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Laboratory and Field Performance of the Biosand Point of Use Water Filtration System in the Artibonite Valley, Haiti

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DEDICATION

This work is dedicated to my lovely wife, Lindsay and my parents for their support and guidance throughout my education

Jesus replied, "If you only knew the gift God has for you and who you are speaking to,
you would ask me, and I would give you living water."
-John 4:10

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ABSTRACT

LABORATORY AND FIELD PERFORMANCE OF THE BIOSAND POINT OF USE WATER FILTRATION SYSTEM IN THE ARTIBONITE VALLEY, HAITI

By Andrew Sisson

The research presented here is summary two years of studying the Biosand filter (BSF) both in Haiti during March 2011 and in the laboratory. In Chapter 2, we examined the long term use and sustainability 55 BSF systems near Deschapelles, Haiti and 47% were found to be no longer in use. Interviews with BSF owners revealed problems related to intermittent filter use. A review of 17 BSF field studies also was included to compare and substantiate observations made in Haiti. Together, previous field studies and our observations point toward the importance of providing culturally appropriate technologies and education materials explaining proper maintenance and operation for improved filter performance and sustainability.

In Chapter 3, we assessed the *E. coli* removal efficiency of the 29 functioning BSFs studied in Haiti. Filtered water from 86% of functioning filters contained *E. coli* concentrations less than 0-10 MPN/100 mL. Bacterial removal efficiency was 94.7% (SE=4.8%). Duration of filter use ranged from <1 to 12 years. Kaplan-Meier analysis of filter lifespans revealed that filter usage remained high (>85%) up to 7 years after

installation. Comparable results from previous studies in the same region and elsewhere show that BSF technology continues to be an effective and sustainable water treatment method in developing countries world-wide.

Finally in Chapter 4, we conducted controlled laboratory experiments to analyze filtration efficiencies of the HydrAid® BSF using two field use practices observed while in Haiti: daily filtering more water than the filter media pore space and extended pause periods of 1 to 4 weeks. Six HydrAid® BSFs were divided into two groups of three replicates each to examine both scenarios. Significantly lower filtration efficiencies occurred when dosing volume exceeded the filter media pore space of 15 liters and extended pause periods up to one month had negative effects on filtration efficiencies for about 4 days before returning to normal. Recommendations were made that filter manuals should more accurately reflect the scientific literature that supports these results to limit the amount of potable water per 12 hour period to 15 liters and more strongly encourage daily use of filters without extended pause periods.

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CHAPTER I

INTRODUCTION

In order for water to be considered potable, it must not contain contaminants that may adversely affect human health. Contaminated drinking water, inadequate sanitation, and hygiene are major health risks in underdeveloped countries, responsible for 88 percent of diarrheal disease in the world that claims an estimated 1.87 million children's lives annually (WHO 2003; Boschi-Pinto et al. 2008). Recent research has suggested improved water quality can reduce diarrheal disease morbidity by more than 30% (Fewtrell et al. 2005; Barnes et al. 2009). In supplying improved water resources, the large centralized waters systems common in the developed nations are too costly and resource intensive for millions of rural dwelling people in the developing world that lack access to safe drinking water (Mintz et al. 2001). This has led to a shift to decentralizing water treatment in worldwide efforts for providing safe drinking water to the developing world using effective, affordable, sustainable technologies often referred to as Point of Use (POU) or household water treatment systems.

Point of Use treatment technologies are primarily based on chemical/solar disinfection, coagulation, and filtration. The most widely used include; liquid or tablet chlorine, solar water purification (SODIS), ceramic filters, Biosand filters (BSF) and PUR© disinfectant and turbidity flocculation powder (Clasen 2008). In a review assessing sustainability of POU technologies, Sobsey et al. (2008) concluded that in addition to being one of the most widely distributed, the BSF is one of the most reliable for removal of harmful diarrhea-causing bacteria, turbidity, and was a highly sustainable technology over long-term use. Since their development in the late 1980's by David Manz at the University of Calgary, Canada, an estimated 500,000 people use BSFs world-wide (Elliott et al. 2008). While most of these filters are housed in a concrete enclosure and are built on site, a plastic version of the filter known as the HydrAid® BSF manufactured by Cascade Engineering in Grand Rapids, MI, USA is distributed globally.

The Biosand Filter

The BSF treats small quantities of water through naturally occurring bacterivory causing the removal of influent bacteria, in addition to adsorption to sand and mechanical filtration mechanisms to provide a household with its daily water requirements (Elliot et al. 2008; Jellison et al. 2000). Typically, a BSF unit is placed in a home by development organizations along with two plastic containers, one for collecting source water and one placed at the filter outlet for collecting filtered water. Upon the receipt of a filter, users receive training for proper operation and maintenance of the filter and are often provided with instructive materials in the native language.

To date, numerous field and laboratory studies have been undertaken aiming to improve the design, evaluate the BSFs filtration efficacy, and understand the mechanisms actively at work removing water contaminants. Such studies have analyzed the effective removal and reduction of *Escherichia coli* (*E. coli*) and other enteric bacteria, protozoan parasites (*Cryptosporidium oocysts* and *Giardia lamblia*), viruses (Hepatitis A virus and echovirus 12), organic and inorganic toxicants, heavy metals, and turbidity (Bauer et al.

2011; Collin 2009; Duke et al. 2006; Earwaker 2006; Lee 2001; Lukacs 2001; Muhammad et al. 1997; Ngai 2003; Palmateer et al. 1999; Stuaber et al. 2006). A summary of some of these studies and others can be found at the Center for Affordable Water and Sanitation Technology website (http://www.cawst.org/).

The technology behind the BSF is based on simple modifications to the centuries old slow sand filtration treatment method that is used for municipal drinking water treatment. Utilizing the natural ecology of the source water to develop a biofilm, intermittent water dosing, and the difference in gravitational head contaminated water flows through layers of sand and gravel filtering out contaminants. The filter consists of diffuser plate (limits disruption of media below), a top layer of fine sand, a middle layer of coarse sand, and bottom layer of drainage gravel (Figure 1.1). When water is initially poured into the filter the water level will rise above the outlet pipe, creating a difference in hydraulic head that will allow the water to flow through the media pore spaces and out of the outlet until water level returns to the level of the outlet (~3-5cm above the sand layer). As water flows through the filter, naturally occurring particulate matter and bacteria are trapped in the top 3-5 cm of sand where a biological layer (biofilm) forms after a period of ripening or maturation time, typically between 2-3 weeks. Slightly enhanced and less variable filtration is achieved over time as

Figure 1.1. Profile view of the HydrAid® Biosand Filter manufactured by Cascade Engineering, Grand Rapids, Mi.

organic and biological activity moves deeper into the sand column, known as “deep-bed media aging”(Elliot et al. 2008; Jellison et al. 2000).

The intermittent use of the BSF and a maintained paused water depth of 3-5 cm above the sand are the primary differences between it and its larger scale predecessor, the slow sand filter. The intermittent time in between when water stops flowing out of the filter outlet until the next time water is poured (dosed) into the filter is known as the pause period. While optimal pause periods vary with the size and model of the filter, between 12-24 hours are the most common recommendations for cement and plastic HydrAid® models (Baumgartner et al. 2007; Stauber et al. 2006). The duration of the pause period is a balance between providing sufficient contact time for microbial removal processes to take place while needing to provide an adequate amount of nutrients and oxygen with the inflow from a new dosing to support the biofilm (Baumgartner et al. 2007). During the pause period water is stored in pore spaces of the media. To obtain optimal filtration efficiencies, the amount of media pore space volume should be enough to hold all the water dosed to the BSF without any of it coming out of the outlet until the next dosing of water (Kubare and Haarhoff 2010). Tracer tests indicate that water flows through BSFs exhibiting the characteristics of plug flow, suggesting that if the amount of media pore space is equal to the volume of water dosed to the filter the entire volume will have roughly the same amount of retention time to be filtered (Kubare and Haarhoff 2010).

