minor leaks.Most factories perform the pressure test by submerging the filter bottom-down in the saturation tank until the water level is just under the rim and then waiting 10 seconds. If water enters the filter within the 10 seconds, the filter must be discarded (Ceramic Manufacturing Working Group 2011). Bradner, however, performs the pressure test by submersing the filter rim down and capturing air in the

Figure 70: Bubble test – failed filter (Courtesy of Bradners)

filterafter ithas soaked for at least 12 hours (Figure 70). If a stream of bubbles emerges from the filter, this indicates cracks or large pores and means that the filter should be discarded. Bradner notes that trained quality control staff can identify a bad filter instantly with this method (Bradner 2011). In her survey of filter factories, Rayner found that 53% of respondents bubble test every filter, while 47% do not bubble test at all (Rayner 2009). Rayner's survey did not specify the method of pressure testing used at each factory (Rayner 2009).

Flow Rate Test and Removal Results

The Bradner set of filters within a 0.6-2.6 L/hr flow rate range (n=46)moved on to the *E.coli* testing stage, and (n=25) were tested for *E.coli* removal between 2/25 and 3/31. These filters were testedusing a different mixture ratio from the previous tests, of 2 liters of septic tank water from the septic tank outside of the PHW Kalpohine office,to 20 liters of municipal water (a 1 to 10 ratio due to the different raw water source). The raw water for testing on 2/25/11-2/28/11 was 260 CFU/100ml and 360 CFU/100ml for testing on 3/31/11. The filters tested range from 49.2-93.1% removal (see tables below).

Filter Composition Ratio	**Filter ID**	**Flow Rate [L/hr]**	***E.coli* Count [CFU/100ml]**	**Percent Removal *E. coli***
Raw Water [CFU/100ml] 1:10 ratio of septic tank to municipal water			260	
11RH-25/75	A	1		TNTC
11RH-50/50	B	2.6		67.7%
12RH-25/75	C	1.8		81.2%
12RH-50/50	D1	.6		68.1%
	D2	.9		50.4%
13RH-50/50	E	2.4		49.2%
mix-50/50	F	1		71.9%

Table 8: Filters Tested 2/25-2/28

Filter Composition Ratio	**Filter ID**	**Flow Rate [L/hr]**	***E.coli* Count [CFU/100ml]**	**Percent Removal *E. coli***
Raw Water [CFU/100ml] 1:10 ratio of septic tank to municipal water			360	
11 RH-25/75	G1	2	52	85.6%
	G2	2	26	92.8%
	G3	.8	54	85.0%
11 RH-35/65	H1	2.8	80	77.8%
	H2	2.4	25	93.1%
	H3	2	65	81.9%
	H4	.8	42	88.3%
	H5	2	67	81.4%
	H6	2.2	99	72.5%
12 RH-25/65	I1	2.8	64	82.2%
	I2	2.6	46	87.2%
	I3	2	89	75.3%
12 RH-35/65	J1	2.8	29	91.9%
	J2	2.2	56	84.4%
13-25/75	K	2.8	68	81.1%
13-35/65	L	2.2	56	84.4%
	L2	2.2	57	84.2%
14-25/75	M	2.2	35	90.3%

Table 9: Filters Tested 3/31/11 (Bradner)

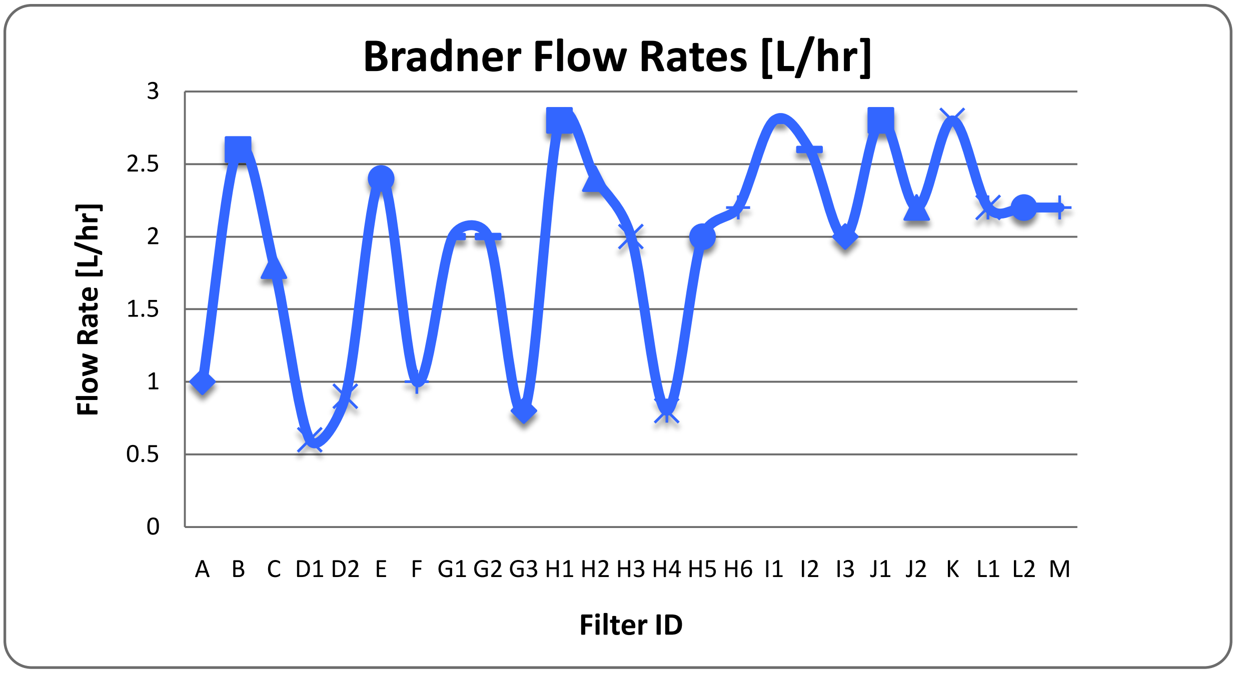


Figure 71: Flow rates for 25 filters with 13 different composition ratios tested 2/25/11-3/1/11

