Investigation of Ceramic Pot Filter Design Variables

By

Molly Klarman
BA Lewis and Clark College

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Approved:

Christine Moe, Thesis Faculty Advisor

Date

Daniele Lantagne, Thesis Field Advisor

Date

Paige Tolbert, Chair, Department of Environmental and Occupational Health

Date

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Address: 32 Lovejoy RD
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The advisor for this thesis is:

NAME: Christine Moe, PhD
Rollins School of Public Health

ADDRESS: 1518 Clifton Road
Atlanta, Georgia 30322

Other committee members for this thesis are:

NAME: Daniele Lantagne, PE
Centers for Disease Control and Prevention

ADDRESS: 1600 Clifton Rd.
Atlanta, GA 30333

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Abstract

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Molly Klarman

Background: Over four billion cases of diarrhea occur worldwide each year that result in about 2.2 million deaths. Household water treatment and safe storage (HWTS) methods, such as ceramic pot water filters, are one of four proven HWTS methods and have been shown to reduce diarrheal prevalence by an average of 45% among users in a randomized control field trial. Although ceramic filters have been proven effective for improving water quality, users and implementers often express concern over their inability to produce a sufficient quantity of water due to their slow flow rate of approximately 1-2 liters per hour (L/H). If flow rate could be increased by altering the current filter design, it would improve the ceramic pot filter's viability as a scalable HWTS option.

Objective: The main objective of this study was to determine if the flow rate of ceramic pot filters could be increased without sacrificing filter effectiveness, in terms of bacterial removal, by examining the effect of altering specific design variables.

Methods: At the FilterPure ceramic manufacturing facility in the Dominican Republic, eight new filter designs were created by changing one of three design variables: 1) type of combustible material, 2) the ratio of combustible material to clay, or 3) the size of the screen used to sift combustible material. These eight new filter designs were produced in triplicate, along with six control filters. Local river water was passed through the filters daily, and they were tested once a week for five weeks for total coliforms (TC), turbidity, pH, conductivity, and flow rate.

Results: The flow rate of all filter designs increased from the first to fifth week by an average of 44.1%. The filters made with alternative combustible materials (coffee husks and rice husks) had average flow rates of 9.9 and 5.0 L/H and average TC reductions of 96.1% and 97.6%. The control filters had an average flow rate of 0.95 L/H and average TC reduction of 99.8%. As the proportion of clay to combustible material decreased from 60% clay:40% sawdust to 40% clay:60%sawdust, the average flow rate increased from 0.38L/H to 5.9L/H and the percent reduction of TC decreased from >99.9% to 98.1%. Once initial flow rate increased above 1.7L/H, TC reductions fell below 99%.

Discussion: Minor alterations in filter design or raw materials can affect the performance of locally produced ceramic pot filters to the point where their ability to produce safe drinking water is compromised. The results of this research suggest that the maximum initial flow rate for a properly functioning FilterPure filter is 1.7 L/H. None of the alternative designs, that had faster flow rates had better TC reduction than the control filters. This indicates FilterPure should not produce filters with a clay to sawdust ratio lower than 53% clay to 47% sawdust and different combustible materials cannot be used interchangeably without first identifying optimal proportions.

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Global Safe Water

Global Burden of Diarrhea

Over four billion cases of diarrhea occur worldwide each year, which result in about 2.2 million deaths (WHO 2008a). Approximately 1.9 million of those deaths occur among children under the age of five years (Boschi-Pinto 2008). Diarrhea not only leads to mortality but also contributes to a host of other health problems. Malnutrition, caused by repeated episodes of diarrhea, leaves children more susceptible to other harmful infections such as malaria or enteric diseases, and can impair cognitive development and lead to stunted growth (WHO/UNICEF 2005). Unlike some childhood diseases, such as measles, mumps, and rubella, there are no vaccines for many of the pathogens that cause diarrhea. Poor physical health and nutrition at a young age have been shown to lead to neurodevelopment delays (Kuklina *et al.* 2006) and affects physical work capacity later in life (Haas JD 1995).

Access to Safe Drinking Water

Approximately 88% of diarrheal disease is related to unsafe water and lack of sanitation facilities (WHO 2007). As of 2006, an estimated 884 million people worldwide did not have access to an improved water source. The World Health Organization has defined the following water sources as improved: public or private stand pipes, tube wells, protected dug wells, protected springs, and rainwater harvesting. An improved water source does not necessarily provide water that is microbiologically safe to drink, which means even more then 884 million people do not have safe drinking water (WHO 2008b). Increasing the number of people who have a reliable source of safe drinking water is a key component in reducing diarrheal disease prevalence.

The need for improvements in safe drinking water coverage worldwide has recently been receiving more attention as one of the global health topics of highest priority. The importance of safe drinking water is highlighted by its presence on the United Nations list of Millennium Development Goals. Goal Seven seeks to halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation (WBG). In order to achieve this goal, it will be necessary for 96,568,000 people to gain access to an improved drinking water source each year (WHO/UNICEF 2005). Although this appears to be a costly goal, the World Health Organization estimates that every one USD invested will yield an economic return of between 3 and 34 USD (depending on the region).

Household Water Treatment and Safe Storage

HWTS Proven Effectiveness

Household water treatment and safe storage (HWTS) methods have been receiving increasing recognition as important interventions to address the safe drinking water problem. In many circumstances, such as disaster situations, HWTS is a more practical option than improving water at the source (Caens 2005, Palmer 2005, Clasen & Boisson 2006). Water that comes from an improved source, and is thought to be safe, is often times susceptible to contamination during collection, transport, or storage (Fewtrell L 2004). When used correctly, HWTS eliminates or reduces the risk of recontamination post-treatment and can be very effective. This was illustrated in a meta analysis, consisting of 41 studies that evaluated the effectiveness of improving microbial water quality on the reduction of diarrheal occurrence (Clasen *et al.* 2007a). In the review of the 35 studies that assessed water quality improvements at the household level, the authors concluded that there was a significant reduction in diarrhea occurrence in both adults and children less than five years of age. The individual studies reported different outcome measurements, so it was not possible to generate a single, pooled estimate for reduction in diarrhea among all studies. The individual outcomes for each measurement are shown in Table 1. The pooled rate ratio from the four studies on source water quality interventions was 0.87, suggesting that household water quality interventions were more effective then source water quality interventions. Other benefits of HWTS compared to source improvements are that HWTS interventions do not require significant start up capital, they can be implemented easily and rapidly, and they do not require extensive infrastructure development.

Table 1. Different outcome measures of reduction in diarrheal occurrence from water quality improvements at the household level (Clasen et al. 2007a)

Pooled Outcome Measure	Number of Studies	Estimate
Rate Ratio	8	0.62
Risk Ratio	7	0.49
Longitudinal Prevalence	10	0.56
Odds Ratio	10	0.65

HWTS Methods

The Centers for Disease Control and Prevention has identified four HWTS methods that have been proven to reduce diarrhea incidences in users and are described in the following subsections (CDC 2008e).

Household Chlorination

Chlorine treatment consists of dilute sodium hypochlorite solution (Figure 1) and a storage container (CDC 2008c). To treat water, a capful of solution is added to the container, and then users must wait 30 minutes prior to consuming the treated water. One of the advantages of chlorination is that it provides residual protection to water during storage. This method costs anywhere between 0.01-0.05 US cents per liter and generally has high user acceptance rates in people who do not object to the slight chemical taste and odor. Diarrheal reductions in users range from 22% to 84%. However, chlorine can be ineffective at killing some parasites and can lose effectiveness when used with highly turbid water.

Figure 1. Sodium hypochlorite solution SFH/Nigeria

Solar Disinfection SODIS

SODIS disinfection requires sunlight and a plastic bottle (Figure 2). The bottles are filled with water, shaken to oxygenate the water, and placed in the sun for one to two days depending on the amount of available sunlight (CDC 2008d). Increased temperatures, UV light, and oxidative chemistry inactivate most bacteria, viruses, and protozoa. The only cost for this treatment method is that of the plastic bottle. Reductions in diarrhea vary between 9% and 86%. Although the treatment process is simple, users may be unsatisfied with the limited quantity of water produced and length of time necessary to treat water. SODIS disinfection is not effective with highly turbid water unless it is pretreated.

Figure 2. Solar disinfection. (www.kwaho.org)

Flocculant / Disinfection Powder

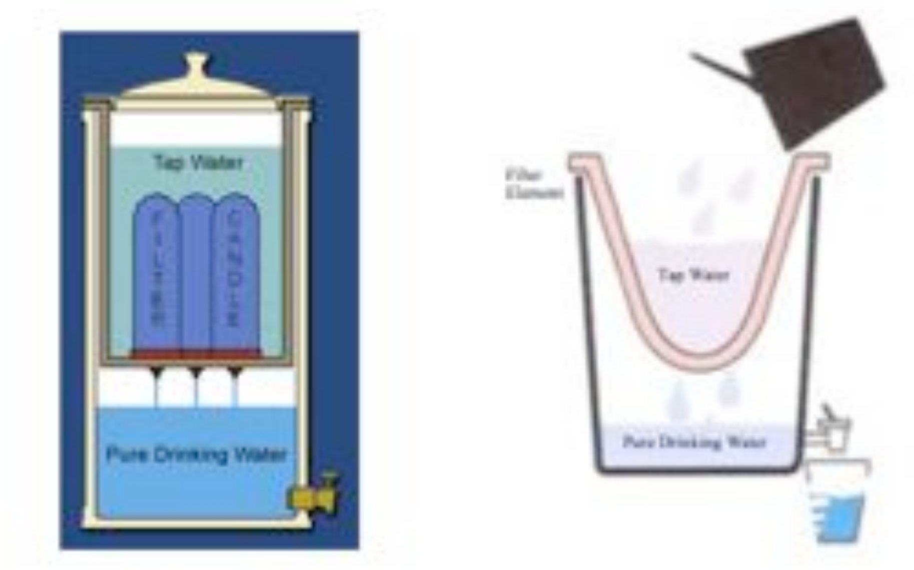
The first step in floccculant/disinfectant treatment is to combine one packet of the flocculant/disinfectant (Figure 3) with 10-20 liters of water in a container (CDC 2008b). Next, it is stirred for five minutes. The solids will coagulate and settle to the bottom of the container and then must be strained through a cloth by pouring the contents into another container. After 20 more minutes the water is fully treated and the hypochlorite component of the product will provide residual protection to stored water. Flocculant/disinfection treatment is capable of removing bacteria, viruses, protozoa, and some heavy metals and pesticides. Reductions in diarrhea range from 16% to 90%. This intervention costs about 1 US cent per liter and requires two buckets, a cloth, and something to stir with. It also requires the user to correctly perform a number of steps and produces a flocculant waste. Flocculant/disinfection is a popular option for responding to emergency and disaster situations.

Figure 3. Flocculant/ disinfection packet (www.daylife.com)

Ceramic Filtration

Ceramic water filtration systems generally consist of a porous ceramic membrane, a plastic or ceramic receptacle, and a plastic tap (CDC 2008a). Water is poured into the upper portion of the receptacle, or directly into the membrane, where gravity pulls it through the pores in the ceramic and into the lower portion of the receptacle. Water is safely stored in the receptacle until it is accessed through the tap. There are two main types of ceramic filters, the candle filter and the pot filter (Figure 4), which differ in the shape and assemblage of the ceramic membrane. Candle filter systems consist of an upper receptacle that sits above, and is separated from the storage receptacle. Candle elements, which are cylindrical, hollow ceramic membranes, are attached to the barrier that divides the two receptacles. The only way in which water can flow into the lower receptacle is if it enters the candle elements, which is where filtration takes place. The pot filter system is simpler, and consists of a single concave membrane, which sits inside the rim of the receptacle.

Figure 4. Ceramic filter styles (www.srvba.com.au) (www.helid.desastres.net)



Candle Filter **Pot Filter**

The main benefits and drawbacks of ceramic filtration as a household water treatment method are listed in Table 2, which was adapted from the CDC fact sheet on ceramic filtration. It is important to consider all of the points listed below prior to designing an implementation program. The benefit of using local supplies and local knowledge is generally only applicable to the pot filters and this issue is further discussed in the operation and maintenance subsection of this document.

Table 2. Benefits and drawbacks of ceramic filtration

Benefits	Drawbacks
• Proven effective in removing bacteria and protozoa resulting in reduction of diarrhea by 60-70%	• Limited removal of viruses, heavy metals, and pesticides
• Can improve taste and smell of water and reduce turbidity	• Water can become re-contaminated as there is no residual protection
• Take advantage of local materials and existing local knowledge	• Filter quality can vary by region (pot) or brand (candle)
• One time investment ranging from 12-25 USD (pot) 12-60 USD (candle)	• Initial price can be relatively high
• Simple to use	• Ceramic membrane is fragile and taps may leak
• Simple to maintain	• Slow rate of filtration, 1-3 Liters per Hour (L/H)
	• The effective life span of the filter is unknown

Ceramic Filter History and Projects

Potters for Peace

Potters for Peace (PFP) is a United States based non governmental organization (NGO) that began manufacturing and distributing ceramic water filters in 1999 (PFP). The original ceramic filter with a silver-impregnated pot-shaped design was developed by the Central American Research Institute of Industrial Technology (ICAITI) in 1986. ICAITI tested ten ceramic filter designs to identify one that could domestically produce a suitable capacity of water, be self sustaining, and would foster economic and local artisan activity (1994). Traditionally, filters were thrown by hand on a potter's wheel. Then in 1999, PFP constructed and began operating a large scale filter manufacturing factory in Nicaragua that was established in response to the devastation caused by hurricane Mitch (PFP). After many years of filter manufacturing, PFP no longer runs this Nicaraguan factory, but has instead focused on achieving their goal of helping people gain access to safe drinking water by assisting in the establishment of other local filter production facilities worldwide. In trying to achieve their goal "to assist with appropriate technologies sustained using local skills and materials", PFP also offers technical and design assistance as well as resources to develop marketing and educational materials. PFP has formed partnerships with NGOs, governments, and private enterprises to distribute over hundreds of thousands of filters in more than 20 countries (PFP 2009b). Although PFP may be the most well known ceramic pot filter organization, not all filter projects are affiliated with PFP, and each project has slight variations in their filter design, and manufacturing process.