Haiti

As one of the most heavily impacted countries in the western hemisphere by water borne disease and illness (Knowles et al. 1999; Cravioto et al 2011), the Republic of Haiti is believed to have had more than 18,000 BSFs distributed throughout the country (http://www.cawst.org/). Haiti is located on the western one third of the Island of Hispaniola, in the Caribbean and is known throughout the world as an impoverished country with inadequate clean water resources and access to improved sanitation and hygiene (Knowles et al. 1999; Cravioto et al. 2011). While recent strides have been made toward improving sanitation and access to safe drinking water, much of Haiti's 8.3 million people are still without such access and child mortality rates are 15 times higher than in the United States, largely due to inadequate access to clean water, proper sanitation, and hygiene (WHO 2006; WHO/UNICEF JMP 2012).

Historically, Haiti had one of the wealthiest economies in the western hemisphere driven by slave labor and the export of sugarcane, coffee and mahogany wood while under French colonial rule (Lundahl 2011). However, this began to change in 1791 when a Voodoo ceremony held in Bois Caiman, in Northern Haiti, rallied the then slaves together and started a series of bloody revolts against French colonization and brought Haitian independence in 1804 (Lundahl 2011). These revolts, as well as Haitian independence, resulted in a rapid decline in exports and caused great land degradation, deforestation, and the destruction of the sugarcane mills, leaving the colony looking like "a big cemetery of ashes and debris" (Lepkowski 1968; Lundahl 2011). Over the course of the nineteenth and twentieth centuries Haiti has transformed into a largely peasant society with a very small, extremely wealthy upper ruling class, most of which are mulattos descendants from French plantation owners having children with their African slave mistresses (Lundahl 2011). During this time period the peasantry, remnant of the African slave population, developed a rich syncretic system of beliefs and language which remains at large today through the commonly practiced religion of Voodoo alongside Catholicism and the national language, Creole (Farmer 2010). Today, Haiti's economy and people struggle to exist by relying on small scale agrarian practices in rural areas, retail and "resale" businesses in the larger towns and cities, and the international aid community's physical and monetary presence within country (Farmer 2010; Lundahl 2011).

While Haiti has a history of extremely unstable and corrupt political turmoil, various natural disasters, and a mix of other environmental, socioeconomic, and health epidemics, the country has recently been in the global spotlight as the capital city of Port au Prince was hit by a devastating magnitude 7.0 earthquake in early 2010. This was followed by the introduction of *Vibrio cholera* into the Artibonite River Valley later that year. Previous to 2010, cholera had never been reported in Haiti, and thus exacerbated historical problems regarding waterborne disease and illness countrywide (Cravioto 2011).

As one of the country's primary food producing regions, the Artibonite Valley has an average annual rainfall between 120 - 200 cm/yr and temperatures range from 15°-35° C (Caillouet et al. 2007). While typically considered rural, the area has a high population density and most residents lack access to electricity, running water, and indoor plumbing. Some main roads are paved, though often poorly maintained, and unpaved mountain paths are the only way to reach many remote mountain villages. Some drainage systems line the most improved paths, but often overflow and/or clog reducing functionality (Caillouet et al. 2007).

In 1999, a large hospital in the region, Hôpital Albert Schweitzer (HAS) began distributing BSF throughout the Valley and surrounding mountain villages (Duke et al. 2006). After the first six years of distribution, one of the now most commonly cited publications on the field use of the BSF was conducted on 107 of the original filters (Duke et al. 2006). Since 1999 over 2000 filters have been distributed in this region by numerous organizations, but little follow up study has been reported since 2006.

THESIS OBJECTIVES

The research presented here is summary of two years of studying the BSF both in Haiti and in the laboratory. In Chapter 2, we examined the long term use and sustainability 55 BSF systems in the Artibonite Valley near Deschapelles, Haiti. Of the 55 BSFs visited, 47% were no longer in use. Interviews with BSF owners revealed problems related to intermittent filter use due to travel for employment or personal matters; broken or missing filter parts; and fears that the filter would not be effective against cholera. A review of 17 BSF field studies also was included to compare and substantiate observations made in Haiti. Together, previously field study and our observations point toward the importance of providing culturally appropriate technologies and education materials explaining proper maintenance and operation are essential for improved filter performance and sustainability (state summary of the results.

In Chapter 3, we assessed the *E. coli* removal efficiency of the 29 functioning BSFs studied in Haiti, which averaged 94.7% (SE=4.8%). We used Survival Analysis to model and predict BSF sustainability after installation and determined that the likelihood of finding filters still in use up to 7 years after installation is >85%. Finally in Chapter 4, we conducted laboratory experiments to analyze filtration efficiencies of the HydrAid® BSF using two of the field use practices observed while in Haiti that differed from recommended BSF operational practice: daily filtering more water than the filter media pore space without a sufficient pause period and extended pause periods of 1 to 4 weeks. We found that filtration efficiencies are significantly reduced when filtering greater volumes of water than the media pore space and that filter biofilms may be compromised, reducing filtration efficiencies to less than 30% several days after not using them for a month. The overall goal of this research was to add new insight to the growing body of studies regarding BSF efficacy, sustainability, and suggest best practices for filter distributors and users.

CHAPTER II

AN ASSESSMENT OF LONG TERM BIOSAND FILTER USE AND SUSTAINABILITY IN THE ARTIBONITE VALLEY NEAR DESCHAPELLES, HAITI

ABSTRACT

A non-randomized assessment of long term biosand filter (BSF) use and sustainability in the Artibonite Valley near Deschapelles, Haiti was conducted during March, 2011. Of the 55 BSFs visited, 47% were no longer in use. Filter lifespan ranged from <1 year to systems still in use after 12 years. Interviews with BSF owners revealed problems related to intermittent filter use due to travel for employment or personal matters; broken or missing filter parts; and fears that the filter would not be effective against cholera. In addition, 17 BSF field studies were reviewed to identify common issues impacting usage. Culturally appropriate technologies and education materials explaining proper maintenance and operation are essential for improved filter performance and sustainability. For Haiti, education materials should be provided in Creole and French and should include, 1) diagrams and descriptions of how the BSF works, 2) how to troubleshoot common problems, 3) how to properly maintain filters, and 4) a contact in case of questions. Operational problems can be minimized by providing long-term technical support, periodic water quality monitoring, and maintenance assistance for filter users.

Keywords: Biosand filtration, slow sand filtration, Haiti, water, Point-of-Use Filtration

INTRODUCTION

Over 780 million people world-wide lack access to safe drinking water sources (World Health Organization/United Nations Children's Fund [WHO/UNICEF] 2012). Contamination of drinking water through poor sanitation and hygiene is a major health risk in underdeveloped countries and is responsible for 88% of diarrheal disease in the world (WHO 2003). In the Republic of Haiti, child mortality rates are 15 times higher than in the United States, largely due to inadequate access to clean water, proper sanitation, and hygiene (WHO 2006). While some strides have been made toward providing improved, safe drinking water sources to Haitians since the 1990s, 49% of rural Haitians still use unimproved sources for drinking water (WHO/UNICEF 2012).

Over the past decade major advances have been made toward understanding and addressing water, sanitation, and hygiene issues in Haiti, and globally through government and non-governmental organization (NGO) collaboration (WHO/UNICEF 2012). UNICEF-led Multiple Indicator Cluster Surveys (MICS) and Water Sanitation and Hygiene (WASH) clusters have fostered collaboration and data sharing between the Haitian National directorate for safe water and sanitation (DINEPA) and regional health units (WHO/UNICEF 2012; UNICEF 2011). WASH clusters in Haiti, NGOs, and national organizations such as the Haitian Rotary share information and facilitate community development initiatives (Johnson, Hôpital Albert Schweitzer, personal communication 2011).