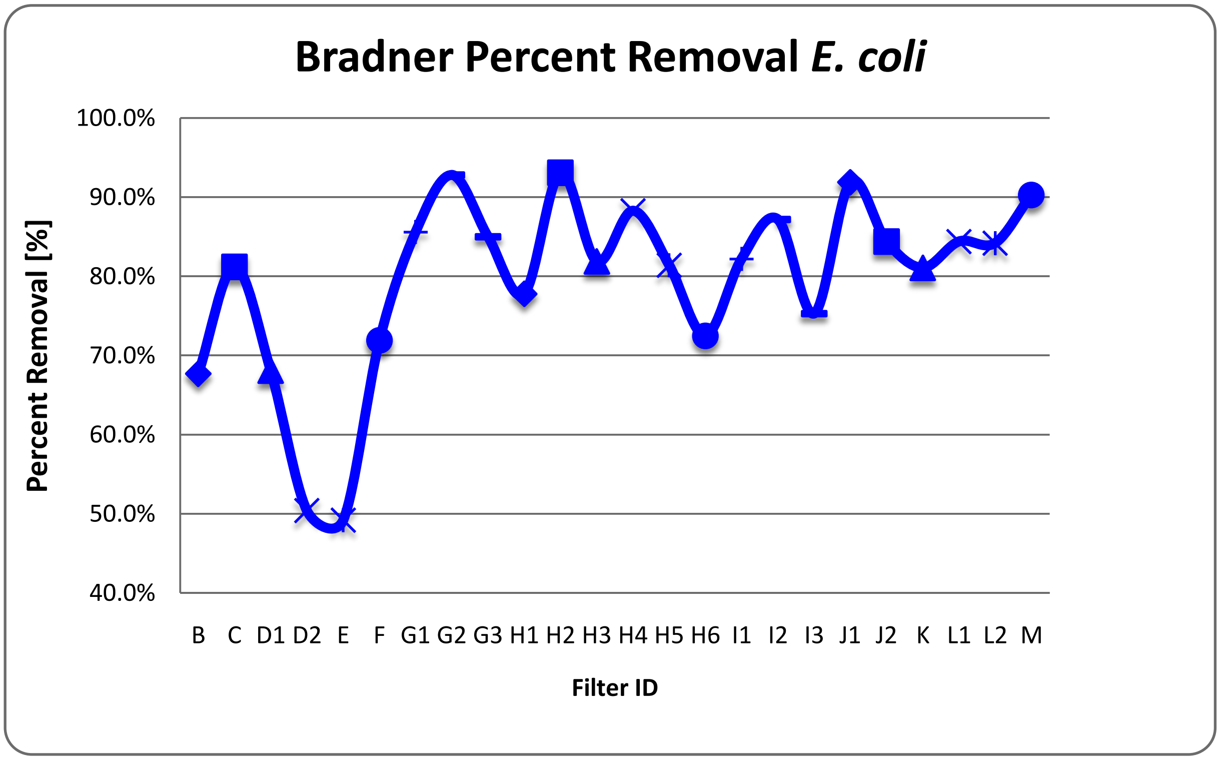


Figure 72: Removal efficiencies for25 filters with 13 different composition ratios tested 2/25/11-3/1/11

New Flow Test Station and Training

Figure 73: Curt teaches Daniel how to use perform microbial tests

In addition to the goal of identifying the optimal filter composition recipe for PHW to use in their filter production, a main objective was to train PHW staff in filter production procedure and quality control testing. Bradner directed the construction of a simple, inexpensive flow test station(Figures 74 and 75) in order to train PHW staff to flow test, bubble test, and record results on logs created by Bradner for recording quality test results (Appendix E).

The flow test station is set up so that the filters are held by macramé rope suspended over buckets. Bradner prefers this set up because the filters and any defects are visible, making it easier to observe how water is flowing through the filters and to spot the location of cracks or inconsistencies in flow.

Bradner's method of training is to engage staff from the very beginning, working together in the process of trial and error as part of the training. In this way, leadership is being transferred from the start, rather than after all the inconsistencies have been worked out. They trained three staff to oversee three quality control areas:

- Mixing and pressing new filters
- Stacking, firing and unloading filters from the kiln
- Post-firing quality control tests including flow tests, bubble tests, microbial tests

All three individuals are also responsible for recording data for their respective area on the logs provided in Appendix F. The person responsible for post-firing quality control is trained to:

- Soak filters for 12 hours
- Bubble test filters and look for cracks (visual inspection)
- Flow test filters measuring the flow rate at 5, 15, 30 minutes and 1 hour (if the filter loses 1L in the first 15 minutes it is rejected).
- Record information for the life of every filter (until it is destroyed or shipped).
- Destroy filters that do not pass the tests (a hole is punched through the bottom of the rejected filters, so that there is no danger of confusing them with functioning filters).

- Provide weekly reports to PHW management and Bradner

Each filter has a unique ID, which is the date it was pressed and the sequence of pressing. The importance of recording information is to have a database of information that can be referred to if there are problems with the filter. A record of flow rates over a number of years allows the manufacturer to map how variables,e.g drying times,seasonal changes, can affect filter production. Bradner states that in Burma, producers will commonly start by losing about 25% of the filters that are produced, but within a year will reduce those losses to only about 10%. Bradner believes that a loss rate of less than 10% indicates that a factory may not be sufficiently rigorous in rejecting unacceptable filters.