FilterPure

One of the non-PFP organizations working with ceramic water filtration is FilterPure, an NGO founded in 2006. FilterPure operates in many different areas of the Dominican Republic where they manufacture and distribute ceramic water filters. The factory is located just outside the city of Moca, and the main office is located in the city of Jarabacoa. FilterPure utilizes several different strategies to distribute their filters. There is an ongoing, local sales network where filters can be purchased directly from the manufacturing facility or project director. Much of the business comes from word of mouth and recommendations by friends and family. Occasionally, other NGOs and organizations working in the country, such as the Pan American Health Organization, will purchase filters and distribute them independently. FilterPure also receives grants from organizations based in the United States such as Instituform, or donations from church groups to fund the manufacture and distribution of filters.

To date, FilterPure has distributed over 11,000 filters (Ballantine & Hawkins 2009). They recently joined with Safe Ceramics of East Africa to assist in the establishment of a ceramic water filter project in Arusha, Tanzania. In the future, they hope to develop additional projects that use their filter design in other locations. FilterPure was host to the investigation of ceramic pot filter design variables presented in this thesis.

Past Research – Ceramic Filtration

As the issue of global safe water has gained momentum over the past twenty years, and as HWTS interventions have been further developed, ceramic filtration has been the focus of a number of laboratory studies, field studies and masters theses. Six randomized control studies have investigated the effectiveness of ceramic filters at improving microbiological quality of drinking water among users in the field (Brown *et al.* 2008, Clasen & Boisson 2006, Clasen *et al.* 2005, Clasen *et al.* 2004, Clasen *et al.* 2006, du Preez *et al.* 2008). Five of these trials went on to assess reductions in diarrhea incidence among users (Brown J 2008, Clasen et al. 2005, Clasen et al. 2004, Clasen et al. 2006, du Preez M 2008). In addition, user acceptance surveys and evaluations of adoption were components of these studies, as well as topics that were assessed in a number of master's theses and additional reports (Caens 2005, Lantagne 2001b, Palmer 2005). Factors such as the implementation setting, operation and maintenance requirements, cost, and life span have all been shown to influence successful user adoption of ceramic filters. Laboratory studies have investigated issues such as flow rate, mechanisms of filtration, and different silver application methods to better understand how the filter functions in the field (Oyanedel-Craver & Smith 2008, van Halen 2006, Franz 2005, Campbell 2005).

Bacterial and Diarrheal Reduction

The majority of studies assessing the performance of ceramic filters have found them to be highly effective in removing total and fecal coliforms from treated water (Clasen *et al.* 2007b). Field trials have extended this conclusion to show that filters are also effective at reducing incidence of diarrheal disease, particularly in children under five years of age. This is highlighted in a meta analysis by Clasen (2007) where all six studies conducted in developing countries found ceramic filters led to significant reductions in diarrhea among users (Clasen et al. 2007b). These studies varied in location, type of filter, study design, and implementation setting.

Two randomized control trials took place in Bolivia. One trial, which distributed Katadyn (Switzerland) candle filters, reported all 96 water samples collected from intervention households over the 25 week study had thermotolerant coliform (TTC) counts of 0, whereas only 13% of control households had TTC counts of 0. The diarrheal reduction in intervention households was 72% among children under five years of age and 57% among adults. In the other Bolivian trial, both Katadyn and Stefani (Brazil) candle filters were distributed to 40 households (Clasen *et al.* 2006). Water samples from the intervention households had a mean TTC count of 0.13 TTC/100ml whereas the control households had a mean TTC count of 108 TTC/100ml. There was a 45% reduction in diarrhea among filter users over the five-month follow up period. In another study involving distribution of Katedyn filters in three geographically different communities in Colombia, 48% of intervention households had no Total Coliforms (TC) in treated water compared to 1% of control households. A 60% reduction in diarrheal prevalence in filter users compared to non-users was observed over a six-month period.

Following flooding in the Dominican Republic, 71% of households who were given Stefani filters had 0 TTC counts in treated water compared to 32% of control households (Clasen & Boisson 2006). However, when investigators returned ten months after their last regular follow-up visit, the percentage of intervention-households who had treated water free of TTC had dropped to 54%. The study that found the strongest effect, an 80% reduction in diarrheal disease, was a randomized control trial in South Africa and Zimbabwe. In South Africa, 74%, and Zimbabwe, 43%, of intervention households met World Health Organization (WHO) guidelines for *Escherichia coli* (*E. coli*) in drinking water of no detectable *E. coli*/100ml (WHO 1997) compared to 55% and 9% of control households. The high percentage of diarrheal reduction reported in this study may not be typical of ceramic filter intervention projects elsewhere, because in this trial, the study populations were specifically chosen for their high levels of diarrhea incidence, and at a cost of 60 USD, the Berkefeld (England) candle filters distributed were more expensive than most HWTS options (du Preez et al. 2008).

The above studies all involved high quality, commercially available, imported candle filters. The only randomized control trial to evaluate diarrheal reductions from locally manufactured pot filters was conducted in Cambodia (Brown et al. 2008). Over 18 weeks of use, treated water from 38.5% of intervention households had no detectable *E. coli* compared with 1% of control households. The reduction of diarrheal prevalence among users of all ages was 45.5%.

The validity of the health improvements reported in studies on HWTS interventions, such as the studies just mentioned, have recently been challenged (Schmidt & Cairncross 2009). The main arguments suggesting that HWTS interventions may not actually lead to significant reductions in diarrhea include; the multiple transmission routes (aside from drinking water) of enteric pathogens, the subjectivity of self-reported diarrhea, and observer and reporting bias of results. To date, no one has been able to devise an ethical way to perform a blinded, randomized control trial using ceramic filters that the authors of this article call for.

Adoption of Intervention

Although it has been well documented that ceramic filters are capable of removing bacteria from water, leading to reductions in diarrhea illness, there are still a number of factors that influence the likelihood that they will be readily adopted and prove to be a sustainable, affordable, effective means of providing safe water.

User adoption of ceramic filters generally varies between 70% (Clasen *et al.* 2004) and 99% (du Preez et al. 2008) during trial interventions. The South Africa/Zimbabwe study interviewed 43 of its intervention households, with just one refusing to use the filter, leading the investigators to conclude the filters were well received during the trial (du Preez et al. 2008). In Cambodia, 97% of filters were in use throughout the 22-month study (Brown et al. 2008). During a surprise follow up visit 16 months after filter distribution in the Dominican Republic, 49% of filters were still in use and operating properly (Clasen & Boisson 2006). In one Bolivian trial, 72% of filters were clearly in use at household visits during the study (Clasen et al. 2004). In the other Bolivian study, nine months after initial filter distribution and five months after the trial was complete, 67% of filters were still being used and had treated water with 0 TTC (Clasen et al. 2006). An evaluation of user acceptability of candle filters distributed in Haiti following flooding reported 72% of filters still in use six months after distribution

(Caens 2005). It appears that filter use is generally high during the course of an intervention trial but will begin to drop once the trial is finished and regular follow-up visits end. However this assumption is based on only two studies where investigators returned after the trial was completed (Clasen & Boisson 2006, Clasen et al. 2006).

One factor that could affect adoption rates is user acceptability. Perceived value, technical complexity, and social acceptance are all aspects that could potentially influence user acceptability (Murcott 2006).

One method to assess user acceptability is to investigate the reasons why people stop using their filters. Data on explanations as to why certain households discontinue filter use typically indicate that either filter hardware or personal opinions about the filter are the main causes for disuse. Some of the most commonly cited reasons why households stop using their filters include the filter and or receptacle were broken, (Lantagne 2001b) inability to pay for or find replacement parts (Clasen & Boisson 2006), and insufficient training and poor implementation (Palmer 2005). A report detailing implementation, critical factors and challenges to scale up of HWTS suggested successful installation, operation, and maintenance as the most critical factors in adopting and sustaining use of a HWTS method (Murcott 2006). All three of these critical factors are consistently reported as barriers to successful user uptake with ceramic filters.

Implementation Setting

The particular reasons for filter disuse are specific to each location and situation, which emphasizes the importance of fully evaluating the setting prior to project establishment. For example, Oxfam distributed filters at emergency shelters in three different regions, following the 2004 tsunami in Sri Lanka (Palmer 2005). Three months later, 8% of households reported regular use and 0% had drunk filtered water on the day of visit. Alternatively, 88% of households reported regular use and 82% had drank filtered water on the day of visit when the same type of filters were distributed to households living in temporary shelters (rather than emergency shelters), in addition to having received filter training. It should be noted that follow up for the first group in this study was limited to those filter recipients who were still living in the emergency shelters, and it is possible that filter use was higher among those people who had left the shelters and had found more permanent homes. In this implementation situation, the investigators concluded that a rushed distribution, without proper training or education at temporary emergency shelters was not ideal for user adoption. In another pilot study, it was suggested that the difference in filter effectiveness, both in terms of diarrhea reduction and user uptake, between different Colombian villages was the environment. The village where filters were least effective was built above and around the river that was both the source of drinking water and location of defecation. Whereas the filters were more effective and more widely used in two farming communities that had rudimentary piped water distribution networks (Clasen *et al.* 2005).

Operation and Maintenance

Candle filters that have been used in the majority of trials demonstrating ceramic filtration to be a viable household water treatment option, are prone to breakage and leakage (Clasen & Boisson 2006). The filter elements are commonly produced abroad (Kancham filters from India, Ceramica Stefani filters from Brazil, Katadyn filters from Switzerland) and it can be difficult to obtain replacement parts (Clasen et al. 2006). In many ways, this characteristic could make the candle filter unsustainable. Pot filters are also prone to breakage. In a cross sectional study, 350 of 506 households in Cambodia who had received pot filters at some point in the previous four years were no longer using their filters, and the reason for 65% of the disuse was due to breakage (Brown *et al.* 2007). However, because pot filters can be manufactured locally, access to replacement parts may not be as problematic with pot filters as it is with candle filters. It is difficult to compare breakage rates between candle and pot filters in the field because only one trial testing pot filters has been published (Brown et al. 2008).

Sixteen months after filter distribution following flooding in the Dominican Republic, the main reasons why 52% of filters were not in working condition were breakage, clogging, or expiration of the useful life of the filter, and it was reported that many people had difficulty finding replacement parts (Clasen & Boisson 2006). In one of the Bolivia studies, 32% of filters had broken by the end of the 25-week trial, (Clasen et al. 2004) and in the other Bolivia study, 25% of filters had broken by the nine month surprise follow up visit (Brown et al. 2008). An evaluation of post-tsunami filter distribution in Indonesia concluded that pot style filters were a more practical filter option because they were easier to assemble/use. In a side-by-side comparison, six of eight households simply preferred the pot style filter (Palmer 2005). However, this study waited only one to two weeks to follow up with filter users, which is still too early to evaluate adoption perceptions.

Life Span and Cost

The effective life of the pot filter was originally estimated at two years and is roughly based on the necessary contact time between colloidal silver and bacteria for inactivation (Lantagne 2001a). A longevity analysis was conducted where the microbial effectiveness of filters, that had been in use anywhere between one and five years, was measured (Campbell 2005). Based on the results, it was recommended to extend the amount of time that filters can be used before replacing the membrane from two to five years. It still remains unclear what the actual life of the membrane is, or if it can even be calculated, due to variations among filter designs and influent water characteristics. The recommended life span of candle filters varies widely, ranging from six months (Stefani 2009) to three years (Clasen et al. 2005), and is also dependent on quality of source water and filter brand. Pot style filters can be produced locally using local knowledge and local materials. This contributes to their relatively low price of 12-25 USD, which varies depending on the region and the resources available (CDC 2008a). The high quality, commercially produced candle filters that have been tested in randomized control studies range from 12-60 USD for the entire filtration system with replacement candles costing around 5-8 USD (Clasen et al. 2006, du Preez et al. 2008). The fact that candle filters and replacement parts need to be imported and distributed may elevate the costs.

Flow Rate

The flow rate of pot style filters varies among production facilities, among daily lots, and even among filters produced in the same lot, but is generally in the range of 1-3 L/H (CDC 2008a). Many facilities actually use this range as a measure of quality control and discard filters above or below the desired flow rate. The flow rate of candle filters also varies among the many brands available. The advertised flow rates range from 0.8 L/H (Berkefeld candle) to 1.3 L/H (Katadyn Ceradyn candle). A study in Kenya comparing five different brands of candle filters reported that flow rates in the field ranged from 0.09-0.24 L/H per candle (Franz 2005). With this type of filter, there is the option of using multiple candles in a single filtration system that allows the total flow rate to be manipulated. However, the majority of filtration systems only use two candles because the price and maintenance requirements increase as the number of candles increase. There are additional factors that will influence flow rate once the filter is in use. The turbidity of source water, the frequency that the filter is scrubbed, and the hydraulic head above the filter, will all affect flow rate and are discussed in further detail in the following subsection.

Water Quantity

The need to improve access to safe water is widely recognized, however the problem of a lack of sufficient quantities of safe drinking water also deserves attention. If a family or community decides to invest their resources into a water treatment system, it is important that they not only get water that is free of harmful bacteria and disease-causing pathogens but also available in sufficient quantities to meet their needs. A water treatment system that provides suitable drinking water is virtually useless if there is not enough of it. People will have to resort back to unsustainable practices or unsafe sources such as purchasing water or drinking untreated water.