In Haiti and other underdeveloped countries, many NGOs and aid agencies have turned to Point of Use (POU) water treatment methods to provide clean water (Sobsey et al. 2008; UNICEF/WHO 2009). POU technologies treat small volumes of water and remove pathogens and contaminants through biological, chemical, solar, coagulation, and filtration methods. The most widely used include; liquid or tablet chlorine, solar water purification (SODIS), ceramic filters, biosand filters (BSFs) and PUR© disinfectant and turbidity flocculation powder (Clasen 2008a). In a review assessing sustainability of POU technologies, Sobsey et al. (2008) concluded that in addition to being one of the most widely distributed POU technologies, the BSF is one of the most reliable for treatment and removal of harmful diarrhea-causing bacteria and turbidity, and was a highly sustainable technology over long-term use. However, some studies suggest that research conducted on POU technologies such as the BSF are biased, lack hard scientific evidence from double blind tests, and that the current trend of world-wide distribution is premature (Schmidt & Cairncross 2009; Hunter 2009). Vanderzwaag (2008) suggested that without a proper implementation strategy, the BSF may not be an appropriate technology and can adversely affect how receptive a population is to future aid. It is estimated that more than 140,000 BSFs are used by half a million people world-wide (Clasen 2008b).

Laboratory studies have demonstrated BSF efficacy, but field performance and usage studies require surveys and user feedback. Many BSF field studies lack data regarding observations and problems leading to BSF disuse (Center for Affordable Water and Sanitation Technology [CAWST] 2010b). The common reasons for the failure of POU water treatment projects are often centered on the lack of consistent NGO support and education, improper maintenance and repair, the absence of user incentives, and the failure to integrate proper POU technology use into daily routines in a culturally sensitive manner (Gadgil & Derby 2003).

Government and NGOs have implemented many different POU treatment technologies in Haiti (Oates et al. 2003; Duke et al. 2006; Lantagne & Clasen 2010). However, there continues to be a critical need for additional efforts to provide clean and safe water (Wampler & Sisson 2010; Wampler 2011). Between 1999 and 2010 over 2000 cement BSFs were distributed throughout the Artibonite Valley of central Haiti by Hôpital Albert Schweitzer (HAS) and other NGOs. During early 2005, Canadian researchers visited 107 of these filter sites and found only 4 that were not working properly (Duke et al. 2006). More information on filters distributed by HAS can be found in Duke et al. (2006). The research presented here summarizes the results of a survey of 55 BSFs in the Artibonite Valley near Deschapelles, Haiti in March 2011, examines the causes of filter abandonment, and provides a review of BSF field studies to identified important factors to facilitate long-term sustainable BSF use.

METHODS

In March 2011, we traveled to HAS located in Deschapelles, Haiti to examine sustained use and efficacy of cement BSFs distributed by HAS, Faith In Action International (FIAI), and the Agency for Technical Cooperation and Development (ACTED). The study area included 14 communities, and extended ~50 km up the Artibonite Valley (Figure 2.1). The communities were primarily located 16 km from Deschapelles, with the furthest sample point 30 km from the city. We initially collaborated with HAS personnel to identify communities which had a concentration of filters in a small geographic area.

Sample selection methods were similar to the 2005 study of the Artibonite Valley (Duke et al. 2006). Homes were selected in a non-random manner based on information from HAS, NGO records, and asking members of the community which households had filters. Assessments were conducted regardless of filter status. In general each community was assessed for half a day (~ 4 filters), while a few larger communities were done in a full day (i.e. Deschapelles and Petite Riviere). All visits were unannounced. This resulted in 55 total BSFs assessed. Time since filter installation was primarily found using HAS installation records (*n* = 41), NGO information (*n* = 9), and in some cases filter user reporting (*n* = 5). For non-functioning filters, duration of use was determined by user reporting.

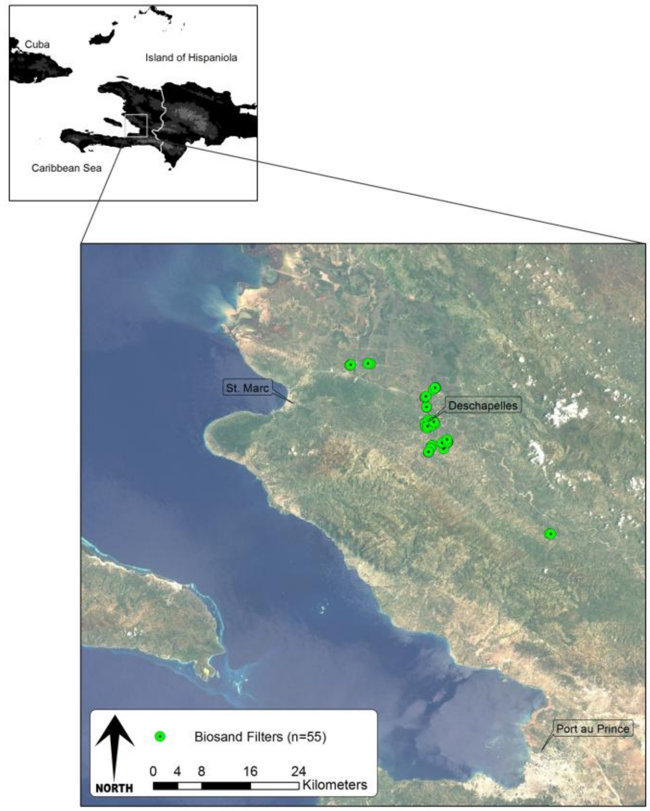

Figure 2.1. Map of the study area and GPS locations of households with Biosand filters visited in Artibonite Valley, Haiti.

An HAS filter installation technician was employed as our interpreter and guide. The technician did not select the communities or areas within the communities. He only assisted in locating the individual homes in the communities we selected. Observations and surveys were used to document common BSF usage problems. At each household, users were questioned regarding filter installation date; filter use and maintenance frequency; number of people using the filter; post-filtration disinfectant usage; and water source. Non-functioning BSFs were evaluated through interviews to determine reasons for discontinued use, duration of service discontinuation; filter use frequency and maintenance; and involvement of filter technicians. The initial response given for disuse by the BSF user was recorded.

In addition to field work, 37 studies were chosen from a comprehensive review of BSF studies. These studies were chosen because they contained significant field evaluation allowing us to compare and further substantiate our findings with the broader BSF literature. Studies were found using Google Scholar, Web of Knowledge^{SM} article database, and the “Summary of Field and Laboratory Testing for the Biosand Filter” (CAWST 2010b). While not all studies were peer-reviewed journal articles they are all easily accessible in electronic format. Non-peer-reviewed studies were master’s thesis, doctoral dissertations, or organization and governmental project reports. A subset of 17 field studies were chosen because they contained data relating to BSF distribution, performance, reasons for filter disuse, and reduced filtration efficiencies. The reviewed literature studies mostly focused on filter design optimization, reporting contamination removal rates, user acceptability, and the effectiveness of filter adaptations such as a double sand layer for reducing turbidity or adding iron for arsenic removal (ex. Barnes et al. 2009; Collin 2009; Ngai et al. 2007; Stauber et al. 2009).