Figure 74: Flow test rack

Figure 75: Karim Flow Tests Filters

Figure 76: Karim keeps records of flow test results

Bradner emphasized the importance of continuity in the training process and states that it takes at least 6 months of continuous training time to get a good factory working. It takes at least 6 months to train employees in production, but also in making and repairing machinery(or factory owners, in the case of Burma, where Bradner worked primarily with business people). After 6 months it is important for the trainers to come back regularly to ensure that the manufacturers understand the process and the importance of producing a quality product that filters as advertised. Bradner finds that when manufacturers and their employees understand that they are making a public health product, adding another level of responsibility to their consumers, greater attention to quality is cultivated.

Figure 77: Karim bubble tests filters

7 Discussion and Research Recommendations

Discussion

While none of the filters tested by Bradner are within acceptable removal ranges for distribution, Bradner feels they are honing in on a composition ratio that produces a strong filter with an appropriate flow rate for the filter volume. But what is an appropriate flow rate? The PFP recommended value of2.5 L/hr 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 is the removal efficiency, for which flow rate testing is supposedly a proxy. In the testing conducted during March and April there seems to be little correlation between flow rate and removal efficiency. It is important to re-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. However, the results do show that, at least in the initial stages of determining an appropriate filter composition using new materials, 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 78).

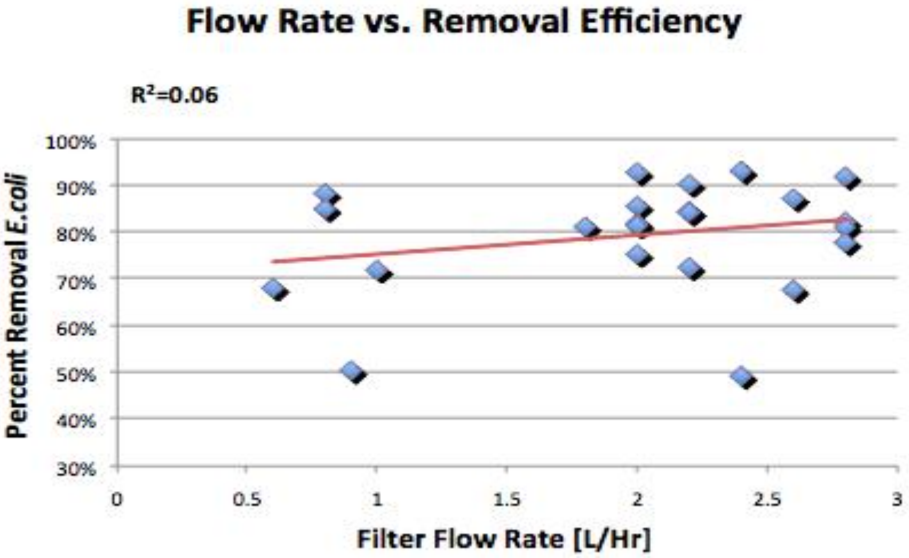


Figure 78: Scatter plot of flow rates vs. removal efficiencies for filters in Tables9 and 10 showing a very weak correlation

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 [L/cm^2/min]. 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. For more information on surface loading rates, filter design, and filter performance, please see the Ghana 2011 Group Project Report on <web.mit.edu /watsan/docs_reports/ghana.html>.

Research Recommendations

Once the optimal filter composition is selected, it would be a valuable research question 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.

In addition, the relationship between flow rate, surface loading rate, and removal may be different for unpainted filters and those painted with 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 rateis an important quality control parameter in that it tests for the standardization of filter performance from the"user's" perspectiveand 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 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.

In their work to train and standardize quality control protocols, Bradner developed a set of flow rate and argonal silver application protocols provided in Appendix G and H.

8 Production Recommendations

This section is adapted from the follow-up Trip Report prepared by Curt and Cathy Bradner (2011) and representsrecommendations resulting from the combination of the MEng team's January work and Bradner's March-April 2011 work at the factory.

While the top *production* priority for the PHW Factory is to determine the composition ratio that provides the strongest filters with acceptable bacterial removal percentages, in order to prepare the factory for distribution grade filters, there are many other areas that also need attention. These areas are highlighted and discussed below.

Water: All water needs to be used carefully with regards to waste and recycling.

- ***The soak tank should be connected to the rainwater harvesting tank so that water can be recycled.***

Flow Testing and Factory Floor Space: The flow test racks and hangers for flow testing are easy to set up in the shade or inside the building during the dry season. However outside, collection of water using Whirl-Pak®bags is made difficult by high winds. Moving the racks insidethe building for test processing resolves the issue for now. As production increases, room inside the building is going to be at a premium.

- ***Building a covered area to the west side of the building for flow testing and water collection for bacteria tests,as is specified in the original design plans, will free up factory floor space.***

Performance Analysis: PHW has a lab equipped for bacteria testing. The majority of filter manufacturers, however, have their filters tested ***after*** the application of silver and only occasionally by outside labs.

- ***Once PHW determines a satisfactory composition ratio and the relationship between flow rate, surface loading rate, and bacterial efficacy, PHW should decide what percentage of filters shouldbe selected for bacteria testing and whether testing will take place after the application of silver.***
- ***In addition, testing media is expensive, so PHW needs to investigate a less expensive media for bacterial testing.***

Staff: Finding qualified staff is one of the biggest hurdles (and not just at PHW). It is difficult to find staff with reading and writing capabilities. Of the 12 daily factory workers,currently employed by PHW, two can read English and 4 can identify numbers and tell time. While a portion of the responsibilities at the PHW factory do not require formal education, they do all require on-the-job training with experienced CPF professionals.