It is difficult to make accurate estimates regarding daily fluid intakes because the requirement is highly dependent on body physiology, activity level, and local climate. An average estimate based on a review of the literature for adult males is 2.9 L/person/day, adult females is 2.2 L/person/day and children is 1.0 L/person/day (Table 3) (Howard & Bartram 2003). An additional point to consider is the many other activities that benefit from the availability of safe water such as cooking and hygiene. When these additional water needs are factored in, the recommended minimum water requirements rise to 7.5-15 L/person/day and is also dependent on climate, daily habits, available sanitation facilities, cultural practices and many other variables (Howard & Bartram 2003).

Table 3. Recommended daily water consumption

		Volume (L/day)	
		Average Conditions	**Manual Labor in High Temperatures**
Adults	**Male**	2.9	4.4
	Female	2.2	4.4
Children		1.0	4.4

With proper use, ceramic filters are technically capable of producing sufficient drinking water for an average five-member household. This is assuming an ideal situation where the filter is consistently refilled throughout the day (to maintain the maximum level of hydraulic head), and is cleaned and properly cared for. Invariably, this is not the case for many filters and filter users, which leads to quantities of treated water that are below the filter's maximum potential. Additionally, there are factors outside of the users' control, mainly turbidity of influent water, which will affect the daily amount of water that can be filtered. It is common for a filter's flow rate to decrease over time as sediment builds up and begins to block the pores. A laboratory analysis found that none of the filters from three different PFP projects had a flow rate greater than 0.5L/H at the conclusion of their 12 week study (van Halen 2006). Similarly, the Kenya study of candle filters reported the Doulton Super Sterasyl filter to have an average flow rate of 0.24L/H in the field when the product is advertised to have a flow rate of 1.3 L/H (Franz 2005). To prevent this type of performance reduction, users are advised to scrub their filter with a brush once it becomes noticeably slower. However, users frequently fail to scrub them as often as they should, fail to scrub them at all, or fail to scrub them properly. Half of the families in one study scrubbed their filters no more than once every other week (Lantagne 2001b). Scrubbing can substantially increase flow rate, as demonstrated when the flow rate of a filter increased from 0.28L/H to 2.0L/H following scrubbing in the laboratory. When taking the above issues into consideration, it becomes important to assess whether ceramic filters are actually providing sufficient water quantity to users in the field.

Flow Rate Acceptability in the Field

In the user acceptability assessment in Haiti, 84% of respondents said their filter was able to produce a sufficient quantity of water for their entire household. However, this study involved candle filters that had an average flow rate of 4.75 L/H which is faster than that of the pot design and most other commercially available candle filters (Caens 2005). One survey investigating the reasons for disuse of filters in Cambodia reported that only 6% stopped using them because they were too slow (Brown et al. 2007). The South Africa/Zimbabwe study reported that only 5% of participants felt the filter was slightly too slow and another 5% felt it was too slow (du Preez et al. 2008). In the Dominican Republic study, 92% of users felt their filter was able to produce sufficient water for their household. One of the Bolivia studies reported the highest dissatisfaction with flow rate where 31% of households thought it to be too slow (Clasen et al. 2006). In summarizing the results just mentioned, the large majority of filter users do not complain about the flow rate of their filters and report that they produce a sufficient quantity of water for their household. However, people in the public health community commonly mention the slow flow rate to be an issue with this particular HWTS option (CDC 2008a, Sobsey *et al.* 2008, Schmidt & Cairncross 2009).

The discrepancy between filter users and the public health community's views on the water quantity produced by ceramic filters may come from a variety of reasons including; users not wanting to disappoint interviewees, users simply being happy to have any sort of method for treating water, or because users are not accustomed to drinking the quantities of water consumed in more developed countries. Whatever the reason for the difference in opinion regarding the ability of ceramic filters to produce sufficient quantities of water, it is worth investigating if the issue can be improved by increasing the filter's flow rate. The following study and discussion examines pot filters because their design can be easily tested and manipulated due to their production in local manufacturing facilities.

Flow Rate Characteristics

Steps in Filter Manufacturing

To identify possible options for increasing the flow rate, it is first necessary to understand how the filter is made and how it functions. The following are the basic steps for making a ceramic pot filter (Hagan *et al.* 2009).

1) The raw materials are prepared
    a) Dry pulverized clay
    b) A combustible material that has been sifted through a screen so that particles are uniform in size (Figure 5)
    c) Clean water that is free of heavy metals and chemicals

2) The materials are thoroughly mixed using a clay mixer (Figure 6)

  a) First the dry ingredients are added to the mixer and mixed dry

  b) Water is then uniformly added to get a smooth clay mixture

  Note: Dry silver crystals can also be incorporated at this step if they are first mixed in with the water

  c) The clay is mixed for at least ten more minutes

3) The clay is divided into blocks of approximately 8 kilograms

4) Each clay block is molded into a pot shape using a hydraulic press (Figure 7)

  a) The outer surface of the pressed filter is smoothed over with a plastic scraper to ensure it is even and the rim is sturdy

  b) Each filter is labeled with a unique stamp/number

5) Filters are dried in the shade for at least three to four hours as they begin to harden

6) Filters continue to dry on a drying rack for 7-18 days (depending on the climate) to remove excess moisture, which could cause the filter to crack during the firing process (Figure 8)

7) Filters are arranged in the kiln so that they are not touching each other and heat distribution will be uniform

8) Filters are fired in the kiln where the combustible material burns away forming pores and the clay becomes hard (Figure 9)

  a) The temperature of the kiln chamber is initially raised to 100 °C for two hours to remove any remaining moisture

b) The temperature is then gradually raised to around 900°C to allow for vitrification (silica and alumina molecules within the clay melt and bond and the chemical structure of the clay is altered)

9) Filters are allowed to gradually cool

a) They are first cooled in the kiln for about 24 hours

b) They are then moved to drying racks where they continue to cool

10) Silver is applied to the filter as a chemical barrier to bacteria

a) The silver solution can be made with silver nitrate or colloidal silver and solution concentrations vary depending on the purity of the silver

b) The silver solution is either painted on to both the inside and outside of the filter or it is submerged in the silver solution

Figure 5. Sifting combustible material

Figure 6. Mixing materials in clay mixer

Figure 7. Forming pot shape with a hydraulic press

Figure 8. Filters drying on racks

Figure 9. Kiln

Mechanism of Filtration

The density and size of a filter's pores are two of the factors that affect filter performance (Hagan et al. 2009). The pores are created when the combustible material, which is mixed in with the clay, burns out during the firing process. Within the filter, multiple pores throughout the membrane are interconnected, forming channels that allow for the passage of water. One method of pathogen removal is to block particles and organisms that are larger in size than the pores from flowing through the outermost membrane layer (Figure 10) (Doulton 2009). Particles that are smaller than the average pore size will not necessarily flow through the entire membrane. It is possible that they will

Figure 10. Blockage by size

Figure 11. Adsorption

Figure 12. Plugged pore

adsorb to the ceramic (Figure 11) or become blocked when larger particles plug up the pores (Figure 12). Colloidal silver acts as a chemical barrier to bacteria and is discussed further in the following subsection.

Flow rate is also dependent on pore characteristics (Hagan et al. 2009). The larger and more connected the pores, the easier it is for water to flow through the membrane. Adjusting pore size, will affect both flow rate and microorganism removal. Filter design variables, that are pore related and could potentially be manipulated to affect flow rate include the type of combustible material, the amount of time the clay/combustible material is mixed, the thickness of the ceramic membrane walls, the size of combustible material particles, and the proportion of combustible material to clay.

The PFP filter design aims for a pore size of 1 μm, that is expected to have a flow rate between 1-2 L/H (Lantagne 2001a). There is evidence that filters with flow rates up to three L/H can remove 100% of total and fecal coliforms (Lantagne 2001a). Another study found that even though the mean effective pore size was measured to be 40 μm, which is much greater than the PFP recommended size, the larger pores did not compromise the filter’s ability to trap microorganisms from effluent water (van Halen 2006). However, in that study both faster and slower filters removed high percentages of microorganisms. If the influent water had higher levels of microorganisms, it is possible that differences in removal corresponding to flow rate would have been observed. Because of the evidence that filters with flow rates above 2 L/H can effectively remove bacteria, perhaps the cut off for an operational filter does not have to be 2 L/H.

The Role of Silver in Filters

Silver that acts as a bacteriocide, can be incorporated into the filter in different quantities, different forms, and using different application methods. The mechanisms by which silver acts as an antimicrobial agent are: 1) reaction with thiol groups in bacterial cells, 2) production of structural changes in bacterial cell membranes, and 3) interaction with nucleic acids (Russell & Hugo 1994). Silver has been used in many different health applications ranging from eradicating *Legionella pneumophila (Liu et al. 1994)* in hospital water supplies to healing wounds in burn patients (Burnell 2003). It does not pose a human health risk when consumed below the recommended levels that the United States Environmental Protection Agency (EPA) has set of 0.1 mg/L for drinking water (EPA 1992). Concentrations of silver in effluent water have been measured at 29-61 μg/L immediately following silver application (Lantagne 2001a). The concentrations in effluent water of the subsequent run decreased to 11-19 μg/mL, all of which are below the EPA guidelines. This study also determined that application method has more of an effect on silver concentrations in filtered water than quantity of silver applied.

Microbial Effectiveness

Studies investigating the importance of colloidal silver for microbial reduction in filters have found it beneficial. Lantagne reported that microbial removal was not complete unless colloidal silver was applied to the outside of the filter (Lantagne 2001a). This conclusion was based on a filter with the traditional silver PFP silver application (1 mL of 3.2% Microdyn solution painted on) that removed all TC, fecal coliforms, and fecal streptococci from influent water, compared to a filter that had no silver application and had TC levels of 55, fecal coliform levels of 47, and fecal streptococci levels of 6 in 100 mL of filtered water. This study also concluded that microbial reduction was better when silver was applied to both the inside and outside of the filter. Another study that supported these findings reported 100% of samples taken from filters with colloidal silver tested negative for TC, and 67% of samples tested negative for *E. coli* (van Halen 2006). In filters without silver, 85% of samples tested negative for TC, and none tested negative for *E. coli*. In this laboratory study, silver had an additional benefit of preventing the growth of a biofilm in the plastic storage container, although this conclusion is based only on observation.

Silver Application

PFP suggests two methods for applying silver to filters. Both require the preparation of 300mL of 220mg/L silver solution for each filter. It can then be painted on to the filter with one third of the solution applied to the outside and two thirds of the solution applied to the inside. Alternatively, the filter can be submerged in the silver solution, which requires a larger quantity of silver solution (PFP 2005). It was concluded by one study that compared the two methods above, that the quantity of colloidal silver has more of an effect on disinfection efficiency of *E. coli* than the application method (Oyanedel-Craver & Smith 2008). One unknown factor regarding silver application is how long the silver remains in the filter, and if frequent scrubbing of the filter will remove the silver. It has been suggested that over time all of the silver will eventually wash out of the filter or will be removed from external scrubbing (Ballantine & Hawkins 2009). Filter Pure has attempted to address this idea by homogenizing the silver into the clay mixture prior to firing in the kiln.

Investigation of Pot Filter Design Variables

Research Objectives

The main objective of this study was to investigate the effect of changing design variables of pot filters to determine if flow rate could be increased, without sacrificing filter effectiveness in terms of microbial removal. An additional goal was to identify the maximum flow rate that could be used to test for quality control in the field.

Increasing Flow Rate

As stated earlier in this report, two of the main weaknesses of ceramic filtration are: 1) slow flow rate; and 2) hardware leakage/breakage/replacement part issues. The issues of leakage and replacement parts can be addressed by increasing efforts to provide a supply chain and more extensive training on filter maintenance. Currently, the only solution to the issue of fragility is to emphasize proper handling of the filter. That leaves addressing the issue of flow rate as an important area for possible improvement of ceramic filtration as a viable, scalable HWTS. In a review of the literature, there are no evidence-based explanations for why the maximum flow rate of a functioning filter has been set at 2 L/H. Initially, flow rate was roughly based on a calculation involving the necessary contact time between colloidal silver and bacteria to cause cell death, which upon review is incorrect and irrelevant (Lantagne 2009). Due to the absence of a scientifically determined maximum flow rate, it is possible that the relationship between microbiological reduction and flow rate can be optimized to produce a faster filter. Support for this idea comes from Lantagne’s study on the intrinsic effectiveness of ceramic pot filters where filters with flow rates of 1.0, 1.5, and 2.1 L/H all removed >99% of total and fecal coliforms from source water with 3108 and 1583 CFU/100mL respectively (Lantagne 2001a). The flow rates of these filters were within or relatively close to the standard flow rate of 1-2L/H so this finding does not provide any information on flow rates above 2 L/H.

In this study, the three filter design variables that were manipulated with the goal of increasing flow rate were: 1) type of combustible material, 2) ratio of combustible material to clay, and 3) particle size of combustible material.

Combustible Material

The original FilterPure filter design uses sawdust as the combustible material. The sawdust is obtained at no cost from a local mill. However, in other locations, different combustible materials may be more readily available, or cheaper to obtain. The role of the combustible material is to form pores when it burns out during the firing process. Because the combustible material determines the pore size, it is hypothesized that alternative combustible materials will not significantly alter the filter's performance. However, it is possible that different physical properties of each material such as the firepoint (minimum surface temperature for a material to combust) or other unknown factors could have an effect on filter performance. There is evidence from other ceramic pot filter factories on successful use of rice husks (Hagan et al. 2009), and flour (Oyanedel-Craver & Smith 2008) as the combustible material. Some other burnout materials that are under investigation at different facilities are dried, milled millet, peanut husks, and paper. This investigation chose to experiment with substituting rice husks and coffee husks for sawdust because both materials were locally available in the Dominican

Republic for free. In this study, the coffee and rice husks were sifted to the same size (0.30µm) and combined with clay in the same proportions (53% C:47% combustible) as sawdust would be in the traditional filter design. FilterPure had not experimented with alternative combustible materials previously so it was unknown if the flow rate would increase, decrease, or remain the same.