RESULTS

Of the 55 households visited, 26 filters were not in use. Nearly two thirds (65%) of non-functioning filters were reported as in use for less than seven years (Figure 2.2). Primary reasons leading to filter disuse are summarized in Table 2.1. BSF owners mentioned difficulty using the filters daily due to frequent prolonged travel to larger cities for work or hospital visits (*n* = 5). This eventually led to sporadic filter usage and abandonment. In two cases, a broken collecting bucket spigot was mentioned as the reason for stopping use. One owner claimed the January 2010 earthquake caused the filter to fall and break, while another owner stopped using the filter because the lid broke. In two of the cases, filters were installed but never used. Filter owners said the filter was provided free of charge, but they were required to buy their own bucket as a way of

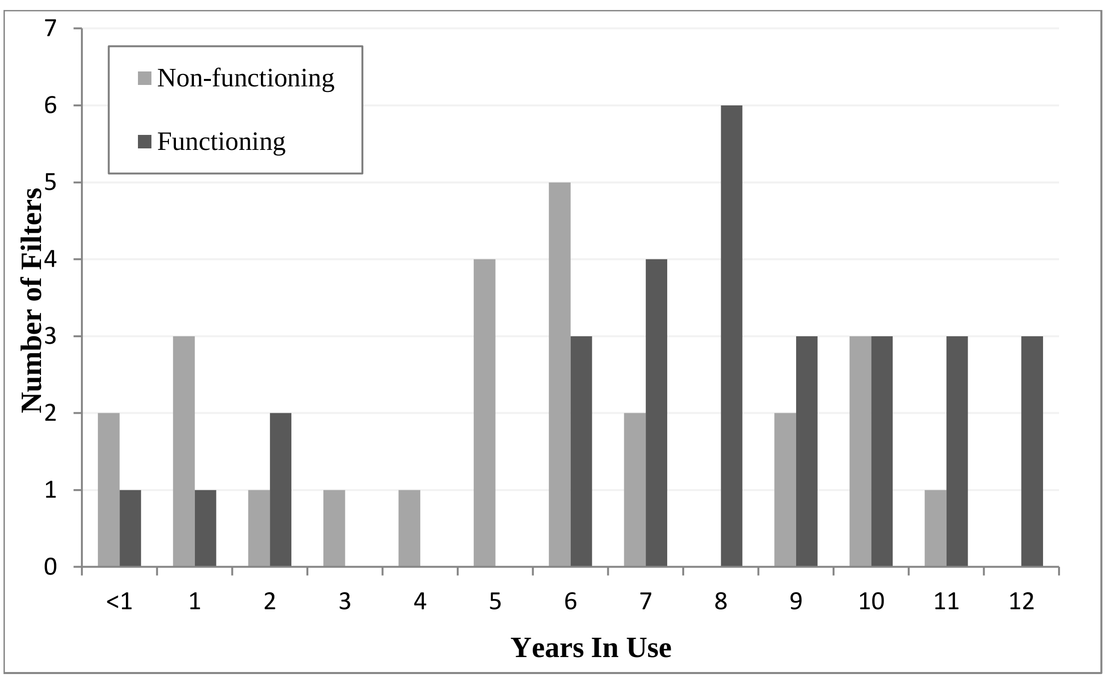

Figure 2.2. Number of non-functioning and functioning filters at the time of study and number of years filters were in use (n=54). One non-functioning filter was not included as installation date and stopping date were unknown.

encouraging ownership of the filters. In a third case, a bucket was supplied as part of a year-long trial period but after it broke, filter use was discontinued. Each of these households said they could not afford a new clean water bucket which costs ~160 Gourde ($4 USD).

Ant infestations occurred in two homes where owners mentioned using filters only once a week. Filter clogging was mentioned in three homes that used hand dug wells which resulted in reduced flow rates and led to filter neglect or malfunction. BSF owners, on average, claimed to clean their filters 2-3 times per year but answers ranged from never to almost weekly. Several owners mentioned cleaning only occurred when a filter technician came to visit. The cholera outbreak in December 2010 was the reason three households stopped using their filters, stating they were told not to rely on the BSF to protect against cholera. These users bought treated water instead. Reasons for stopping use were not given for two filters and chlorination of source water was given once.

Table 2.1. Summary of operational problems based on observations in Haiti, March 7-19, 2011.

Operational Problems	Number (%) of filters problem was observed (n=26)
Ant Infestation	2 (7.7)
Bad smell and taste	3 (11.5)
Broken Part/or crack in filter	4 (15.3)
BSF not-compatible with lifestyle	5 (19.2)
Filter clogging/stopped functioning	3 (11.5)
Inadequate resources for bucket	3 (11.5)
Stopped use because of cholera scare	3 (11.5)
Other	3 (11.5)

An additional concern mentioned on four occasions involved chlorination of water prior to filtration. In one case, the homeowner had stopped using his filter two weeks prior to our visit as a result of smelling chlorine in his water. The source water in this case was a capped spring which was piped to a large reservoir. After the cholera outbreak, a local NGO added a chlorine dispenser to the reservoir without informing the HAS community development center, who originally built the reservoir, or the community members. HAS records showed as many as 20 BSFs could have been affected by reservoir chlorination. The three remaining cases were in a different community where filter users were adding chlorine tablets prior to filtration.

Many issues, related to sustainability and effective use, were in agreement with previous studies. Factors affecting sustainable and effective BSF use from studies in 14 different countries included improved BSF owner education; poor understanding of the linkage between water quality and sanitation; source water causing filter clogging; water recontamination due to animal or human contact; and inadequate maintenance (Table 2.2).

Table 2.2. Biosand filter field studies chosen and common problems mentioned as leading to filter disuse or improper functioning of filters. Median number of filters studied is 67.5.

Reference	Country of Study	Common Problems	# of Filters in Study
Current Study	**Haiti**	**2,6,7,8**	**55**
Aiken et al. 2011	Dominican Republic	7,8	328
Baker 2006	Haiti	2,4	80
Clasen 2008b	Lao PDR	4	320
Collin 2009	Ghana	4	25
Duke et al. 2006	Haiti	2,4	107
Earwaker 2006	Ethiopia	2,4,7,8	37
Fewster et al. 2004	Kenya	5,6,8	51
Fiore et al. 2010	Nicaragua	4,5,8	199
Hurd et al. 2001	Nepal	3	39
Kaiser et al. 2002	Kenya, Cambodia, Mozambique, Vietnam, Honduras, Nicaragua	1-6,8	600
Klopfenstein et al. 2011	Cameroon	1,2	89
Lantagne and Clasen 2010	Haiti	8	46
Lee 2001	Nepal	6,8	39
Liang et al. 2010	Cambodia	2,4	336
Lukacs 2001	Nepal	1,2	12
Mahmood et al. 2011	Pakistan	3	42
Vanderzwaag 2008	Nicaragua	2,5,7,8	234
Total	**14 countries**		**2639**

[1] Knowledge of Filter maintenance varied by household and between household members

[2] Insufficient/improper Training/Education

[3] Poor Understanding of linkage between water, sanitation, and hygiene and illness

[4] Post-filtration recontamination

[5] Filtered water was accessible to animals

[6] Clarity of source water causing filter clogging

[7] Poor Distributor/Caretaker follow-up

[8] Cracks in filter body/Loss of sand/Slow flow rates

DISCUSSION

We recognize that some error is likely associated with the duration of filter use, as it was determined by user reporting, but note that exact installation dates were obtained from implementing organizations for all but one of the non-functioning filters and that this does not interfere with the issues given for filters no longer being used. It is also important to note that while 47% of filters were non-functioning at the time of this study, all but one (broken beyond repair) could be brought back into use with biofilm re-establishment and/or other minor maintenance. Our sample size was comparable to previously published studies on BSF use (median = 67.5, Table 2.2). Issues identified both in our study and previously published studies can be grouped into common themes, education and technical support, cultural sensitivity and BSF suitability, and organization collaboration. In consideration of the lack of randomization in the sample design, the 47% non-functional filters we determined should not be considered representative of the communities within the Artibonite Valley. Since the previous study of the Artibonite Valley (Duke et al. 2006) also used non-randomized methods and yielded different results (only 4 of 107 not functioning), a randomized study is needed to determine the actual extent of filters still in use.