- ***When working with such a wide range of analytical competencies,management and oversight is especially important***.

- ***Currently, there are not enough full-time staff that have experience with firing the kiln. Two full-time employees were trained by Bradner, but one employee needs to divide his time between firing and other responsibilities. An additional person needs to be trained as a kiln-master.***

- ***The lab technician is well-trained in Quality Control (QC) post-kiln procedures, but QC is a huge job and the technicianneeds help. Once he is a bit more experienced with the QC process, he should train others.***

Hardware:Huge improvements in product quality and manufacturing efficiency can be made with the following relatively inexpensive and simple additions.

- ***Dry mixer*** – a simple 50 gallon drum with a spiral mixer (it can be human powered and a cement mixer could be modified, though this probably wouldn't save much money)

- ***Clay Grinder*** – will replace 160 hours of manual labor with 4 hours of machine labor. Does require gas motor.

- ***Framed screens*** for sieving rice husk. Ideally need two screens. Otherwise a ***shaker*** with screens on inclined plane could be made.

Production Plan:A comprehensive plan for the future of the factory and production is needed so everyone is on the same page.

- ***Developing and staying focused on one plan with defined roles and responsibilities will help maintain good morale and improve productivity.***

From CPF production to a successful CPF program: The work detailed in this thesis represents the effort of many to produce a functioning CPF product that is thoroughly screened, and acceptable for sale and distribution. Bradner emphasizes, however, that the work of establishing a ***successful ceramic water filter program*** is distinct from making functioning***ceramic filters*** and that the work of building a successful program involves planning and discussion requiring a different set of recommendations.

9 Management Recommendations

One key difference between Bradner's Thrist Aid factories in Burma and Pure Home Water is that in Burma, Thirst Aid works primarily with independent private enterprises that it has trained to produce ceramic filters, whereas PHW is an NGO that produces ceramic filters *and* manages sales and distribution of the filters.

The private enterprises that Thirst Aid works with are mostly businesses,which, prior to producing the ceramic water filter, produced other ceramic products and understood ideas of production and sales.Thirst Aid's role is to introduce a new product and to monitor quality. One of the incentives for factories in Burma to uphold quality control standards for their products is that about 97% percent of the filters in Burma are sold to large NGOs or government entities with whom Thirst Aid has relationships. Therefore, if manufacturers are producing subpar filters, Thirst Aid will not be able to sell them, and the company will no longer be included in future business deals.

A difference with training PHW staff is that they work for an organization that, while registered and based in Ghana, is currently managed primarily by non-Ghanaians who are trying to navigate and negotiate how to run a sustainable business in Ghana, how to produce a quality ceramic product, and how to manage and train and motivate Ghanaian staff to have the attention to quality that is required of a factory that produces a public health product. This difference in ownership structure may mean that a different approach has to be taken with regards to motivating and ensuring that staff meet the quality control guidelines. Of particular importance is the continued presence and guidance of management and training staff during these initial stages of refining production.

10 Conclusion

From January-April 2011, substantial progress was made in moving the PHW factory closer to full-scale production mode. However, there is still much work to be done before PHW can begin producing and distributing a high quality ceramic filter. This thesis recorded work done at the PHW factory to build water infrastructure for the PHW factory and improve quality control for CPF production, as well as provides recommendations for areas of research needed to improve the quality control protocol.

The progress made in the areas of water infrastructure and quality control tools include the construction of a filter saturation tank, a 30m^3 rainwater tank, flow test racks, and calibrated T-devices. 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. Finally, the research questions identified in this thesis will help PHW develop quality control procedures that are based on appropriate removal efficiencies and standard metrics, such as surface loading rate, that will be a good basis for comparisons over time and between different filter designs.

Priorities for the months ahead are to definitively identify the PHW filter composition based on acceptable bacterial removal percentages, to research the relationship between flow rate, surface loading rate, and bacterial removal so that a protocol for frequency of bacterial tests can be determined, and to train new staff in the firing protocol. Equally important will be the development of clear production, filter program, and management plans for long term sustainability that will help PHW reach its goal of bringing ceramic pot filter (CPF) use and household water treatment and safe storage (HWTS) to scale in Northern Ghana.

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Appendix : Tank Calculator (Ludwig 2005a)(Ludwig 2005b)

Rectangular Tank - Concrete Block			Comments
Tank volume	16643.00	Gallons	Volume excluding space under domed roof
Tank volume	2671.43	Cubic feet	Volume excluding space under domed roof
Height	8.00	Feet	Height of tank walls (not roof height)
Height below grade	5.00	Feet	
Height above grade	3.00	Feet	
Width	20.00	Feet	
Length	15.00	Feet	
Wall thickness (av)	5.00	Inches	
Roof thickness*	1.75	Inches	
Floor thickness*	5.00	Inches	
Roof rise/tank diameter*	0.00	Ratio	Ratio of roof rise to tank diameter. 0 for flat roof, 1/2 diameter for hemisphere
Floor beyond walls*	1.00	Inches	Distance that floor extends beyond walls. Used only to calculate amount of material. But we can use for safety factor against uplift if this is increased
Density of material	140.00	Lbs/ft3	Used to calculate load on ground under tank.
Width	20.00	Feet	
Width/ height	**2.50**	**Ratio**	
Volume	2224.70	Cubic feet	Conversion: 7.481Gallons/Cubic Feet
Volume under roof	0.00	Cubic feet	Assume zero for conservative estimates of uplift
Total volume	**2224.70**	**Cubic feet**	
Roof rise	0.00		Assume zero for conservative estimates of

			uplift
Roof area	300.00	Square feet	
Wall area	560.00	Square feet	
Wall area below grade	350.00	Square feet	
Total stucco area	860.00	Square feet	
Floor area	305.86	Square feet	Including 1 inch over-hang from wall
Total surface area	**1165.86**	**Square Feet**	
(Volume of Cement)			
Roof volume	43.75	Cubic feet	
Wall volume	233.33	Cubic feet	
Wall volume below grade	145.83	Cubic feet	
Wall volume below grade	4131255.90	Cubic cm	
Total stucco volume	**277.08**	**Cubic feet**	
Floor volume	**127.44**	**Cubic feet**	
Total volume	**404.53**	**Cubic feet**	
Material vol/water vol	**5.50**	**Ratio**	
Weight of material	56,633.56	Lbs	
Weight of water	138,802.62	Lbs	
Total weight	195,436.18	Lbs	