Ratio of Combustible Material to Clay

The ratio of sawdust to clay in the original FilterPure design is 53% clay to 47% sawdust. If the percentage of sawdust is increased, more pores will be created in the filter, and it is likely that water will flow through the filter at a faster rate. It is possible that this could compromise the filter's ability to remove pathogens from water even though the pore size does not change. If the density of combustible material is raised, the likelihood that two or more pores will become connected, allowing for the passage of larger particles, increases. It is also possible that the filter will become more fragile and less solid if it is composed of a higher proportion of pores. It is important to avoid compromising the durability of the filter because breakage is a main factor of filter disuse (Brown et al. 2007). It was hypothesized that, as the proportion of sawdust to clay is increased, the flow rate will increase, and at some point, the amount of bacteria in effluent water will also increase. This study experimented with the following proportions: • 40% Clay (C):60% Sawdust (S), •45% C:55% S, •50% C:50% S, •55% C:45% S, and • 60% C:40% S.

Particle Size of Combustible Material

The original FilterPure design uses a screen size of 0.30 µm to sift the sawdust particles to create a target pore size of 1.3 µm. The filter's actual pore size created from this process is unknown because no tests to measure this have been performed on FilterPure's filters. PFP has suggested that the effective pore size should be 1 µm (Lantagne 2001a). The expectation is that ceramic filters will remove both bacteria and protozoa from effluent water through its main mechanism of trapping particles that are larger than the pores (Hagan et al. 2009). Bacteria can range in size from 0.30 to 100 µm, and most are greater than 1 µm. Protozoa can range from 8 to 100 µm in size. So a pore size of 1 µm should be sufficient to exclude most bacteria and protozoa from passing through the filter membrane (Lantagne 2001a). However, the actual pore size in PFP filters has been measured at a range of values. Pores of 0.6 to 3.0 µm were measured using a scanning electron microscope in one study of Nicaraguan filters, (Lantagne 2001a) and another used the bubble test to measure pore size in filters from Cambodia, Ghana, and Nicaragua that ranged in size from 33 to 52 µm (van Halen 2006). Both of these studies reported that the filters performed adequately in reducing TC from influent water.

It should be possible to increase pore size by increasing the size of the sawdust particles. If pore size is increased, it is likely that flow rate will increase, and at some point the concentration of bacteria in effluent water will also begin to increase. The pore size at which this will occur warrants investigation because of evidence that filters can maintain effective bacterial removal at a wide range of pore sizes. In this study, a screen size of 0.45 µm was used to sift the sawdust particles in an attempt to increase particle size.

Testing for Quality Control in the Field

In the majority of locations where ceramic filter manufacturing facilities are needed and likely to be established, microbiological water quality testing can be very expensive and is logistically difficult to perform. Therefore, it is not practical to perform microbiological testing on each filter or even each batch of filters prior to use. If certain design criteria can be established, such as the maximum flow rate for a functioning filter, the need for frequent microbiological testing could be reduced.

This study attempted to determine parameters that indicate an adequately functioning filter that can be used by others who produce ceramic water filters. Once a well functioning design is established at one facility, it is not always possible to produce exact replicates of that filter in other locations. One of the fundamental ideas behind the use of ceramic pot filters is that they are made with local materials. Available local materials will differ depending on where the factory is located and what type of resources the manufacturer has access to. Many characteristics of clay, such as plasticity, density, or sand content, will vary depending on where it comes from, and all these factors can affect the performance of the filter (Hagan et al. 2009). In addition, the tools and equipment available to the manufacturer will vary from place to place, and this affects how the filter is manufactured and how it performs. However, if there is a pre-established maximum flow rate, perhaps manufacturers could use that as a proxy for a functioning filter rather than performing frequent microbiological testing. It is advisable, however, that all new designs and new facilities perform preliminary microbiological tests. The current guideline from PFP for a properly functioning filter is a flow rate of 1-2 L/H.

FilterPure Filters

This study was carried out at the FilterPure factory in Higüerito de Moca, Dominican Republic. FilterPure's manufacturing facility was the ideal environment for the study due to the fact that they have recently done extensive testing and design modification on their filters. This means that variants of the current filter design could be reliably and consistently produced, and the filter manufacturers already had new ideas for design variations based on previous experience. There is a difference between the method by which FilterPure and PFP apply colloidal silver to their filters. FilterPure adds pure silver into the water that is then combined with the clay and sawdust, so that the silver is incorporated throughout the entire filter and then fired in the kiln. This is in contrast to the more traditional method of external application by submersion or painting, after the filter has been fired. A laboratory study, carried out at Lehigh University, compared the two types of filters and found that there was no difference in bacterial reduction between the PFP and FilterPure filters after six weeks of use (Napotnik *et al.* 2009). The results of this study may be extrapolated to filters made with the PFP silver application method, although it is still necessary to recognize the natural variability between filters manufactured in different locations.

Methods

Setting

This study was conducted in June and July of 2008, in the town of Higüerito de Moca, situated in the Cibao Valley in the north central region of the Dominican Republic. The area is known for its artisan ceramic community and is the location of the FilterPure ceramics manufacturing facility.

Study Design

The focus of this investigation was to determine if, and by how much, the flow rate of ceramic filters can be increased without reducing the effectiveness of the filter to reduce turbidity and bacterial indicator organisms. Eight new filter designs were developed with the intent of increasing flow rate.

Filter Designs

New filter designs were developed through collaboration with FilterPure's director and ceramicist. The designs were created by modifying one of the following variables: ratio of clay to burnout material, type of burnout material, or particle size of burnout material (Table 4). The general procedure for making FilterPure's filter was followed in the production of three replicates of each new filter design as well as six traditional filters (Controls). Prior to testing, water was continuously passed through the filters for two weeks, and the filters were heated in a kiln at 400 ˚C for one to two hours in an attempt to eliminate any possible bacteria growth.

Table 4. Filter designs

Design	% Clay	% Combustible Material[1]	Type of Combustible Material	Screen size (μm)[2]	Reference Name[3]
Control	53	47	Pine sawdust	0.30	53C:47S
1	50	50	Pine sawdust	0.30	50C:50S
2	55	45	Pine sawdust	0.30	55C:45S
3	60	40	Pine sawdust	0.30	60C:40S
4	45	55	Pine sawdust	0.30	45C:55S
5	40	60	Pine sawdust	0.30	40C:60S
6 [4]	53	47	Pine sawdust	0.45	0.45 μm
7	53	47	Coffee husks	0.30	Coffee husks
8	53	47	Rice husks	0.30	Rice husks

[1] Combustible material burns out during the firing process forming pores in the ceramic membrane.
[2] Screen size determines particle size of the combustible material.
[3] Reference name indicates how the filter will be referred to in the remaining sections.
[4] Only two replicates of design 6 were made because of limited materials.

Schedule

In order to evaluate filter performance, samples of filter influent and effluent water from all filters were tested for five water quality parameters and flow rate, once per week for five consecutive weeks according to the schedule shown below (Table 5).

Table 5. Schedule for filter testing

June-July 2008						
Sunday	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday
22	23	24	25	26 ●	27 ◆	28
29	30	1	2 ●	3 ◆	4	5
6	7	8	9 ●	10 ◆	11	12
13	14	15	16 ●	17 ◆	18	19
20	21	22	23 ●	24 ◆	25	26

● Samples from filters 1,2,3,4, Control 1 and river water were collected and tested.
◆ Samples from filters 5,6,7,8, Control 2 and river water were collected and tested.

Sample Water and Flow through the Filter

Throughout the five week testing period, each filter was filled two times daily, six days a week. Depending on the flow rate of the filter, between six and twelve liters of water was passed through each day. The influent water, which originated from a nearby river, was collected from the local water distribution center prior to any treatment. The water was stored in large plastic holding tanks at the testing site and was obtained every one to two days. This water was tested for all water quality parameters, twice weekly, on the same days that the experimental filters were tested.

Each filter was cleaned once a week on the day prior to testing. The filters were scrubbed with a brush inside and out and then rinsed with its own filtered water. The storage buckets and lids were rinsed with chlorine. This is the same cleaning procedure that FilterPure recommends to their users. Separate water collection buckets were created by removing a portion of the bucket's side so that water could be collected directly from the filter prior to contact with any other surfaces (Figure 13). The top portions of the testing buckets were rinsed with chorine and allowed to dry before a new filter was suspended inside.

Figure 13. Water collection bucket

Water Testing Parameters

To evaluate the performance of each filter, the difference in water quality of influent and effluent water was measured. Water quality testing parameters included, microbiological tests for total coliforms, turbidity, pH, and conductivity. The flow rate of each filter was also measured. The presence of chlorine in source water was tested prior to Week One and during Week Four of the study period. The absence of chlorine in the preliminary tests made it unnecessary to continue testing for chlorine.

Microbiological Testing

Effluent water samples were collected in either Whirl-Pak bags or sterile 120 mL disposable vessels that contained a thiosulfate tablet that deactivates any chlorine present in the sample. During sample collection, the bags/vessels were held directly underneath the filters through a hole cut out of the side of a testing bucket. All samples were processed within one hour of collection.

Water samples were measured for *E. coli* and total coliforms using the IDEXX Quanti-Tray®/2000 system (Westbrook ME, USA) following product manual instructions. The general procedure consisted of the addition of one Colilert reagent pouch to a 100 mL water sample, shaking the mixture until the reagent dissolved, pouring the solution into a Quanti-Tray, sealing the tray so that the solution was equally distributed among the 97 wells, and incubating the tray for 24 hours at 35°C. The tests were analyzed by counting the number of wells that turned yellow (TC) and fluoresced under an Ultra Violet light (*E. coli*). A Most Probable Number (MPN) table was used to quantify the results.

The IDEXX system is only capable of measuring up to 2419.6 CFU/100mL. Generally, the influent source water had TC levels above 2419.6 CFU/100mL, thus making it necessary to dilute source water with sterile water to proportions of 1:10 and 1:100. Water that had been boiled and subsequently allowed to cool was used for source water dilutions. The 1:10 dilutions were performed by filling a Whirl-Pack bag with 90 mL of sterile water followed by the addition of 10 mL of source water. The 1:100 dilutions were performed by filling a Whirl-Pak bag with 99 mL of sterile water followed by the addition of 1 mL of source water.

Turbidity

Turbidity was measured using a LaMotte 2020e (Chestertown, MD, USA) Portable Turbidity Meter that was calibrated bi-weekly with turbidity standards of 0, 1, 10, and 100 NTU.

pH and Conductivity

Both pH and conductivity were tested using a Hanna 9811-0 pH/conductivity meter that was calibrated bi-weekly with buffer solutions of pH 4, 7, 10 and 1413 uS/cm calibration solutions.

Flow Rate

Flow rate was measured using a 16-ounce styrofoam cup to directly capture the total volume of water that passed through the filter in the first ten minutes (timed with a stopwatch) immediately after it was filled, so that hydraulic head would be at its greatest. The quantity of water collected was then measured using a 1 L graduated cylinder and the value was converted from mL/10 minutes into L/Hr. The same water that was collected for determining flow rate was stored in the styrofoam cup, and used to measure turbidity, pH and conductivity within five hours of collection.

Chlorine

The presence of free residual chlorine was tested using a LaMotte (Chestertown, MD, USA). Test-tube DPD color comparator test kit and was tested two times prior to Week One and during Week Four of the study period.

Quality Control

To determine the consistency of microbiological water testing procedures, 20% of tests were run in duplicate and a negative control was tested each day. Water for the negative control tests was the same boiled water that was used for dilutions. All other water testing parameters were not duplicated.

Data Analysis

Data was entered into and analyzed using Microsoft Excel 11.3.7 (Redmond, WA, USA).

It was necessary to determine an average level of TC in source water on each testing day by combining the results of the undiluted, 1:10 dilutions, and 1:100 dilutions source water tests. The test results are based on a MPN table and in order to exclude outliers from samples with either very low or very high TC levels, only tests that had between 15-85 (out of 97 total wells) positive wells for TC were included in the average. The data from the triplicates of each design were averaged on a weekly basis.

The sample error mean for each design was calculated using the flow rate of the individual filters during Week One. The sample error mean of the combined replicates was compared to the average flow rate of the respective design.

The results from *E. coli* testing were not included in the analysis because levels in the influent source water ranged from 0 to 4.4 CFU/100mL, which was too low to quantify any type of meaningful difference between influent and effluent water. Turbidity results were excluded for the same reason because influent levels ranged from 2.8 to 4.8 NTU. Results of pH and conductivity testing were also excluded from the analysis because there was very little difference between pre and post-filtered water.

Two control filters were excluded from the analysis because they were not performing as well as expected, possibly due to microbial colonization (Table 6). The results from the 0.45 µm filters (Filters 6A and 6B) were excluded for Weeks One and Two because the filters themselves were colonized, and higher levels of *E. coli* in effluent water than influent water were observed. Two other outlying points were dropped because of elevated levels of TC post filtration that were likely due to contamination during the testing procedures.