Education and Technical Support

Culturally appropriate, initial and follow-up education of users regarding BSF parts, the importance of daily usage, and need for periodic maintenance are essential for sustainable and effective BSF use (Vanderzwaag 2008; Clasen 2008a; Baker 2006; Liang et al. 2010; Lukacs 2002). Many of the 17 reviewed studies and the present study identify the need for improved education in the areas of BSF function and maintenance, effective education techniques, or the proper combined use of chlorination with BSF.

In Haiti, issues like recontamination of filtered water, filtered water buckets left uncovered, cracks in the filters, loss of sand, and increased paused water depth could be addressed through education materials presented in Creole and French. Ability for BSF owners to troubleshoot and address their own operational problems would be improved by knowledge and understanding of how filters work and what parts are required for maintenance and proper operation. Cleaning too often can be detrimental to maintaining a viable biofilm and cause significant loss of sand, while not cleaning may lead to clogging and eventual disuse. In several other field studies, long-term use and regular cleaning was shown to lead to a decrease in sand height and increase the paused water depth (Lee 2001; Kaiser et al. 2002; Fewster et al. 2004; Earwaker 2006; Fiore et al. 2010).

In Haiti, ineffective maintenance, lack of understanding BSF operation, and uncertainties about cholera removal efficiency have resulted in distributions of Aquatabs® and Clorox® disinfectant powder to BSF users. Survey results revealed a risk to BSF owners who were uninformed about chlorination of the water sources and improperly used chlorine prior to filtration. This highlights the need for further education to address the proper use of chlorination with BSFs. Similar concerns of BSF owners using chlorine disinfectant were expressed by Lantagne and Clasen (2010) in their draft report for UNICEF. We speculate that chlorination prior to BSF filtration and sporadic chlorination of source water may pose potential health risks to BSF owners; however, further research regarding the use of chlorination and its effects on the filter biofilms is needed. Adding pre-chlorinated source water to a BSF may compromise the function of the biofilm by killing those organisms necessary for proper filter function. There also is a risk in sole use of chlorine to treat water as *Giardia* and *Cryptosporidium* cysts have increased resistance to chlorination (Korich et al. 1990; Lisle & Rose 1995; Betancourt & Rose 2004). The best practice is utilizing chlorination as a post filtration step to deactivate any potential harmful organisms that may have survived sand filtration (Lantagne et al. 2006).

Several studies have noted that regular follow-up by technicians lasted for the first few years after initial installation, and then the lack of funds and other issues led to discontinued technical support (Fewster et al. 2004; Clasen 2008b; Fiore et al. 2010). Consistent and continued technician follow-up is clearly helpful in fixing problems and encouraging continued BSF use (Earwaker 2006). For the majority of the filters in this study, funds supporting HAS follow-up programs ran out after several years. Unfortunately, the support program was assigned to another organization specializing in BSFs that also ran out of funds (Johnson, Hôpital Albert Schweitzer, personal communication 2011). Information and training provided to teachers, nurses and doctors, pastors, and others who routinely interact with BSF users may be an effective approach to enhance sustainability. For Haitians, a phone call or text-in service number could be very beneficial as many Haitians own or have access to a cell phone. It is clear from this study and others that educational efforts should be focused toward the primary operators of the filter (Kaiser et al. 2002; Klopfenstein et al. 2011; Lukacs 2001).

<u>Cultural Sensitivity and BSF Suitability</u>

In order for BSFs to be properly and reliably used they must be placed in settings where BSF use is compatible with source water and cultural practices. Some of the most commonly observed problems leading to filter disuse in Haiti were associated with Haitian culture, lifestyle, and beliefs. Haitians commonly mentioned the incompatibility, or difficulty of continually using the BSF due to the travel requirements of their lifestyle.

A similar problem leading to the disuse of several filters was noted in the Dominican Republic (Aiken et al. 2011). Several BSF owners noted they had stopped using their filter because they regularly spent extended time away from home, and it became a nuisance to maintain the recommended charging and maintenance regime for proper biofilm function. For many rural Haitians, their lifestyle includes extended periods of time away from home for work, personal or family illness, or visiting family and friends. Intermittent use may pose a health risk to users whose biofilm is not regularly maintained. In such situations, BSF owners should allow for a (re)start-up period in addition to utilizing post-filter chlorination to disinfect water before drinking. Bottled water also could be consumed during the start-up period. While unexpected travel due to illness and work may not be predictable by BSF distributors, having a good understanding of the culture and lifestyle of the target users will result in providing the most appropriate water treatment technology (Sobsey et al. 2008).

Survey results from our study indicate that there is still a lack of understanding of the connection between water and illness, and how the BSF functions to prevent water-borne disease. As cited in the literature and noted in this study, it is very important to connect the effects of water, sanitation, and hygiene (Gadgil & Derby 2003; Mahmood et al. 2011; Molla 2008). A lack of data and accurate information about BSF effectiveness for cholera removal resulted in several filters falling into disuse over time. More studies are needed to evaluate BSF effectiveness for specific pathogens such as *Vibrio cholerea*.

Haitian culture and beliefs often associate illness with religion or political suspicion rather than unsafe water, sanitation and hygiene (Smith 2001; Grimaud & Legagneur 2011). Current education campaigns are working to understand people's perceptions of cholera while providing proper education as to the cause of the disease and the need for improved water, sanitation and hygiene (Grimaud & Legagneur 2011). In addition to culturally sensitive education campaigns linking these concepts together, it is important for BSF owners to understand how and why their filters work to clean their water of harmful microorganisms to increase owner trust and foster continued use of the technology.

Rural Haitians often experience financial hardship which can make proper maintenance of a BSF difficult. Based on the literature review, the three BSF owners who were unable to use their filters because they could not afford buckets represent a unique situation. Organizations may choose to provide BSFs for free, for a heavily subsidized price, or at full price based on project funding (Aiken et al. 2011; Earwaker 2006; Duke et al. 2006; Fewster et al. 2004; Stauber et al. 2012). Some charge a small fee to motivate and instill a sense of ownership, value, pride, and trust in using the technology. While this practice has been widely recognized and believed to improve user acceptability in some regions, there are questions as to whether charging a fee actually improves the likelihood of sustainable filter performance or addresses the needs of the most vulnerable populations (Kaiser et al. 2002; Clasen 2008b; Fiore et al. 2010). Regardless of the financial model used to distribute filters, it is important for organizations to evaluate individual user needs and means to make appropriate filter recommendations (Lantagne et al. 2009).

Organization Collaboration

In order for effective and sustainable water project implementation cultural knowledge, sensitivity, and community and organization collaboration are vital. This will help reduce duplication of efforts and benefit BSF users. An example of collaboration and communication is shown by the WASH cluster systems implemented by UNICEF and DINEPA throughout Haiti to improve the responsiveness and effectiveness of aid relief and development. Similar partnerships between organizations and local universities, schools, or churches also have great potential for creating long lasting relationships that result in more reliable funding and long term BSF sustainability.

CONCLUSIONS AND RECOMMENDATIONS

Insights gained through the literature review and field study in Haiti indicate three critical areas that need to be addressed in future BSF implementation projects to increase filter longevity and provide the greatest benefit to users: 1) distributors must provide long-term educational and technical support upon distribution and throughout the project's lifetime; 2) distributors must continually seek a better understanding of changing societal needs, cultural beliefs, lifestyle habits, and BSF suitability; and 3) continued improvement in collaborative work through partnerships with established community groups, local governments, and other organizations working in the same area. Specific recommendations based on our field study include the development of educational materials in Creole and French, family lifestyle assessment to provide most appropriate technology, and the development of ways to enhance collaborations between distribution organizations and local universities, hospitals, and community groups.