Bulk Density of Soil	1.50	g/cm^3	Assume 1.5 although this can range from 1-2 g/cm^3 depending on soil type
Particle Density	2.50	g/cm^3	Assumed value: Reference: http://www.agronomy.ksu.edu/Teaching/DesktopDefault.aspx?tabid=49
Porosity	40.00	percent	Percentage of soil not occupied by solid soil particles. If flooded then all of this space is water.
Specific Weight of Water	62.4	lb/ft^3	
Density of Water	1	g/cm^3	
Density of Flooded Soil	1.3	g/cm^3	
Density of Flooded Soil	81.15	lb/ft^3	
UPLIFT CALCULATIONS			
Full Tank			These calculations do not include reinforcement or rebar or weight of soil on overhang.
Buoyancy Force (tank volume*density of water)	166,697.14	lbs	
Pressure on soil from structure (total weight/floor area)	638.97	psf	Force per unit area
Pressure from Buoyancy Force (FB/floor area)	545.01	psf	Force per unit area
Net Force	93.96	psf	
Safety Factor	1.17		*Tank is stable, but for areas with seasonal flooding we should design for a safety factor of 1.25
TANK IS STABLE			http://www.precast.org/precast-magazines/2010/07/why-buoyancy-

			forces-cannot-be-ignored/
Empty Tank			
Buoyancy Force (tank volume*density of water)	166,697.14	lbs	
Pressure on soil from structure (weight of material/floor area)	185.16	psf	Force per unit area
Pressure from Buoyancy Force (FB/floor area)	545.01	psf	Force per unit area
Net Force	-359.85	psf	
Safety Factor	0.34		
TANK WILL FLOAT			

CylindricalTank - Concrete Block			Comments
Tank volume	16643.00	gallons	Volume excluding space under domed roof
Height	8.00	feet	Height of tank walls (not roof height)
Wall thickness (av)	5.00	inches	
Roof thickness*	1.75	inches	
Floor thickness*	5.00	inches	
Roof rise/tank diameter*	0.00	ratio	Ratio of roof rise to tank diameter. 0 for flat roof, 1/2 diameter for hemisphere
Floor beyond walls*	1.00	inches	Distance that floor extends beyond walls. Used only to calculate amount of material.
Density of material	140.00	lbs/ft3	Used to calculate load on ground under tank.
Hoop spacing			Vertical space between rebar hoops on ferro-cement tank. For calculating hoop stress only
Major reinforcing diameter			Diameter of reinforcing members (rebar hoops for ferro-cement tank). For calculating hoop stress only
Note that volume under roof below is in ADDITION TO capacity above.			
Diameter	18.82	feet	
Diameter/ height	**2.35**	**ratio**	
Volume	2224.70	Cubic feet	
Volume under roof	0.00	Cubic feet	
Volume under roof	0.00	Gallons	
Total volume	**2224.70**	**Cubic feet**	

Radius	9.41	Feet
Roof rise	0.00	Feet
Circumference	59.11	Feet
Roof area	278.09	Square feet
Wall area	472.87	Square feet
Total stucco area	750.96	Square feet
Floor area	283.04	Square feet
Total area	**1034.00**	**Square feet**
(cylinder)	1029.05	
Roof volume	40.55	Cubic feet
Wall volume	197.03	Cubic feet
Total stucco volume	**237.59**	**Cubic feet**
Total stucco volume	8.80	Cubic yards
Floor volume	**117.93**	**Cubic feet**
Floor volume	4.37	Cubic yards
Total volume	355.52	Cubic feet
Total volume	**13.17**	**Cubic yards**
Material vol/water vol	**6.26**	**ratio**
Weight of material	49,772.31	lbs
Weight of water	138,802.62	lbs
Total weight	188,574.93	lbs

Force on soil	4.63	psi
Force on soil	666.26	psf
Max hoop stress	78.55	psi

UPLIFT CALCULATIONS

Full Tank			These calculations do not include reinforcement or rebar or weight of soil on overhang.
Buoyancy Force (tank volume*density of water)			
Pressure on soil from structure (total weight/floor area)	143,270.85	lbs	Force per unit area
Pressure from Buoyancy Force (FB/floor area)	666.26	psf	Force per unit area
Net Force	506.19	psf	
Safety Factor	160.07	psf	*Tank is stable, but for areas with seasonal flooding we should design for a safety factor of 1.25
TANK IS STABLE	1.32		http://www.precast.org/precast-magazines/2010/07/why-buoyancy-forces-cannot-be-ignored/
Empty Tank			
Buoyancy Force (tank volume*density of water)			
Pressure on soil from structure (weight of material/floor area)			Force per unit area
Pressure from Buoyancy Force (FB/floor area)	143,270.85	lbs	Force per unit area
Net Force	175.85	psf	
Safety Factor	506.19	psf	
TANK WILL FLOAT	-330.34	psf	