Table 6. Data that was excluded from analysis

Filter	Week	TC in effluent water	*E. coli* in effluent water
Control 4 (53C:47S)	1	435.2	
	2	81.3	
	3	261.3	
	4	125.9	
	5	11.9	
Control 6 (53C:47S)	1	0	
	2	>2419.6	
	3	214.3	
	4	37.9	
	5	103.9	
6A (0.45 µm)	1	99.0	57.6
	2	>2419.6	11.0
6B (0.45 µm)	1	4.1	
	2	90.6	29.7
4B (45C:55S)	3	>2419.6	
Control 1 (53C:47S)	1	121	26.2

Results

Source Water Quality

Total Coliforms

Testing for Filter Set 1 (Filters 1-4 and C1) and Filter Set 2 (Filters 5-8 and C2) took place on different days. Therefore, the source water quality was different between the two sets of filters and was different each week that testing occurred. During the study, ten source water samples were collected and the microbiological quality of the samples varied considerably on a daily basis (Table 7). TC levels ranged from a minimum of 535 CFU/100mL to a maximum of 11,567 CFU/100mL (mean=4610, stdev=4036). On all but two days, the water had TC levels well above the “very high risk water” category (>1000 CFU/100mL) designated by the WHO for drinking water quality standards (WHO 1997). These results show that the source water had sufficient levels of TC to demonstrate each filter's ability to reduce TC from influent water.

Turbidity, pH, and Conductivity

Throughout the five weeks, turbidity levels in source water ranged from a minimum of 1.16 NTU to a maximum of 4.80 NTU (mean= 3.0 NTU, stdev=1.0) (Table 7). All samples had turbidity levels below the WHO's recommended limit for drinking water of 5.0 NTU (WHO 1997). Additional parameters tested to characterize source water included conductivity that ranged from 100 uS/cm to 310 uS/cm, and pH that ranged from 8.0 to 8.4 over the five-week study period. There are no WHO designated limits for pH or conductivity in drinking water. However, drastic fluctuations in pH or conductivity can indicate contamination from human or animal waste, agricultural runoff, or chemicals and may influence the effectiveness of some water treatment methods (Mechenich & Andrews 2006). Neither pH nor conductivity of source water varied substantially over the five-week study period.

Table 7. Total coliforms and turbidity in source water samples

	Source Water									
	Week 1		**Week 2**		**Week 3**[3]		**Week 4**[3]		**Week 5**	
	Set 1[1]	Set 2[2]	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2	Set 1	Set 2
TC (CFU/100 mL)	535	1343	5140	7415	4291	2355	820	1993	11567	10640
Turbidity (NTU)	4.80	4.25	2.82	2.43	3.77	2.64	1.16	2.57	2.93	2.36

[1] Set 1- Source water that was passed through filters 1-4, Control 1.
[2] Set 2- Source water that was passed through filters 5-8, Control 2.
[3] Turbidity meter was calibrated during weeks three and four without the 0 NTU turbidity standard.

Quality Control

Ten negative control samples were tested during the study, one on each of the ten water quality testing days. The water used for the negative control samples was the remaining diluent water after dilutions of source water were completed. Of the ten controls performed throughout the study, 90% had TC results of 0 CFU/100mL, and one negative control test result was 1.0 CFU/100mL. These results indicate that there was little to no microbiological contamination during the testing procedure. Out of the 122 total water samples tested for TC, 24 samples (19.7%) were done in duplicate. The R^2 correlation between original and duplicate results was 0.973, which shows good consistency in the results.

Flow Rate

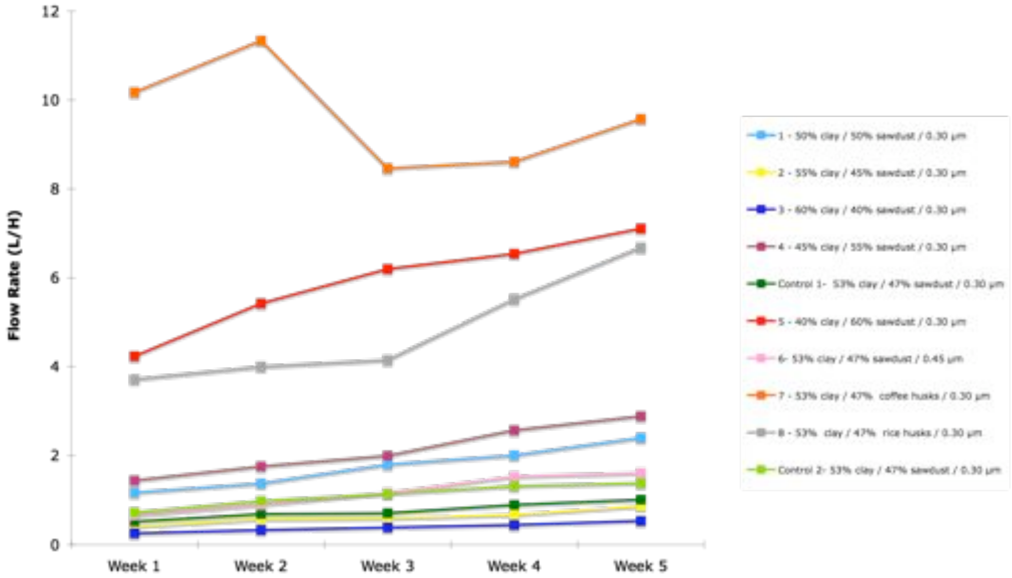
The flow rates of all the filters increased over the five-week period with the exception of the filter made with coffee husks (Filter 7) that was the fastest filter (Figure 14). It is likely that this filter did not follow the same trend as the other filters because two of the three replicates broke during the second and third weeks of the study. The data for the remaining weeks were only based on a single filter that was the slowest of the three replicates. The combined average increase in flow rate from the first to fifth week of all filter designs was 44.1% (1.075 L/H) (Table 8). The flow rates for five filters (Filters 1-4, and 6,) increased by more than 50% over the course of the study. The flow rate of the 0.45 μm filter (Filter 6) increased the most with a 59.3% increase from its original flow rate. The flow rate of the 40C:60S filter (Filter 5) increased the least with a

40.4% increase from its original flow rate. The largest total flow rate increase was that of the rice husks filter (Filter 8), which increased 2.964 L/H over the five weeks.

Table 8. Percent increase in flow rate from original flow rate (Week 1)

Filter Design	**Week 1 Flow Rate (L/H)**	**% Increase at Week 2**	**% Increase at Week 3**	**% Increase at Week 4**	**% Increase at Week 5**
1 - 50% clay / 50% sawdust / 0.30 µm	1.168	15.0	35.1	41.8	51.4
2 - 55% clay / 45% sawdust / 0.30 µm	0.398	30.4	32.8	40.6	54.0
3 - 60% clay / 40% sawdust / 0.30 µm	0.252	21.3	33.7	42.5	51.5
4 - 45% clay / 55% sawdust / 0.30 µm	1.440	17.9	27.7	43.9	50.1
Control 1: 53% clay / 47% sawdust / 0.30 µm	0.518	24.3	26.4	41.8	48.7
5 - 40% clay / 60% sawdust / 0.30 µm	4.236	21.9	31.7	35.2	40.4
6 – 53% parts clay / 47% sawdust / 0.45 µm	0.654	26.6	43.8	57.3	59.3
7 – 53% clay / 47% coffee husks / 0.30 µm	10.174	10.2	-20.3	-18.2	-6.3
8 - 53% clay / 47% rice husks / 0.30 µm	3.716	-20.3	10.5	32.7	44.4
Control 2: 53% clay / 47% sawdust / 0.30 µm	0.720	26.4	36.8	45.5	47.8

Figure 14. Flow rates of all eight alternative designs and control filters

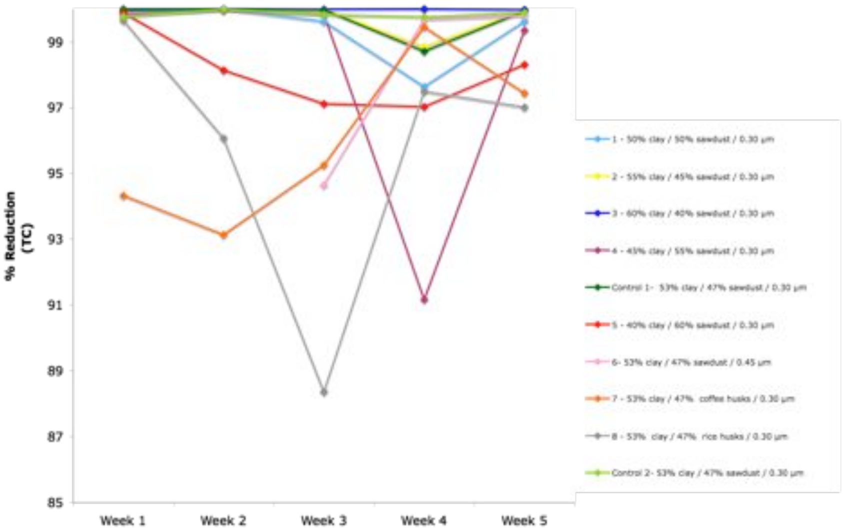


Percent Reduction of Total Coliforms

The average percent reduction of TC for all filters over the five-week period was 98.47%, ranging from a minimum reduction of 88.4% to a maximum reduction of >99.9%. There were some filter designs that consistently performed better than others at reducing TC levels. Filters 50C:50S, 55C:50S, 60C:40S, and 53C:47S (Filters 1-4, C1, and C2) had greater reductions of TC than filters 40C:60S, 0.45 µm, coffee husks, and rice husks (Filters 5-8) (Figure 15). The better performing filters maintained levels of TC reduction greater than 91.2% over the course of the entire study, and average TC reduction was 99.6% when Week Four data are excluded. The TC levels in source water during Week Four, Set 1 were particularly low (820 CFU/100mL) which lowers the percent TC reductions for all filters. The 60C:40S filter (Filter 3) consistently gave the best performance with >99.9 % TC reduction during all five weeks. The rice husks filter (Filter 8) performed the worst, with the lowest total average TC reduction of 95.7%.

Log reduction values (LRV) of TC were also calculated for each filter and are listed in Appendix 1. The LRV results were not included in the analysis because the values are dependent on the level of TC in source water that varied by as much as 1.3 logs between testing days. Therefore, the LRV were not informative for comparing filters across testing days. In the following sub-sections, the reduction in TC is discussed for each of the three variables (type of combustible material, screen size, and ratio of clay to combustible material) that were analyzed in this study.

Figure 15. Percent total coliform reduction for all eight alternative designs and control filters



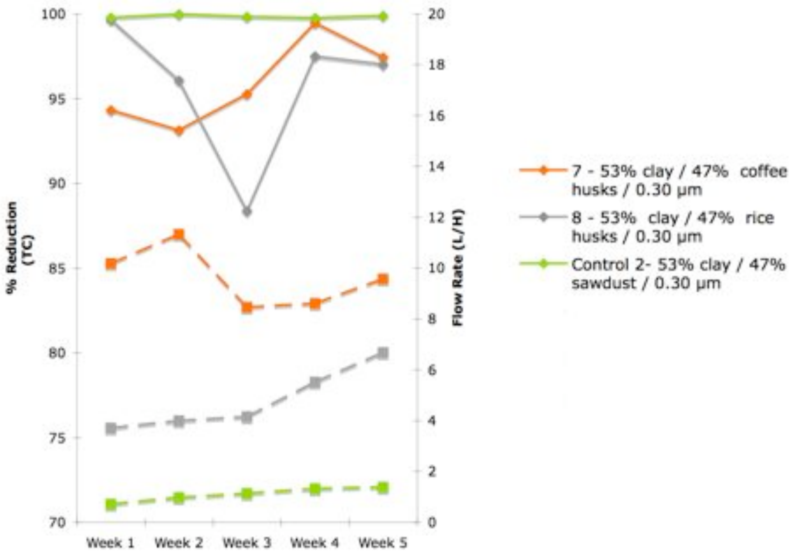
- Negative Control for week 3 (Filters 5-8 and Control 2) measured 1.0 CFU/100mL.

Effect of Alternative Design Variables on Filter Performance

Combustible Material

The two filters made with alternative burnout materials, rice husks (Filter 7) and coffee husks (Filter 8), did not reduce TC as well as the control filters that were made with pine sawdust (Figure 16). The control filters maintained TC reduction levels above 99.8% throughout all five weeks of testing. The TC reductions for the coffee husk filters ranged from 93.1% to 94.3%. TC reductions for the rice husk filters started with a high level of TC reduction (99.7%) during week one but dropped down to 96.1% during week two and never got higher than 97.5% during the remaining three weeks. The flow rates of the filters made with alternative combustible materials were consistently higher than the flow rates of the control filters. The average flow rates, over all five weeks, for the coffee husk filters, the rice husk filters, and the control filters were 9.63 L/H, 4.63 L/H, and 1.11 L/H respectively.