An unfortunate reality is that NGOs, implementers, and stakeholders often struggle for ways to convince funders that long term monitoring, evaluation, and technical support are not financial black holes, but these efforts are equally valuable in the effective and sustainable installation of POU treatment devices (Gadgil & Derby 2003). It is generally accepted that sustainable public health systems and education require ongoing contact with the people they serve, but this is often an inconsistent feature of water and sanitation projects. Many of the problems observed in Haiti were not due to neglect or lack of effort from the implementing organizations. Many of the recommendations made here were implemented but had to be discontinued due to lack of funding. In Haiti, governmental agencies and NGO’s have started working together through the DINEPA and WASH cluster programs to address water, sanitation, and hygiene needs. Hopefully these collaborations will continue and expand to include more academic institutions in Haiti and abroad.

Lastly, understanding water resources from an ecological, biological, geological, and anthropological context by region is needed to ensure that suitable water interventions are implemented. Every year, thousands of new BSFs are shipped around the world to remote communities. A generalized distribution plan is unlikely to meet the individual needs of all the families in the region and provide a sustainable solution to clean water needs. Incorporating scientific studies, observations, and recommendations in these efforts, especially in the area of culturally appropriate education, follow up, and maintenance will make sure these efforts are effective.

CHAPTER III

LONG-TERM FIELD PERFORMANCE OF THE BIOSAND FILTER THE ARTIBONITE VALLEY NEAR DESCHAPELLES, HAITI

ABSTRACT

A field study assessing the sustainability and efficacy of 55 Biosand filters (BSFs) installed between 1999 and 2010 was conducted in the Artibonite Valley, Haiti during 2011. Twenty-nine filters were still in use. Duration of filter use (lifespan) ranged from <1 to 12 years. Water quality, microbial analysis, and flow rate were evaluated for each functioning filter. Kaplan-Meier analysis of filter lifespans revealed that filter usage remained high (>85%) up to 7 years after installation. Several filters were still in use after 12 years, which is longer than documented in any previous study. Filtered water from 25 filters (86%) contained *E. coli* concentrations of less than 0-10 MPN/100 mL. Recontamination of stored filtered water was negligible. Bacterial removal efficiency was 94.7% (SE = 4.8%). Comparable results from previous studies in the same region and elsewhere show that BSF technology continues to be an effective and sustainable water treatment method in developing countries world-wide.

Keywords: Biosand filtration, Haiti, water, point-of-use filtration, sustainability

INTRODUCTION

Poor access to clean drinking water is a widespread problem facing the world today, with a disproportionate effect on developing nations. The United Nations Children's Development Fund and the World Health Organization estimate that more than 800 million people—roughly 10% of the world population—do not have access to safe drinking water (WHO/UNICEF 2010). Along with poor sanitation and hygiene, unsafe drinking water is one of the three main health risks in developing countries that contribute to 88% of diarrheal disease in the world (WHO 2003). Several studies have shown that interventions which improve water quality can reduce diarrheal disease morbidity by more than 30% (Aiken et al. 2011; Fewtrell & Colford 2004; Stauber et al. 2009).

As international aid organizations and government programs focus on providing adequate water resources to the millions of people without, many have turned to household or point-of-use (POU) water treatment methods and water filtration (WHO/UNICEF 2010; Duke et al. 2006; Sobsey et al. 2008). Biosand filters (BSFs) are one of the most widely used POU treatments (Clasen 2009). First installed in Nicaragua in 1993, BSFs are estimated to be used by nearly 500,000 people world-wide (Clasen 2009).

BSFs are household-scale slow sand filters that provide microbiologically safe drinking water by removing biological contaminants that cause amoebic and bacillary dysentery, typhoid, and cholera. They have been evaluated in numerous laboratory and field studies to assess effectiveness and sustainability (Duke et al. 2006; Sobsey et al. 2008; Stauber et al. 2006), where sustainability refers to the length of time a filter is likely to remain in use when adequately maintained. BSFs have been shown to effectively remove up to 90% of viruses, >99.9% of protozoa and helminthes, 90 to 98.5% of *Escherichia coli* (*E. coli*), and up to 85% of turbidity (Aiken et al. 2011; Duke et al. 2006; Stauber et al. 2006). But while BSFs utilize simple technology that has been proven appropriate for many developing countries, few field studies have evaluated how effective and sustainable they are beyond six years (Liang et al. 2010; Vanderzwaag 2008; Earwaker 2006). As a result, there currently is little empirical evidence that BSF technology is effective and sustainable in the long term.

In 2005, Duke et al. (2006) performed one of the first long-term field studies of cement BSFs in the Artibonite Valley, Haiti. Between February and March of 2005, 107 households with BSFs were evaluated. The filters ranged from 1-5 years old and were part of a large-scale distribution of over 2000 filters in the region by a local hospital; Hôpital Albert Schweitzer (HAS), starting in 1999. Overall, the BSFs they tested averaged 98.5% removal efficiency of *E. coli* and 85% reduction in turbidity. Since 2005, additional BSFs have been distributed throughout the Artibonite Valley by HAS and other non-governmental organizations (NGOs).

We studied a group of 55 concrete BSFs distributed in the Artibonite Valley since 1999 to evaluate their sustained use and effectiveness. Our primary research goals were to determine BSF efficacy through water quality analysis and document BSF sustainability in the region through informal surveys (Sisson et al. 2012). This study presents efficacy data for filters still in use up to 12 years.

METHODS

Filter performance data were collected from homes throughout the Artibonite Valley during March, 2011. Our study area extended ~50 km up the valley to 14 communities and 55 BSF installations (Figure 3.1). While sampling was partially