Appendix A: Underground Water Storage Tank Costs

Date	Activity	Work Description	Quantity (Units)	Unit Price	Total Amount (GHC)
12/22/10	Water sealant for rainwater harvesting tank	Foundation	0.3	750.00	225.00
1/5/11	Cement	Foundation	20	14.00	280.00
1/5/11	1 1/2" PVC pipe	Foundation	1	9.00	9.00
1/5/11	1/2" PVC		1	9.00	9.00
1/6/11	Sea sand	Foundation	1	150.00	150.00
1/6/11	3/8" rebar	Foundation	28	4.57	127.96
1/6/11	1/8" plywood	Foundation	6	11.50	69.00
1/6/11	Metal mesh wire for reinforcement	Foundation	6	12.50	75.00
1/6/11	Binding wire - 1 roll, 1/20"	Foundation	1	42.50	42.50
1/7/11	Chips	Foundation	1	180.00	180.00
1/7/11	Lumber 1" x 6" x 15 ft	Foundation	9	14.00	126.00
1/7/11	Lumber 1" x 12" x 15 ft	Foundation	4	14.00	56.00
1/10/11	1" nails - box	Foundation	1	25.00	25.00
1/10/11	Glue for PVC pipe	Foundation	1	15.00	15.00
1/10/11	3" Schedule 80 (heavy) PVC pipe + 1" PVC pipe x 18 ft + Teflon tape	Foundation	1	49.00	49.00
1/11/11	1/4" iron rod	Foundation	1	2.50	2.50
1/11/11	Cocoa sacks	Foundation	20	2.00	40.00
1/11/11	Chips	Foundation	1	180.00	180.00
1/12/11	1/2" (6 mm) iron rod for reinforcement of RWH tank @3/ft	Foundation	40	3.00	120.00
1/12/11	Binding wire	Foundation	1	5.00	5.00
1/12/11	3" PVC with 45 degree bend	Foundation	1	3.00	3.00
1/18/11	Ghana Water Co. Tanker Water delivery	Foundation	1	50.00	50.00
1/19/11	4" nails - 1 box	Foundation	1	4.00	4.00
1/21/11	Cocoa sacks	Foundation	20	2.00	40.00

1/21/11	Ghana Water Co water for concrete tank curing	Foundation	1	50.00	50.00
1/28/11	Cement Blocks	Walls	507	1	507
1/28/11	Cement	Walls and Roof	50	15.00	750.00
1/28/11	Water	Walls and Roof	1	50.00	50.00
2/8/11	Gravels	Walls and Roof	7	50.00	350.00
2/11/11	Sand	Walls and Roof	1	150.00	150.00
2/11/11	Water	Walls and Roof	1	50.00	50.00
2/11/11	2 x 4 wood	Roof casting	2	3.50	7.00
2/11/11	3/8 Iron Rod	Roof casting	14	5.00	70.00
2/11/11	5/8 Iron Rod	Roof casting	1	25.00	25.00
2/25/11	Water	Roof casting	1	50.00	50.00
3/2/11	Gravel	Roof casting	3	50.00	150.00
3/4/11	Plywood	Roof casting	4	25.00	100.00
3/4/11	Metal Mesh	Roof casting	4	12.00	48.00
3/4/11	Wire Mesh	Roof casting	5	1.70	8.50
3/11/11	Water	Roof casting	1	50.00	50.00
1/11-3/11	Labor				1,510.00
1/11-3/12	Local Consultant/Manager				300
			TOTAL (GHC)		6,108.46
Exchange Rate: US$1.00 = GHC 1.46 (1-10-11)			**TOTAL (USD)**		4183.89

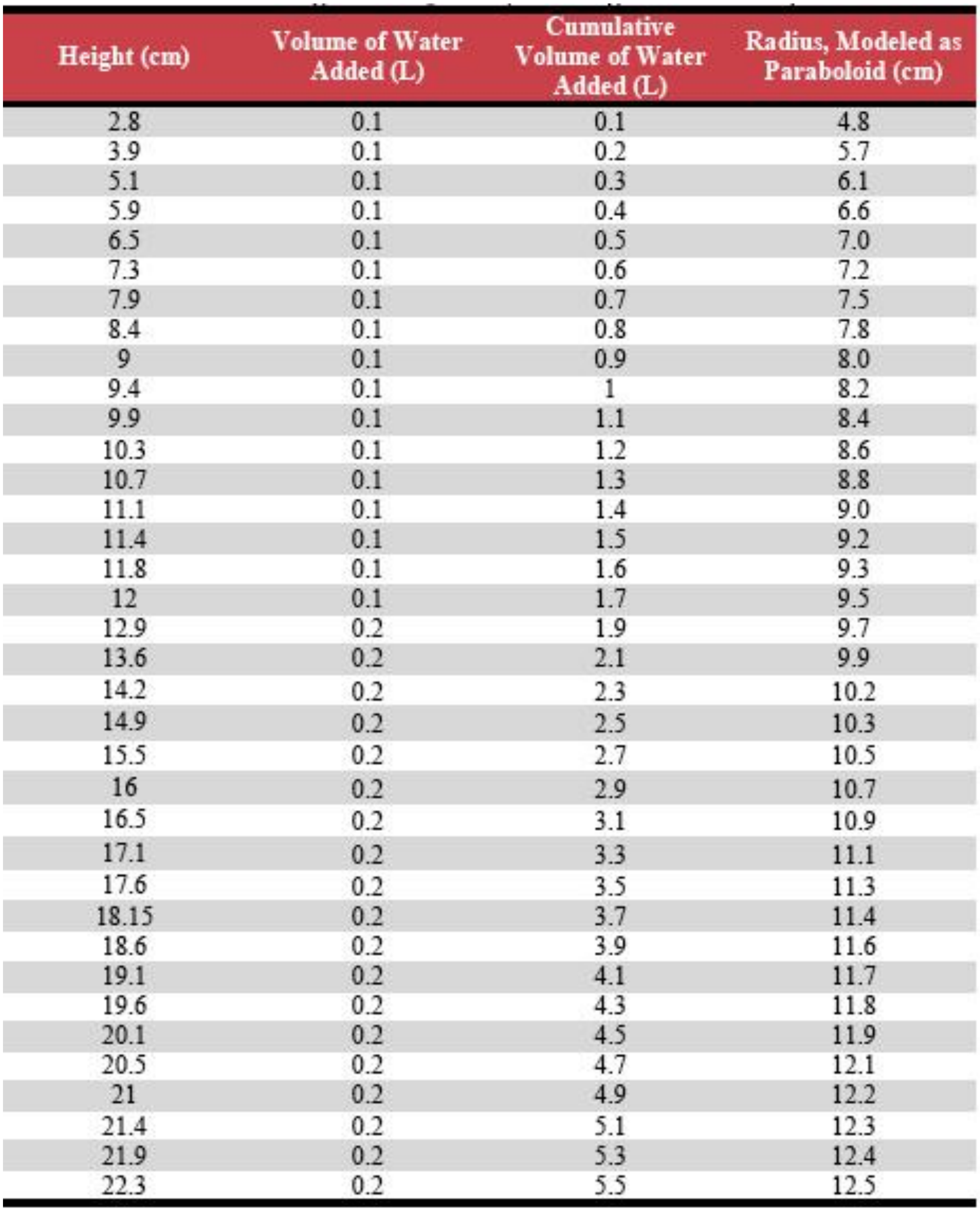
Appendix B: Ferro-cement Materials Calculator (Ludwig 2005b)