Figure 16. Flow rate and percent total coliform reduction of filters made with three different combustible materials

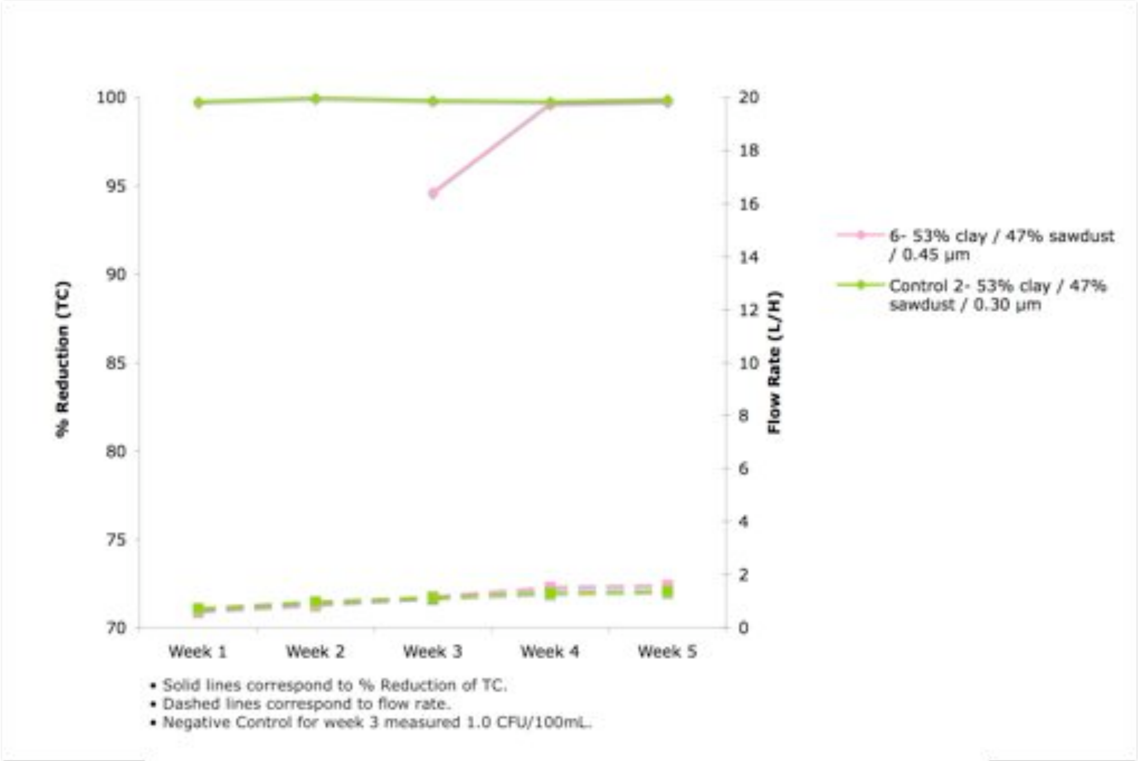


- Solid lines correspond to % Reduction of TC.
- Dashed lines correspond to flow rate.
- Negative Control for week 3 measured 1.0 CFU/100mL.

Screen Size

There was little difference in TC reduction between filters made with a screen size of 0.45 µm (Filter 6) and control filters made with a screen size of 0.30 µm (Figure 17). However, there is not enough data to make meaningful comparisons between the two filter designs due to the fact that there are only three weeks of reliable TC reduction measurements for the 0.45 µm filter, and they do not follow any particular trend. Results from the 0.45 µm filter were excluded from analysis for Weeks One and Two because the filters themselves were colonized and had higher levels of *E. coli* in effluent water than influent water. The flow rate of the 0.45 µm filter was very similar to that of the Control filter. The 0.45 µm filter and the Control filter had five-week average flow rates of 1.17 L/H and 1.11 L/H respectively.

Figure 17. Flow rate and percent total coliform reduction of filters made with different screen sizes



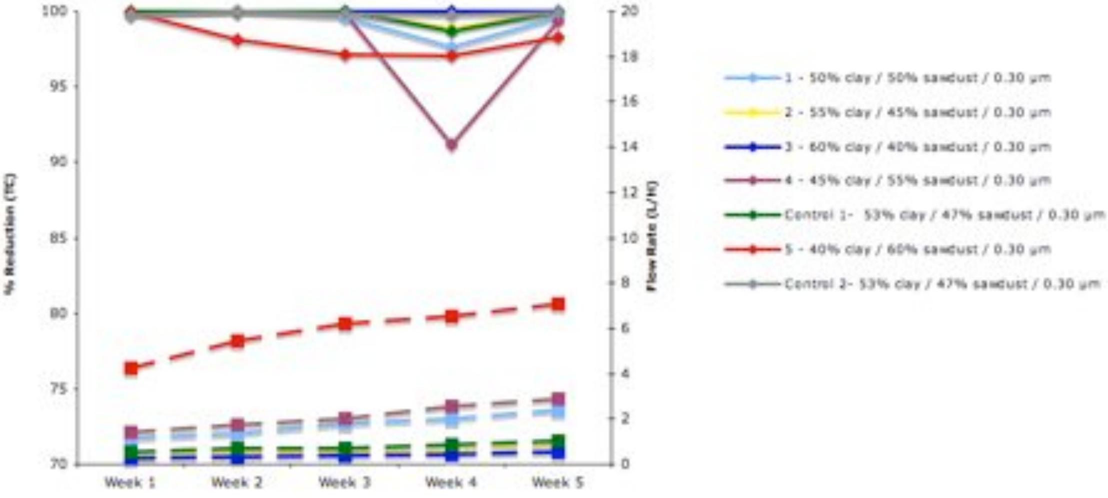
- Solid lines correspond to % Reduction of TC.
- Dashed lines correspond to flow rate.
- Negative Control for week 3 measured 1.0 CFU/100mL.

Ratio of Clay to Sawdust

As the proportion of clay to sawdust decreased, the flow rate increased, and the TC reduction was lower (Figure 18). The difference in percentage of TC reduction between any of the filters made with clay in the range of 45% to 60% (Filters 1-4, C1, and C2) was not dramatic and was never greater than 0.6% (with the exception of Week 4, 8.8% difference between 60C:40S and 45C:55S (Filters 3 and 4)). TC levels in the source water during Week Four, Set 1 were particularly low (820 CFU/100mL), which lowered the TC reductions for that week. When the proportion of clay was reduced from

45% (Filter 4) to 40% (Filter 5), there was a greater decrease in TC reduction from 98.1% to 99.7% (excluding Week 4). In contrast to the TC reduction results, there was a step-wise increase in flow rate as the proportion of clay to sawdust decreased. This trend is consistent from week-to-week throughout the study. Similar to the TC reduction results, a greater difference in flow rate was observed once the proportion of clay was reduced from 45% (Filter 4) to 40% (Filter 5). The average five-week flow rate for the 45%C:55%S filter was 2.13 L/H, and the average five-week flow rate for the 40%C:60%S filter was 5.90 L/H.

Figure 18. Flow rate and percent total coliform reduction of filters made with different ratios of clay to combustible material



- Solid lines correspond to % Reduction of TC.
- Dashed lines correspond to flow rate.
- Negative Control for week 3 (Filter 5 and Control 2) measured 1.0 CFU/100mL.

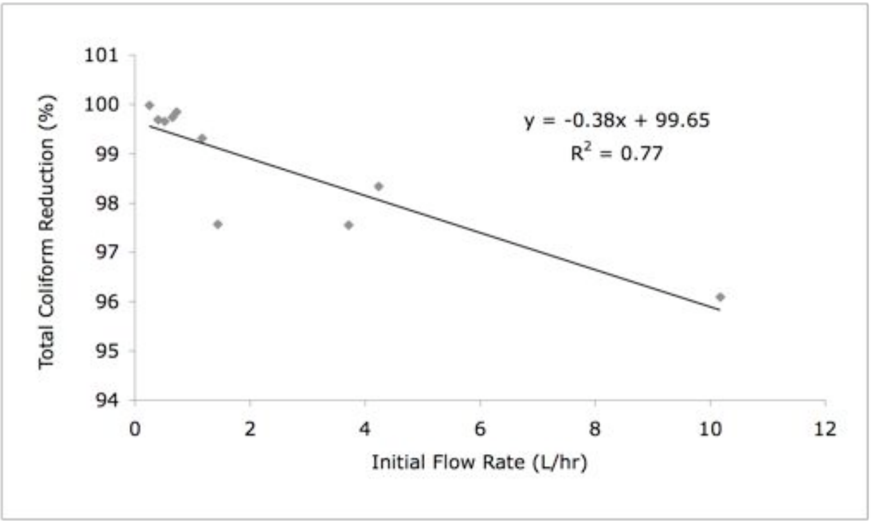
Relationships between Parameters

Table 9 shows correlation coefficients between flow rate, percent reduction of TC, and turbidity based on the entire data set. A negative correlation between percent reduction of TC and flow rate was observed. The correlation coefficient was calculated using data averaged in two different ways. The correlation was 0.77 when the results of Week one for each filter design were included (ten data points). The correlation was 0.70 when the results for every individual filter, for every week were included (45 data points). The former analysis approach reduces the impact of outlying data points. From this correlation, it is possible to show that once the flow rate of a filter reaches 1.7 L/H its ability to decrease TC falls below 99% (Figure 19). There were no meaningful correlations between percent reduction in turbidity and flow rate (R^2=0.07) or between percent reduction in turbidity and percent reduction in TC (R^2= 0.03).

Table 9. Relationships between percent total coliform reduction, flow rate, and turbidity

Comparison	R^2	Comments
% Reduction TC vs. Flow Rate	0.77	* Based on results of Week one for each filter design (10 points)
% Reduction TC vs. Flow Rate	0.70	* Based on results of each filter each week (45 points) * 3 outlying data points were dropped (R^2=0.2856 when all data are included)
% Reduction Turbidity vs. Flow Rate	0.07	* Based on weeks 1, 2, 5 due to problems with turbidity meter calibration
% Reduction Turbidity vs. % Reduction TC	0.03	* Based on weeks 1, 2, 5 due to problems with turbidity meter calibration

Figure 19. Correlation between percent total coliform reduction and initial flow rate based on all study filter designs



Consistency between Filter Replicates

The sample error mean for each design was calculated based on the flow rates of all individual filters during the first week of testing. This was done to evaluate the variation in flow rate of each replicate from the average flow rate of all three replicates of a single design. There was considerable variation in the sample error mean between the different filter designs (Table 10). The only designs for which the sample error mean was less then 10% of the average flow rate of the replicates combined were the control filter, the coffee husk filter and the 0.45 µm filter. The other filter designs were within 10-20% of their respective average flow rates, except the 45C: 55S (Filter 4) and the rice husk filter (Filter 8), which were 25.0% and 22.2% of the average flow rate of their respective designs.

Table 10. Sample error mean of flow rates between replicates of each design

Filter Design	**Sample Error Mean (week 1)**	**Percent of average Flow Rate (week 1)**
1 - 50% clay / 50% sawdust / 0.30 µm	0.20	17.1
2 - 55% clay / 45% sawdust / 0.30 µm	0.04	10.6
3 - 60% clay / 40% sawdust / 0.30 µm	0.05	19.8
4 - 45% clay / 55% sawdust / 0.30 µm	0.36	24.9
Control 1 and 2- 53% clay / 47% sawdust / 0.30 µm	0.05	8.7
5 - 40% clay / 60% sawdust / 0.30 µm	0.45	10.6
6 – 53% parts clay / 47% sawdust / 0.45 µm	0.02	3.7
7 – 53% clay / 47% coffee husks / 0.30 µm	0.83	8.1
8 - 53% clay / 47% rice husks / 0.30 µm	0.82	22.2

- Calculations for each design are based on three filter replicates except the Control filter consists of four replicates and Filter 6 consists of two replicates.

Discussion

The objective of this study was to create a filter design with a faster flow rate than the traditional design, while maintaining high levels of bacterial reduction. In trying to achieve this goal, new filter designs were created by altering the type of combustible material, increasing the ratio of sawdust to clay, or increasing the screen size used to sift the combustible material. These new filters were tested for bacterial reduction and flow rate and were then compared to the traditional filter design. The majority of alternative designs did have increased flow rates, however they were not able to consistently reduce high levels (99%) of TC from influent water. General trends regarding flow rate of all filters and the effect of each of the design modifications are discussed in the following subsections.

Flow Rate

Increase in Flow Rate

The flow rate of all the filters, except the designs made with coffee and rice husks, increased from week to week throughout the five-week study period. This finding is contrary to the results of the majority of previous research on this topic. Van Halen's study of PFP filters showed that flow rate decreased over the 12-week testing period with a 70-80% decrease in filter discharge (van Halen 2006). Similarly, the original study on pot style filters by the Central American Industrial Research Team reported that flow rate decreased between 39% and 64% over one year of use (Lantagne 2001a). It has been shown that the original flow rate of PFP filter's can be restored by scrubbing the filter

(Lantagne 2001a). This suggests that flow rate declines over time as the pores become clogged. In this study, the source water had relatively low turbidity, with a five-week average of 3.0 NTU, and consequently was not clogging the filter's pores.

When first time users receive a FilterPure filter, it is important that they are informed of this filter characteristic. New users might be frustrated with the initial slow performance of their filter, but the flow rate may increase with consistent use. The flow rate of eight of the filters included in this study had doubled by Week Five. The exact length of time that the flow rate increases could not be determined from the limited length of this study, but it is unlikely that the rate continues to increase throughout the life of the filter. A likely explanation for the increase in flow rate in these filters is that there are bits of clay and combustible material clogging and blocking the pores of the filter after being burned in the kiln. Obstructions get "washed out" of the filter as water is continuously passed through it. Support for this hypothesis is given by the fact that turbidity in post filtered water was considerably higher during Week One (average 2.5 NTU), following exposure to high temperatures in the kiln than during the other weeks that turbidity was measured (average 0.5 NTU). Van Halen's study also found that effluent turbidity was approximately four times higher in water during the first two weeks of testing than the remaining 11 weeks of the study (van Halen 2006).

Relationship between Flow Rate and Microbial Reduction

This study determined that a flow rate of approximately 1.7 L/H is the threshold where TC reduction begins to drop below 99%. Once this limit is exceeded the filter loses its ability to consistently reduce TC levels. These results are in contrast to a recent six-month study of Research Development International filters in Cambodia that reported filters with initial flow rates up to 7.2 L/H showed no significant difference in LRV of *E. coli* compared to filters with initial flow rates of 1.8 L/H (Bloem *et al.* 2009). However, the methods of this investigation are unclear making the validity of the results questionable.