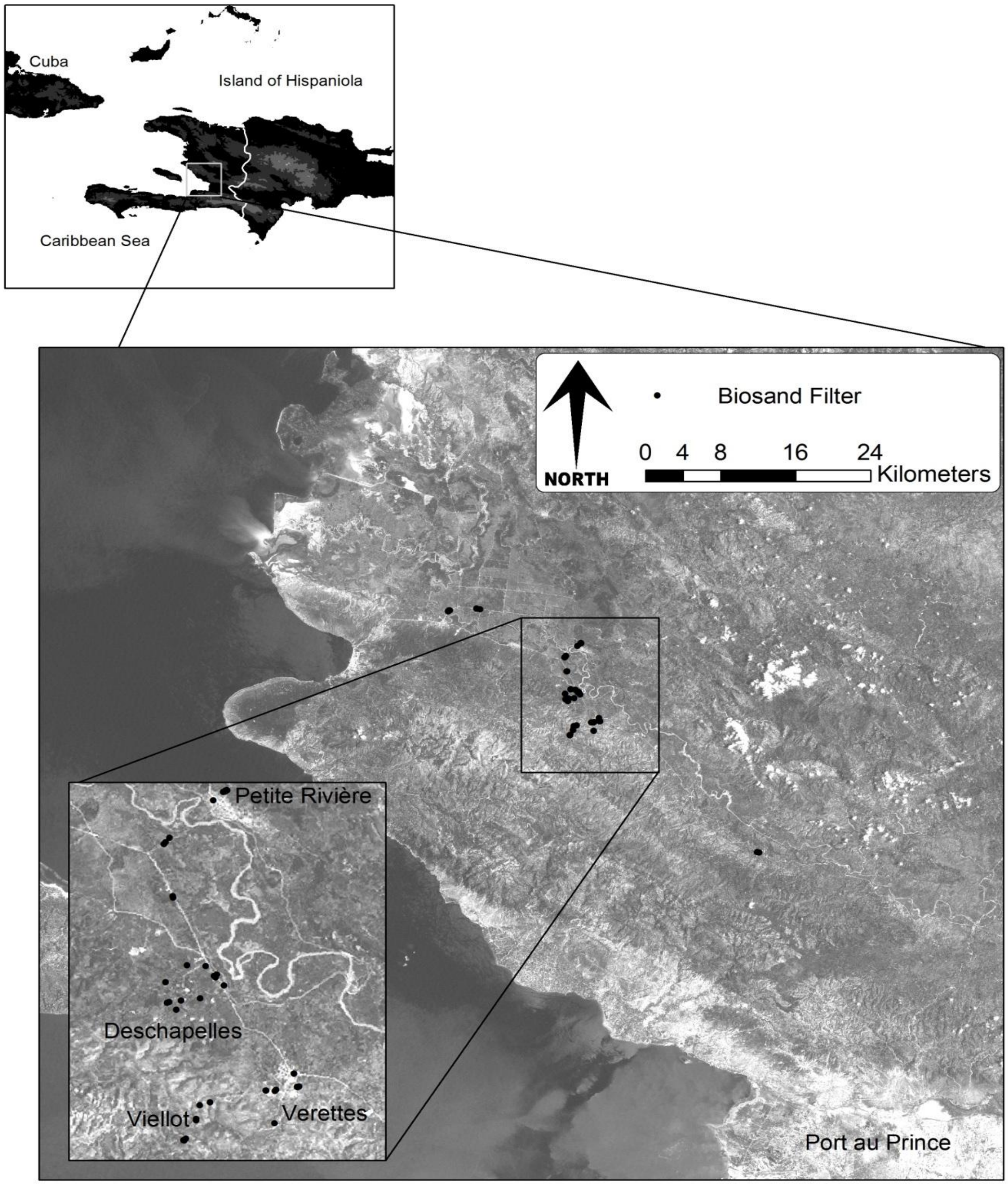

Figure 3.1. Map of the study area in Artibonite Valley, Haiti, showing locations of households with Biosand filters visited March 7-21, 2011.

convenience based, in each community, an effort was made to evaluate all filters that could be located, regardless of whether they were in use. Global Positioning System (GPS) locations were taken for each BSF using a hand-held Garmin GPSMAP 76Cx.

Our team included a microbiologist, a geologist, and a filter installation technician from HAS as an interpreter. HAS installation records and information from NGOs were used to obtain accurate installation dates. We were unable to determine whether filters we examined were included in the 2005 study by Duke et al. (2006). When non-functioning BSFs were encountered, the last date of operation was determined by questioning the primary filter user. Water quality, microbial analysis, and filter flow rates were evaluated at each functioning filter.

Water quality and microbial analysis

Three water samples were taken at each BSF location: one from the user's primary water source, one from BSF treated water, and one from stored filtered water (when available). An Oakton T-100 Turbidity Meter was used to measure turbidity. Water samples were analyzed for *E. coli* contamination using the IDEXX Colilert Quanti-Tray system (IDEXX Laboratories, Westbrook, ME). All water samples were collected in sterile Whirl-Pak® bags (NASCO: Atkinson, WI, USA) and stored on ice for no more than four hours before microbial analysis at the HAS Community Development Center laboratory. Samples were removed from ice and Colilert 18 reagent powder was added directly to samples in Whirl-Pak® bags and then incubated in sealed Quanti-Trays for 18-24 hours at at 35 ˚C (± 0.5). For purposes of quality assurance, sterile water blanks containing purchased bottled water were run with each batch of 10 samples. Blanks were also mixed with reagent powder in sterile Whirl-Pak® bags and run along with all water samples. Results of quality assurance tests were always negative for *E. coli* contamination and in only one case positive for total coliform. Positive results for total coliform alone do not indicate outside contamination of water samples by *E. coli*.

Statistical analysis

Colilert trays were counted manually for *E. coli*. The data were recorded in a Microsoft Excel spreadsheet (Microsoft Corp., Redmond, WA) as MPN/100 mL and were analyzed to determine the arithmetic mean and percent reductions between source water, filtered, and filtered-stored water. Because the number of MPN/100ml for the Colilert 2000 method is too numerous to count at 2419, the mean *E. coli* contamination of hand dug wells was calculated using the lowest probable accurate estimate in one instance (i.e., 2419), as we felt it necessary to still include this data.

Based on BSFs with installation dates ranging between 1999 and 2010, a Kaplan-Meier (KM) estimate of the survivor function for filter lifespan was computed using the `survfit()` function from the survival package of R statistical software, version 2.13.2 (R Development Core Team, 2011). The KM estimator is a non-parametric estimator of the survivor function (or complementary cumulative distribution function) for time-to-event data with censored observations (e.g., where some of the event times are known to exceed a particular value but the exact times are not known) (Kalbfleisch & Prentice 2002; Klein & Moeschberger 2003; Lawless 2003). It is most commonly used in medical and reliability statistics, but has also been shown to be an effective tool for other types of time-to-event data, such as seed germination times (McNair et al. 2012). In the present case, it provides a statistically sound estimate of the relationship between the probability that a BSF will still be in use and the time (years) since it was installed, while properly accounting for BSFs that were still in use when the data were collected (so the complete lifespans are not known). Output is given in tabular form and also graphically as a step function of time since installation, with decreases in the step function occurring at times when the use of one or more BSFs ended. Point-wise 95% confidence intervals for the survivor function are also given, along with the median BSF lifespan and its 95% confidence interval.

RESULTS

The 55 filters visited in 2011 had been installed by three organizations: HAS (n=41), Faith in Action International (FIAI) (n=9), and the Agency for Technical Cooperation and Development (ACTED) (n=5). Organizations started installing filters in 1999, 2006, and 2010 respectively. Only 53% of the filters were still in use (Table 3.1). Functioning filters ranged from <1 to 12 years old. All BSF users reported cleaning their filters, although only a few reported ever having a technician come to clean their filter for them, and none had been visited in the last several years. KM analysis revealed that the probability of a filter still being in use remains high (>85%) up to 7 years after installation, with several filters still in use after 12 years (Figure 3.2). The median duration of use was 9 years, with a 95% confidence interval of 8 to 11 years.

Table 3.1. Summary of Biosand filters visited in March, 2011 near Deschapelles Haiti.

Total BSF Visited	55
Total BSF in Use	53%
Median Years of Use	9
95% confidence interval of median (years)	(8, 11)
Oldest Working (years)	12 (n=3)
Newest Working (years)	<1 (n=2)
Average Maintenance (times/year)	3.4
Average Persons Served per Household	5.5

Flow rates ranged from 3 to 64 L/hr, while filtration reduced turbidity by 82% on average (Table 3.2). User source water types included undeveloped open springs, developed capped or piped springs, shallow hand-dug wells, and hand pump wells. Hand-dug wells/open springs had the highest level of *E. coli* contamination for source water at 290 MPN/100 mL. Limited contamination was found in source water from piped springs and hand-pumped wells. Filtered water from 25 filters (86%) contained *E. coli* concentrations of less than 0-10 MPN/100 mL. Recontamination of stored filtered water was negligible. In 11 cases, source water and filtered water had no detectable *E. coli*, while in 3 cases, the concentration of *E. coli* in filtered water exceeded that in source water (Table 3.3); data for these cases were excluded from removal efficacy calculations. The overall bacterial removal efficiency based on testing 14 filters was 94.7% with a standard error of 4.8% (Table 3.4). No stored water buckets had *E. coli* concentrations greater than 10 MPN/100 mL, and users often reported using a chlorination disinfectant after filtration and before drinking.