Material	**Unit cost**	**18.9 m^3**		**37.8 m^3**		**56.8 m^3**	
3/8” rebar (20’ pieces)	$3.11	30	$93.30	50	$155.50	60	$186.60
1/2” rebar (20’ pieces)	$4.98		$0.00		$0.00		$0.00
Lath (27”x8’ pieces)	$5.36	27	$144.72	40	$214.40	50	$268.00
6x6x10x10 Welded Wire Mesh (7’x200’ rolls)	$138.00	1	$138.00	1.25	$172.50	1.5	$207.00
1/2” Hardware cloth (4’x100’ rolls)	$39.94	1	$39.94	1.75	$69.90	2	$79.88
Tie wire (big looped bundles)	$2.60	2	$5.20	2	$5.20	3	$7.80
Cement (94 lb bags)	$5.65	18	$101.70	25	$141.25	32	$180.80
Plaster sand (yd3)	$29.50	4	$118.00	4.5	$132.75	5.5	$162.25
Water (gal)	$0.01	500	$5.00	750	$7.50	1000	$10.00
Thoroseal/Bonsal Sure Coat (50 lb bags)	$19.20	7	$134.40	10	$192.00	15	$288.00
Color (lbs)	$2.88	5	$14.40	7	$20.16	10	$28.80
Hog rings (25 lb boxes)37	$38.40		$0.00		$0.00	1	$38.40
Hog ring staples (boxes of 10,000)	$10.00	1	$10.00	2	$20.00	2	$20.00
Dobies	$0.50	30	$15.00	50	$25.00	65	$32.50
Poles	$16.50	6	$99.00	10	$165.00	15	$247.50
Concrete (yd3)	$91.50	2	$183.00	3.5	$320.25	4.5	$411.75
Approx. cost ($)			**1,102**		**1,641**		**2,169**

Appendix C: Calculations for PHW Water Demand

```
%50 filters

S=2848; %Saturation Tank
F=500;  %Flow Rate Tests
P=100;  % Filter Production
E=400;  %Employees


%Total Monthly Water Demand
Td=2*S + 20*(F+P+E);

%td=24,968

%Total Monthly Water Extraction
Tde=2*S+20*F;
%tde=14,968

%Total Monthly Water Inputs
Tdi=2*(0.5*S)+20*(F-P-E)*0.9;

%tdi=2,484

sto=Tdi-Tde;
%sto=-12,484/mo

three_mo=sto*3;
%three_mo=-38,544

six_mo=sto*6;
%six_mo=-77,088

nine_mo=sto*9;
%nine_mo=-115,632


%100 filters

S=4968;
F=1000;
P=200;
E=400;

%Total Monthly Water Demand
Td=2*S + 20*(F+P+E);

%td=41,936

%Total Monthly Water Extraction
Tde=2*S+20*F;
%tde=29,936

%Total Monthly Water Inputs
Tdi=2*(0.5*S)+20*(F-P-E)*0.9;

%tdi=12,168

sto=Tdi-Tde;
%sto=-17,768/mo

three_mo=sto*3;
%three_mo=-53,304

six_mo=sto*6;
%six_mo=-106,608

nine_mo=sto*9;
%nine_mo=-159,912


%100 filters using both water and wastewater tanks

waste_sto= (20*(F-P-E)*0.9)+2*(0.5*S);
extract=2*S;
excess_sto=waste_sto-extract
```

Appendix D: Measurements of Filter Capacity with Change in Height (Miller 2010)