Understanding the maximum flow rate could have important implications for ensuring quality control in filter production. If each filter's flow rate is measured prior to distribution, any defective or poorly made filters can be identified without performing any microbiological tests. Flow rate could act as a simple, inexpensive proxy for determining filter effectiveness. However, the flow rate range for an acceptable filter may need to be determined for each manufacturing facility. Initially, only four of the 29 filters would have passed the PFP commonly used "flow rate test" of 1-2L/H, but by Week Five, 11 filters would have met this criterion. It is important to note that the maximum flow rate of 1.7 L/H may only be applicable for the first five weeks of the filter's life. Because flow rate increases over time, it is possible that effective filters will have a flow rate higher or lower (due to clogging) than 1.7 L/H once they have been consistently used for a period greater than five weeks. It is also possible that a filter may become less effective for microbial reduction once the flow rate increases above the threshold. However, this is unlikely based on tests of FilterPure filters that have been in use for longer than two years (Ballantine & Hawkins 2009).

Combustible Material

When the type of burnout material was changed, even if all other filter components were kept constant, the flow rate increased to the point that the filter lost its effectiveness. Although the rice husks and coffee husks were sifted using the same size screen (0.30 μm) as the sawdust, there is some characteristic of combustible material other than size that influences flow rate and microbial reduction. Perhaps the unknown characteristic is that coffee and rice husks clump and are not able to mix with the clay as homogenously as sawdust. The results of this study show that different types of combustible materials cannot be used interchangeably. If alternative materials, such as rice or coffee husks, are used in manufacturing effective filters it would first be necessary to test a range of particle sizes and ratios of clay for each specific material in order to optimize filter performance. The RDI facility in Cambodia successfully uses rice husks in an approximate proportion of 23% rice husks to 77% clay that is quite different than the unsuccessful proportions of 47 % rice husks to 53% clay used in this study.

An anecdotal observation that also warrants consideration is that the filter made with coffee husks did not feel as sturdy as the other filters. The rims of two of the three replicates broke during the second and third weeks before the study was complete (Figure 20). This information about the need for experimenting with the type of combustible material is important for anyone planning to develop a new facility for manufacturing water filters.

Figure 20. Coffee husk filter (Filter 7) with partially broken rim

Screen Size

In an attempt to increase filter flow rate, one of the alternative designs was made with a screen size of 0.45 µm rather than 0.30 µm, while keeping all other design variables constant. It was hypothesized that larger particles of combustible material would create larger pores resulting in a faster flow rate. The results of the study did not support this hypothesis. There was almost no difference in flow rate between the control filter and the alternative filter with larger particles of sawdust. However, it is difficult to compare the ability of the two designs to reduce TC levels because there is limited data (three weeks) on the filters with a larger screen size due to possible bacterial colonization. Overall, these findings suggest that there was little difference in filter performance when using a screen size of 0.45 µm rather than 0.30 µm. It is possible that other filter characteristics influence pore size, and therefore flow rate, to a greater extent than a small change in combustible particle size. Oyenedel-Craver found that filters made with natural soil from Mexico had an average pore diameter of 14.3 µm and filters made by the same procedure, using commercial redart clay, had an average pore diameter of 2.03 µm (Oyanedel-Craver & Smith 2008). In that study, the type of clay was an important determinant of pore size. It is possible that the type of clay that FilterPure uses is more influential in determining pore size than a small change in the particle size of the combustible material.

Ratio of Sawdust to Clay

Another approach to increase the flow rate was to increase the number of pores in the filter by raising the proportion of sawdust to clay. If there are more pores in the filter, then water should flow through faster. The study results support this hypothesis in that as the percentage of sawdust increased for each filter design so did the flow rate. The difference in flow rate between the filters made with 40% and 55% sawdust was minimal, and their ability to reduce TC was similar, all in the range of 99%. However, once the proportion of sawdust was ≥ 60%, flow rate and TC reduction were quite different from the other filters. These findings suggest that, once the proportion of sawdust reaches 60%, the filter's effectiveness in reducing TC is compromised.

Study Limitations

The major limitation to this study is whether the filters were reliably made. Ideally, effective pore size and porosity would have been measured to ensure that the intended filter variations were successfully created and that the replicates were similar to each other. However, the equipment and resources for this type of testing were unavailable, and it was necessary to rely on similarities in flow rate between the three filter replicates of each design as a measure of consistency in filter production. The control filter and the 0.45 μm filter were among the most consistently made designs, with the mean percent error comprising 8.7% and 3.7% respectively, of the design's average flow rate. It is interesting that both of these filters were made with the same clay to burnout material ratios (43C:53S) and used sawdust as the combustible material, which are both part of FilterPure's traditional filter design. The high sample mean errors of the 45 C:55 S filter (Filter 4) and the rice husk filter (Filter 8) could be cause for concern as they made up 25% and 22% respectively, of the average flow rate of the three replicates combined. Additional limitations of this study are the short duration and limited number of filters tested. More filters would reduce the probability of outside factors such as the two-week contamination of the 0.45 μm filter (Filter 6) from affecting the results and would decrease the influence that inconsistently made filters could have had.

Future Research

In addition to the main research objectives presented in this thesis, a number of additional research questions were raised during the study. Some of these topics were informally investigated, and merit future, more formal investigation. These research topics include: Contaminated Filters, Method of Silver Application, Colloidal Silver Impregnated Ceramic Discs, Larger Screen Size, Long Term Studies, and, Locally Produced Candle Filters. The results of the informal investigations and recommendation for future testing are described in the following sections.

Contaminated Filters

The initial experimental setup for this investigation caused all 29 filters to function poorly, in terms of bacterial reduction. It was likely that the filters were contaminated through exposure to the environment because the filters were not secured in storage buckets, which is the typical practice. The high bacteria levels in effluent water filtered by the control filters indicated there was a problem. Prior to bacteriological testing, the filters were dipped in boiling water and scrubbed internally and externally with boiling water but still had higher TC levels than expected, suggesting they were not just contaminated externally. In trying to identify the cause, three under performing filters were put into the kiln for three hours at 400 °C. Samples of water collected from these filters were immediately tested for TC, and all three were completely free of TC.

These findings indicated that the filters had become internally contaminated from the environment and could be restored to working order after exposure to high temperatures.

Aside from the situation just mentioned, two filters had higher *E. coli* levels in the effluent water than influent water over the first two weeks of the study. These filters were not reheated in the kiln, but after three weeks of continuous use, they were able to "clean themselves out" and began functioning properly. Once it became clear that filters in this study were being environmentally contaminated, the question of whether filters could get environmentally contaminated during storage arose. At the time, the storage method consisted of stacking the filters in a garage/warehouse where they remained until distribution (Figure 21). Water samples filtered through two random filters that had been stored in different locations in the warehouse for at least a month were tested for TC. One of the filters had 106 CFU/100mL and the other had 6.0 CFU/100mL in effluent water.

Figure 21. Filter storage in warehouse

Filter contamination was also noted in a study investigating the longevity of PFP filters in Nicaragua. The investigators collected 19 filters that were between 1.7 and five years old and transported them in cardboard boxes from the users' homes to a laboratory in the capitol. After preliminary tests, they found that none of the filters performed well and labeled them “contaminated”. The investigators then put the filters in a kiln at 400°C for four hours, and the next set of water quality tests had no bacteria present in effluent water (Campbell 2005). It is important to determine how to keep the filters clean during storage and transport. Distributing contaminated filters that are properly manufactured can be dangerous and unnecessarily wastes money and materials. Following this study, FilterPure began painting an extra, protective layer of colloidal silver on each filter and wrapping individual filters in plastic prior to distribution.

The issue of what to do if filters become contaminated in users’ homes still remains. Perhaps baking them in an oven would be sufficient, but many filter users do not have ovens. It is uncertain how frequently filter contamination occurs in the field, and this would be important to understand in order to identify a solution to this problem. Perhaps this contamination issue was only a problem with FilterPure filters because, at the time of this study, they did not have the outer, protective layer of silver that PFP filters have. Future research on this topic could involve exposing newly manufactured filters to a variety of potential sources of contamination, evaluating how prevalent filter contamination is in the home, or testing a variety of methods to restore contaminated filters to working order.

Method of Silver Application

FilterPure’s method of incorporating silver into the clay mixture prior to pressing the filter into the pot shape and firing requires the use of a larger quantity of silver that in turn raises the cost of producing the filter (Ballantine & Hawkins 2009). One theory is that, when silver is applied externally, it will eventually rinse out of the filter over time, and there is widespread concern that filters should not be used with chlorinated water (Ballantine & Hawkins 2009). The rationale for the FilterPure silver application method is that the silver will never "wash out" of the filter, nor will it oxidize or react with chlorine because it binds to the clay in the firing process. Future research on this topic could evaluate the amount of silver still present in filters with both types of silver application after a year of continuous use. Additionally, a long-term study that compares the microbial reduction of the three most common silver application methods (submersion, painting, mixing pre-firing) is needed to determine if the use of additional silver is cost effective.

Silver-Impregnated Ceramic Discs

The idea that simple contact between water contaminated with bacteria and silver-impregnated ceramic could be sufficient to purify water could have important implications. During this investigation, one water sample taken from the collecting bucket of a poorly performing filter had no TC. The bucket was completely full, indicating that the water had been in contact with the filter membrane for two days. It is possible that the reason there were no TC in this sample was because any TC that had passed through the filter were killed through contact with the colloidal silver in the ceramic membrane. Samples taken directly from this particular filter during the study had TC levels that varied from 38 to 214 CFU/100mL. Although this filter had a history of not functioning well, no samples were tested directly from the filter, so it is possible that during this particular run there were no TC in the effluent water. It is also possible that the bucket had residual chlorine from a previous washing. After discussing this result with the ceramicist, he proposed the idea of adding a round ceramic slab in the bottom of the receptacle. The ceramic slab would be the same mixture of clay, sawdust, and silver from which the filter membranes are made. Four of these slabs were created about an inch thick. An informal experiment was performed where water samples were collected directly from three faster and under performing filters and were also collected from their respective storage buckets with discs after 24 hours. The samples taken directly from the three filters had TC levels of 6.3, 7.5, and 7.3 CFU/100mL. The samples taken from the collecting buckets of the same filters after 24 hours all had TC levels of 0. All three water samples tested negative for chlorine, so it is unlikely that residual chlorine from washing the buckets was a factor. These results suggest that contact with silver-impregnated ceramic was responsible for inactivating the low levels of TC that passed through the membrane.

At the time, the researcher and ceramicist had no previous knowledge that the silver/ceramic slab idea was being studied or developed, but there was mention of this in the PFP September 2008 report (PFP 2008) and the RDI factory in Cambodia has been experimenting with different designs. PFP recently studied rates of receptacle recontamination in user homes but has yet to report the results. This idea has potential to either act as an extra safeguard for those filters that are not able to remove 100% of bacteria. These discs could provide residual protection to buckets that are not thoroughly cleaned, or they could possibly be used as the second step in a two-step disinfection process. A filter with a faster flow rate could provide preliminary filtration, and then the disc could act as the second step of treatment. However, this two-step treatment possibility requires investigation into the contact time between the water and silver-impregnated slab that is required to fully deactivate bacteria. Adding extra parts and instructions for use may also complicate the filter technology, which is often times praised for being simple and user friendly. Future research on this topic would involve comparing rates of recontamination of filtered water between filter users who had silver-impregnated discs and those that did not. It could also involve a study determining the necessary contact time between silver-impregnated ceramic and water with known bacteria levels. (PFP 2009a)

Larger Screen Size

In this study, there was no difference in flow rate and little difference in TC reduction (based on available data) between filters made with a screen size of 0.45 μm or a screen size of 0.30 μm. Future research could examine the use of an even larger screen size, such as 0.60 μm or greater. Perhaps at this size, filters would show a significant increase in flow rate that this study was unsuccessful in doing.

Long Term Studies

It would be interesting to see if the short-term trends identified in this study continued over a longer period of time. Our observations of increasing flow rates over time is of particular interest. Possible questions to investigate include: At what point do the flow rates stop increasing; Will the filter's bacterial removal efficiency become compromised due to the increasing flow rate; Will the filter's flow rate eventually begin to decrease from a clogging of the pores? Additionally, knowing the effective life of the filter would be valuable information so that users know when it is time to replace the membrane. Future research on this topic would require a structured investigation of how much water, of a specified quality, can pass through the filter before it loses its effectiveness measured in terms of bacterial and turbidity reduction.

Local Candle Filters

The possibility of locally manufacturing candle filters is a topic that is currently under investigation (Harvey 2009). An ideal ceramic filter would combine the best features of both the pot and candle style filters. If a design for this type of filter could be created, the result would include the benefits of pot filters, such as their affordability and use of local materials and knowledge, as well as the benefits of candle filters, such as the ability to manipulate flow rate by increasing the number of candles in each filtration system. However, a locally fabricated candle filter still requires additional parts, plastic end caps and some type of adhesive that would likely not be locally available and therefore the problems of leakage and replacing broken parts that are associated with candle filters would still not be resolved. Once the design for a locally-produced candle filter is fully established, it will be important to conduct an investigation that compares them to the locally-produced pot filters.

Although manufacturing facilities all over the world are currently producing functioning filters that improve the microbiological quality of water and reduce diarrheal incidence, there are still many design-related topics that warrant further research. Understanding some of the specific causes of filter contamination and methods for subsequent decontamination of filters, will help reduce the number of users who receive poor quality water. It is possible that a specific silver application method is superior to the others, and determining which method is best will help to maximize the cost effectiveness of the silver application and the effective life of the filter. Silver-impregnated ceramic discs have the potential to provide residual protection in storage buckets or to compensate for under-performing filters. Long-term studies are needed to examine the effective life of the filter. If users have a clear indication when it is time to replace the membrane, they can maximize filter life but know when to stop using it once it is no longer functioning properly. Finally, locally manufactured candle filters could provide filtration systems that have faster flow rates and high quality water treatment, while improving the network for replacement parts through local production.

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Appendix 1- Filter Data

Table 11. Total coliform and flow rate data

		6/26/08 (Week 1)		
Source Water	**CFU/100mL**			
No Dilution	488.4			
1:10	583.0			
Average	**535.7**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
1a	0.0	100.00	2.7	1.380
1b	0.0	100.00	2.7	0.768
1c	0.0	100.00	2.7	1.356
Average	**0.0**	**100.00**	**2.7**	**1.168**
2a	1.0	99.81	2.7	0.414
2b	0.0	100.00	2.7	0.462
2c	0.0	100.00	2.7	0.318
Average	**0.3**	**99.94**	**2.7**	**0.398**
3a	0.0	100.00	2.7	0.228
3b	1.0	99.81	2.7	0.348
3c	0.0	100.00	2.7	0.180
Average	**0.3**	**99.94**	**2.7**	**0.252**
4a	1.0	99.81	2.7	0.870
4b	0.0	100.00	2.7	1.350
4c	2.1	99.61	2.4	2.100
Average	**1.0**	**99.81**	**2.6**	**1.440**
C1	121.0	81.88	0.65	0.534
C2	0.0	100.00	2.7	0.468
C3	0.0	100.00	2.7	0.552
Average	**40.3**	**93.96**	**2.7**	**0.518**
		6/27/08 (Week 1)		
Source Water	**CFU/100mL**			
1:10	1086.0			
1:100	1600.0			

Average	**1343.0**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
5a	3.1	99.77	2.6	3.954
5b	2.0	99.85	2.8	3.642
5c	0.0	100.00	3.1	5.112
5c (duplicate)	1.0	99.93	3.1	
Average	**1.5**	**99.89**	**2.9**	**4.236**
6a	99.0	92.76	1.1	0.630
6c	4.0	99.70	2.5	0.678
6c (duplicate)	2.1	99.85	2.8	
Average	**35.0**	**97.44**	**2.1**	**0.654**
7a	115.3	91.41	1.1	11.448
7b	95.9	92.86	1.1	10.446
7c	17.3	98.71	1.9	8.628
Average	**76.2**	**94.33**	**1.4**	**10.174**
8a	0.0	100.00	3.1	2.610
8b	13.5	98.99	2.0	5.328
8c	1.0	99.93	3.1	3.210
8c (duplicate)	4.1	99.69	2.5	
Average	**4.7**	**99.65**	**2.7**	**3.716**
C4	435.2	68.15	2.6	0.870
C5	3.1	99.77	0.5	0.720
C6	0.0	100.00	3.1	0.552
Average	**146.1**	**89.31**	**2.2**	**0.714**
		7/2/08 (Week 2)		
Source Water	**CFU/100mL**			
1:10	7270.0			
1:100	3010.0			
Average	**5140.0**			
Filter	**CFU**	**% Reduction TC**	**Log Reduction TC**	**L/H**
1a	0.0	100.00	3.7	1.230
1b	0.0	100.00	3.7	1.218
1c	0.0	100.00	3.7	1.674
Average	**0.0**	**100.00**	**3.7**	**1.374**
2a	0.0	100.00	3.7	0.522
2a(duplicate)	0.0	100.00	3.7	

2b	1.0	99.98	3.7	0.666
2b(duplicate)		100.00	3.7	
2c	0.0	100.00	3.7	0.528
Average	**0.3**	**100.00**	**3.7**	**0.572**
3a	0.0	100.00	3.7	0.300
3b	0.0	100.00	3.7	0.420
3c	0.0	100.00	3.7	0.240
Average	**0.0**	**100.00**	**3.7**	**0.320**
4a	0.0	100.00	3.7	1.038
4b	1.0	99.98	3.7	1.932
4c	4.1	99.92	3.1	2.292
4c (duplicate)	3.1	99.94	3.2	
Average	**2.1**	**99.96**	**3.4**	**1.754**
C1	0.0	100.00	3.7	0.594
C2	0.0	100.00	3.7	0.534
C3	0.0	100.00	3.7	0.924
C3(duplicate)	1.0	99.98	3.7	
Average	**0.3**	**100.00**	**3.7**	**0.684**
		7/3/08 (Week 2)		
Source Water	**CFU/100mL**			
1:10	6867.0			
1:100a	5480.0			
1:100b	9900.0			
Average	**7415.7**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
5a	135.4	98.17	1.7	4.920
5b	29.9	99.60	2.4	5.064
5c	248.9	96.64	1.5	6.288
Average	**138.1**	**98.14**	**1.9**	**5.424**
6a	>2419.6	N/A	N/A	0.960
6c	110.6	98.51	1.8	0.822
6c	70.6	99.05	2.0	
Average	**N/A**	**N/A**	**N/A**	**0.891**
7a	broke 6/30/08			
7b	727.0	90.20	1.0	13.908
7c	290.9	96.08	1.4	8.760

Average	**509.0**	**93.14**	**1.2**	**11.334**
8a	435.2	94.13	1.2	3.408
8a(duplicate)	290.9	96.08	1.4	
8b	261.3	96.48	1.5	5.502
8c	178.9	97.59	1.6	3.090
Average	**291.6**	**96.07**	**1.4**	**4.000**
C4	81.3	98.90	2.0	0.840
C5	1.0	99.99	3.9	0.978
C6	>2419.6	N/A	N/A	0.630
Average	**N/A**	**N/A**	**N/A**	**0.816**
		7/9/08 (Week 3)		
Source Water	**CFU/100mL**			
1:10	5475.0			
1:100 a	3410.0			
1:100 b	3990.0			
Average	**4291.7**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
1a	13.4	99.69	2.5	2.052
1b	24.9	99.42	2.2	1.560
1c	11.0	99.74	2.6	1.788
Average	**16.4**	**99.62**	**2.4**	**1.800**
2a	0.0	100.00	3.6	0.540
2a(duplicate)	0.0	100.00	3.6	
2b	1.0	99.98	3.6	0.690
2c	0.0	100.00	3.6	0.546
Average	**0.3**	**99.99**	**3.6**	**0.592**
3a	0.0	100.00	3.6	0.312
3b	1.0	99.98	3.6	0.528
3c	0.0	100.00	3.6	0.300
Average	**0.3**	**99.99**	**3.6**	**0.380**
4a	2.0	99.95	3.3	1.668
4b	>2419.6	N/A	N/A	1.968
4c	14.8	99.66	2.5	2.340
4c (duplicate)	4.1	99.90	3.0	
Average	**N/A**	**N/A**	**N/A**	**1.992**
C1	1.0	99.98	3.6	0.612

C2	0.0	100.00	3.6	0.540
C2(duplicate)	1.0	99.98	3.6	
C3	2.0	99.95	3.3	0.960
Average	**1.0**	**99.98**	**3.6**	**0.704**
		7/10/09 Week 3		
Source Water	**CFU/100mL**			
1:10	2187.0			
1:100 a	2720.0			
1:100 b	2160.0			
Average	**2355.7**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
5a	49.5	97.90	1.7	5.814
5b	66.3	97.19	1.6	5.970
5c	87.8	96.27	1.4	6.816
Average	**67.9**	**97.12**	**1.6**	**6.200**
6a	119.8	94.91	1.3	1.350
6a	224.7	90.46	1.0	
6c	33.6	98.57	1.8	0.978
Average	**126.0**	**94.65**	**1.4**	**1.164**
7a	Broke 6/30/08			
7b	Broke 7/11/08			
7c	118.7	94.96	1.3	8.460
7c (duplicate)	104.6	95.56	1.4	
Average	**111.7**	**95.26**	**1.3**	**8.460**
8a	275.5	88.30	0.9	3.402
8b	111.9	95.25	1.3	5.160
8c	435.2	81.53	0.7	3.888
Average	**274.2**	**88.36**	**1.0**	**4.150**
C4	261.3	88.91	1.0	0.870
C5	4.1	99.83	2.8	1.140
C5(duplicate)	4.1	99.83	2.8	
C6	214.3	90.90	1.0	0.738
Average	**121.0**	**94.87**	**1.9**	**0.916**
		Week 4 (7/16/08)		
Source Water	**CFU/100mL**			

1:10	820.0			
Average	**820.0**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
1a	9.8	98.80	1.9	2.352
1b	28.8	96.49	1.5	1.632
1b(duplicate)	21.3	97.40	1.6	
1c	17.5	97.87	1.7	2.040
Average	**19.4**	**97.64**	**1.7**	**2.008**
2a	13.4	98.37	1.8	0.636
2b	9.7	98.82	1.9	0.756
2c	5.2	99.37	2.2	0.618
Average	**9.4**	**98.85**	**2.0**	**0.670**
3a	0.0	100.00	2.9	0.354
3b	0.0	100.00	2.9	0.552
3c	0.0	100.00	2.9	0.408
Average	**0.0**	**100.00**	**2.9**	**0.438**
4a	52.1	93.65	1.2	1.218
4b	95.9	88.30	0.9	3.000
4b(duplicate)	75.9	90.74	1.0	
4c	65.7	91.99	1.1	3.480
Average	**72.4**	**91.17**	**1.1**	**2.6**
C1	13.2	98.39	1.8	0.678
C2	14.4	98.24	1.8	0.672
C3	4.1	99.50	2.3	1.320
Average	**10.6**	**98.71**	**1.9**	**0.9**
		7/17/08(Week 4)		
Source Water	**CFU/100mL**			
1:10	1396.0			
1:100	2590.0			
Average	**1993.0**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
5a	62.0	96.89	1.5	6.900
5a(duplicate)	40.4	97.97	1.7	
5b	38.4	98.07	1.7	6.210
5c	96.0	95.18	1.3	6.510
Average	**59.2**	**97.03**	**1.6**	**6.540**

6a	4.1	99.79	2.7	1.800
6c	8.6	99.57	2.4	1.260
Average	**6.4**	**99.68**	**2.5**	**1.530**
7a	Broke 6/30/08			
7b	Broke 7/11/08			
7c	10.7	99.46	2.3	8.608
Average	**10.7**	**99.46**	**2.3**	**8.608**
8a	49.5	97.52	1.6	4.818
8b	52.9	97.35	1.6	7.458
8c	47.1	97.64	1.6	4.278
Average	**49.8**	**97.50**	**1.6**	**5.518**
C4	125.9	92.74	1.2	0.990
C5	7.5	99.62	2.4	1.320
C5(duplicate)	2.0	99.90	3.0	
C6	37.9	97.82	1.7	0.858
Average	**43.3**	**97.5**	**2.1**	**1.056**
		7/23/08 (Week 5)		
Source Water	**CFU/100mL**			
1:10	15531.0			
1:100 a	8360.0			
1:100 b	10810.0			
Average	**11567.0**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
1a	26.2	99.77	2.6	2.880
1b	39.7	99.66	2.5	1.962
1c	66.3	99.43	2.2	2.370
Average	**44.1**	**99.62**	**2.5**	**2.404**
2a	6.3	99.95	3.3	0.780
2b	5.2	99.96	3.3	1.086
2c	2.0	99.98	3.8	0.732
2c (duplicate)	1.0	99.99	4.1	
Average	**3.6**	**99.97**	**3.6**	**0.866**
3a	1.0	99.99	4.1	0.390
3b	2.0	99.98	3.8	0.750
3c	1.0	99.99	4.1	0.420
3c (duplicate)	3.1	99.97	3.6	

Average	**1.8**	**99.98**	**3.9**	**0.520**
4a	**21.8**	**99.81**	**2.7**	**1.932**
4b	**7.3**	**99.94**	**3.2**	**2.820**
4b(duplicate)	**12.1**	**99.90**	**3.0**	
4c	**261.3**	**97.74**	**1.6**	**3.900**
Average	**75.6**	**99.35**	**2.6**	**2.884**
C1	**8.6**	**99.93**	**3.1**	**0.750**
C2	**6.3**	**99.95**	**3.3**	**0.690**
C3	**8.6**	**99.93**	**3.1**	**1.590**
Average	**7.8**	**99.93**	**3.2**	**1.010**
		7/24/09 (Week 5)		
Source Water	**CFU/100mL**			
1:100 a	12500.0			
1:100 b	8780.0			
Average	**10640.0**			
Filter	**CFU/100mL**	**% Reduction TC**	**Log Reduction TC**	**L/H**
5a	153.9	98.55	1.8	7.230
5b	135.4	98.73	1.9	6.330
5c	248.9	97.66	1.6	7.770
Average	**179.4**	**98.31**	**1.8**	**7.110**
6a	21.6	99.80	2.7	1.830
6a(duplicate)	17.5	99.84	2.8	
6c	25.0	99.77	2.6	1.380
Average	**21.4**	**99.80**	**2.7**	**1.605**
7a	Broke 6/30/08			
7b	Broke 7/11/08			
7c	272.3	97.44	1.6	9.570
Average	**272.3**	**97.44**	**1.6**	**9.570**
8a	185.0	98.26	1.8	4.800
8b	307.6	97.11	1.5	10.170
8c	435.2	95.91	1.4	5.070
8c(duplicate)	344.8	96.76	1.5	
Average	318.2	97.01	1.5	6.680
C4	11.9	99.90	3.0	1.068
C5	13.5	99.87	2.9	1.380
C5(duplicate)	9.8	99.91	3.0	

C6	103.9	99.09	2.0	0.960
Average	**34.8**	**99.70**	**2.7**	**0.852**

Table 11. Negative controls

Date	**TC CFU/100mL**
6/26/08	0.0
6/27/08	0.0
7/2/08	0.0
7/3/08	0.0
7/9/08	0.0
7/10/08	1.0
7/16/08	0.0
7/17/08	0.0
7/23/08	0.0
7/24/08	0.0