Height (cm)	Volume of Water Added (L)	Cumulative Volume of Water Added (L)	Radius, Modeled as Paraboloid (cm)
2.8	0.1	0.1	4.8
3.9	0.1	0.2	5.7
5.1	0.1	0.3	6.1
5.9	0.1	0.4	6.6
6.5	0.1	0.5	7.0
7.3	0.1	0.6	7.2
7.9	0.1	0.7	7.5
8.4	0.1	0.8	7.8
9	0.1	0.9	8.0
9.4	0.1	1	8.2
9.9	0.1	1.1	8.4
10.3	0.1	1.2	8.6
10.7	0.1	1.3	8.8
11.1	0.1	1.4	9.0
11.4	0.1	1.5	9.2
11.8	0.1	1.6	9.3
12	0.1	1.7	9.5
12.9	0.2	1.9	9.7
13.6	0.2	2.1	9.9
14.2	0.2	2.3	10.2
14.9	0.2	2.5	10.3
15.5	0.2	2.7	10.5
16	0.2	2.9	10.7
16.5	0.2	3.1	10.9
17.1	0.2	3.3	11.1
17.6	0.2	3.5	11.3
18.15	0.2	3.7	11.4
18.6	0.2	3.9	11.6
19.1	0.2	4.1	11.7
19.6	0.2	4.3	11.8
20.1	0.2	4.5	11.9
20.5	0.2	4.7	12.1
21	0.2	4.9	12.2
21.4	0.2	5.1	12.3
21.9	0.2	5.3	12.4
22.3	0.2	5.5	12.5

Appendix E: Filter Factory Quality Control Logs

Thirst-Aid Myanmar

Pure Home Water

Flow Testing - Data Collection Sheet

Serial Number	Test Date	Bubble Test p/f	15 Minute Flow Rate	30 Minute Flow Rate	1 Hour Flow Rate - E=Estimate A=Actual	Remarks

Pure Home Water

Thirst-Aid Myanmar

Production - Data Collection Sheet

Date	Number of Filters Produced	Days required for drying	Number of Filters Rejected Before Firing	Remarks

Thirst-Aid Myanmar

Pure Home Water

Bacteriological Testing - Data Collection Sheet

Serial Number	1-hour Flow Rate (lit/hr)	Test Date	Without CS	With CS	Total Coliform	*E.coli*

Bacteriological Testing - Data Collection Sheetcont.

Incubation Temperature	Hours Incubated	Raw Water			Average	Remarks
		10 ml	25 ml	50 ml		

Appendix F: Bradner Recommendations for Filter Flow Rate Test Protocol

PHW Flow Test Procedure for 6 liter cone filters

1. As filters are removed from the kiln, inspect them for quality. They should be free of cracks that would tend to weaken the filter (especially in the rim area) or cracks that would affect the flow rate.
2. Let filters cool on the factory floor until cool to the touch, then put them in the soak tank ***making sure that they are either*** **<u>Rim Up,</u>** ***or on their sides so as to prevent any chance of trapping air inside of the filter.***
3. Soak at least 12 hours
4. Bubble test each filter as it's being removed from the tank. Record the filter's serial number on the flow test data collection sheet and also record the results of the bubble test (note if there is a small stream of bubble or multiple streams). If show an obvious flaw (crack or hole), discard the filter and make a note to this effect in the records.
5. Hang the filters in the rope cradles over plastic buckets so that the draining water can be recycled. Once there are five filters hanging, fill them all and record the time.
6. Repeat steps 4 and 5 for the next 5 filters.
7. 15 minutes after filling the filters measure how much water has drained. If it's more than 1 liter – reject the filter.
8. 30 minutes after filling the filters measure how much water has drained again. If it's between .6 liters and 1 liter – consider the filter acceptable. Double the 30 minute flow rate to estimate the per hour flow rate and write this number on the filter with caulk (ex: .8 liters after 30 minutes would equal an estimated 1.6 liters per hour)
9. If the flow rate is greater than 1.5 liters after 30 minutes reject the filter.
10. If the flow rate is greater than 1 liter per hour but less than 1.5 test the filter for another 30 minutes (one hour total). If the flow rate is less than 2.2 consider the filter acceptable. If the flow rate at this time is greater than 2.2 reject the filter.
11. Put a hole in all rejected filters
12. Store all accepted filters in a way that they can dry quickly.
13. Apply colloidal silver to DRY filters, mark them clearly with ***<u>CS</u>*** in chalk, and store in separate place.

Appendix G: Bradner Recommendations for Silver Mixing Protocol

Mixing Argonal Silver

Note 1: Wear rubber gloves and eye protection for this. It's highly unlikely that anyone would encounter health problems due to expose to powdered silver BUT getting it in your eye is simply a bad idea and it will stain your flesh like a tattoo if even a tiny bit gets on you and you sweat. (The tattoo will last about a week.)

NOTE 2: Filters should be 100% dry before applying colloidal silver)

To make a concentrated 3.2 % Colloidal Silver Solution, add 50 grams of powdered Argonal silver to 1 liter of purified water and mix completely (I usually just shake the solution rather than try to mix it with a spoon or stick. As mentioned, if this solution gets on your skin or clothing at this point it will stain it dark grey. In clothing it never comes out, on your skin it will wear off eventually.) As the solution will turn a thick brown it's difficult to know if it's been mixed thoroughly until you pour it out – so I usually mix in one container and store in another so I can examine the solution as I make the transfer.

For application to filters, further dilute this mixture in a 1 to 125 ratio or, ***8 ml to 1 liter of water***. Then, using a 1.5 inch wide (or so) brush, apply 200 ml of this solution to each ***cone*** filter (if you ever change filter size, calculate about 33 ml of solution per liter of capacity – so if you increase the size of the filters to 10 liters, apply 330 ml per filter), applying one third to the inside, then one third to the outside, then the last third on the inside again.

The colloidal silver gets absorbed into the filter and if the walls are the correct thickness, it penetrates all the way through.

Filters should be dried again before packaging and shipping.

Once the powdered silver is mixed with water it's photosensitive and should be stored in a dark container and in a dark cupboard. As I've never been able to get reliable information on how much this solution degrades over time my practice is to not mix any more of the 3.2% solution than I think I'll be using in a month.

At the above application rate, 1 liter of 3.2% would be enough to treat 625 filters. Obviously, if you're only going to produce 400 filters a month, mix in smaller batches, like 25 grams to 500 ml.