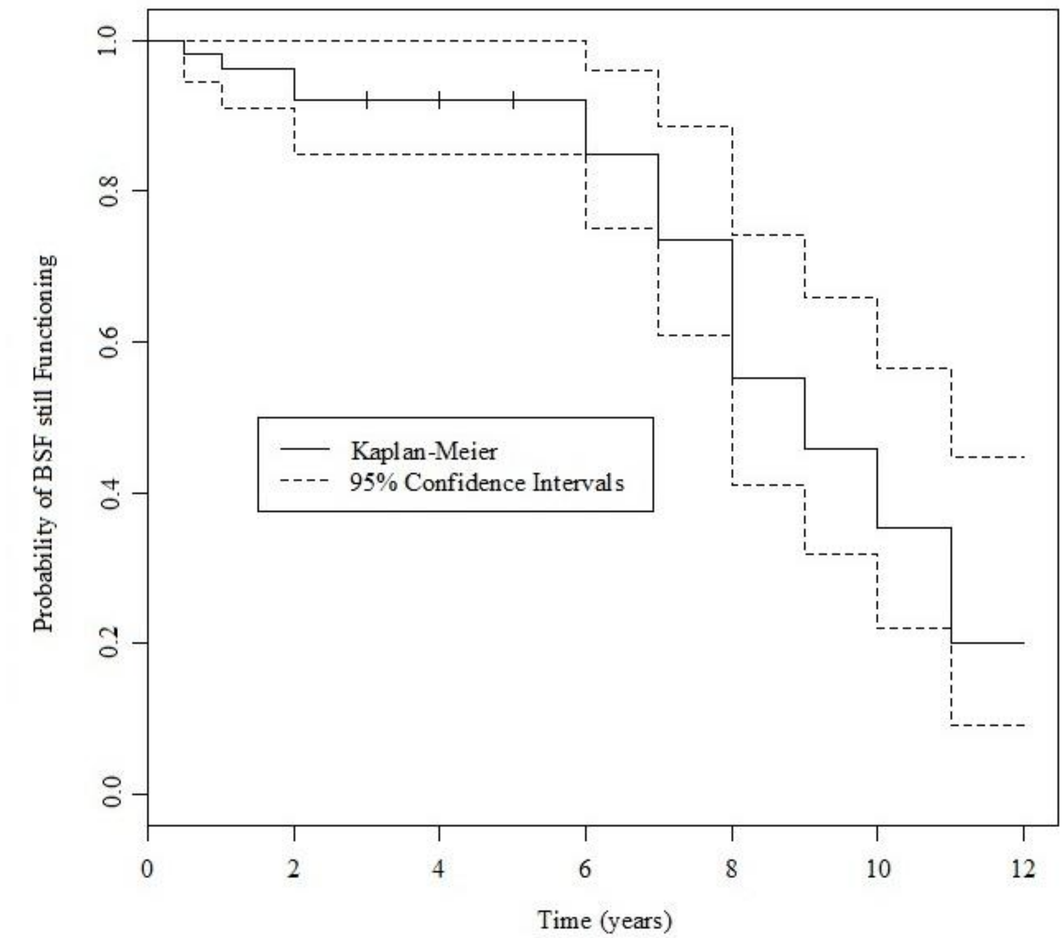

Figure 3.2. Kaplan-Meier survivor function showing the probability that a Biosand filter will still be in use versus time (years) since installation in the Artibonite Valley, Haiti. Analysis based on filter usage data collected in March, 2011, near Deschapelles, Haiti. Fate of filters after 12 years is unknown.

Table 3.2. Study results comparing Biosand filter data from Artibonite Valley, Haiti collected in March, 2011 with previously published data from Duke et al. (2006) collected in the same region.

	Duke et al. 2006	This Study, 2011
Persons per Household	5.4	6.0
Number of Households Visited	107	55
% Filters Still in Use	98%	53%
Filter Lifespan		
Range	1 - 5	<1 - 12
Flow Rate (Liters/hour)		
Range	11-95	3-64
Average	35	25
E. coli Levels		
Hand-dug Well/Open Spring	234	290*
Piped Spring/Deep Well	195	3
% Filtered water 0-10 MPN/100ml	97%	86%
Stored Filtered Water % >10 MPN/100ml	22%	0%
Overall Bacterial Removal Efficiency	98.5%	94.7%**
Turbidity		
Average Source Water	6.2	4.7
Average Filtered Water	0.9	0.9
Percent Reduction	85%	82%
Regularity of Post Chlorination	Never	Often

* Includes one well as 2419 MPN/100mL that was too numerous to count or > 2419.

** Excludes 11 filters which had no *E. coli* in either source water or filtered water and three filters which had higher contamination after filtration.

Table 3.3. Three Biosand filters tested near Deschapelles, Haiti not included in filtration efficiency data because concentration of *E. coli* (MPN/100mL) in filtered water exceeded that of source water.

Source Water Type	Source Water	Filtered Water	Percent Change
Hand-dug Well/Open Spring	61	387	-532%
Piped Spring/Pump Well	0	2	-200%
Hand-dug Well/Open Spring	24	45	-85%

Table 3.4. Source water E. *coli* concentrations and Biosand Filter removal efficiencies of 29 individual functioning filters tested in March 2011, near Deschapelles Haiti.

E. *coli* filtration Efficiencies			
Source Type	**Source Water**	**Filtered on Site**	**Percent Reduction**
Hand-dug Well/Open Spring	93	0	100%
Hand-dug Well/Open Spring	158	5	97%
Hand-dug Well/Open Spring	0	0	-
Hand-dug Well/Open Spring	7	0	100%
Hand-dug Well/Open Spring	41	0	100%
Hand-dug Well/Open Spring	24	5	-85%
Hand-dug Well/Open Spring	74	2	97%
Hand-dug Well/Open Spring	38	26	32%
Hand-dug Well/Open Spring	**TNTC**	64	-
Hand-dug Well/Open Spring	61	387	-532%
Hand-dug Well/Open Spring	548	0	100%
Hand-dug Well/Open Spring	548	0	100%
Piped Spring/Deep Well	12	0	100%
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	2	-200%
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	3	0	100%
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	12	0	100%
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	0	0	-
Piped Spring/Deep Well	20	0	100%
Piped Spring/Deep Well	2	0	100%
Piped Spring/Deep Well	0	0	-
Unknown	687	0	100%
Mean	83.2	16.7	94.7%
Standard Error	35.0	13	4.8%

Our data were compiled and descriptively compared to data collected by Duke et al. (2006) (Table 3.2). While the sample sizes were substantially different, many of the results of the two studies were similar. The average number of residents per home served by one BSF was roughly the same, as were the ranges of filter flow rates and *E. coli* and turbidity removal efficiencies. Sustained use of filters declined dramatically with increasing number of years of use (Duke et al. 2006). Duke et al. (2006) reported the mean years filters had been in use was 2.5 years, while our median was 9 years. When comparing source water *E. coli* contamination, we found similar levels of *E. coli* in hand-dug wells/open springs as reported by Duke et al. (2006). However, much lower levels of *E. coli* were found in piped springs/pump wells compared to those reported by Duke et al. (2006). In addition post-filtration use of chlorine disinfectant was more prevalent in our study.

DISCUSSION

The sustainability of BSFs was assessed in this study by examining statistical properties of the length of time they remained actively in use. Reasons for terminating the use of a BSF are numerous and include ant infestation, bad tasting water, filter clogging, and incompatibility of the technology with a user's lifestyle (Sisson et al. 2012). Thus, the fact that a BSF was no longer in use does not necessarily imply that it failed. As a result, estimates of sustainability in this study are probably conservative as estimates of time to failure and are more accurately viewed as estimates of time to filter disuse.

The main statistical tool employed in this study to assess BSF sustainability is the KM estimator of the survivor function for duration of use. As a nonparametric method, it makes no assumptions about the form of the survivor function and is asymptotically unbiased (Lawless 2003). To our knowledge, the present study is the first to employ this method of statistical time-to-event analysis (also known as survival analysis, reliability analysis, and failure-time analysis) to assess sustainability of POU filters. This class of statistical techniques also includes nonparametric methods for comparing groups (e.g., log-rank test), semi-parametric methods for assessing potential fixed effects of categorical and continuous covariates (e.g., Cox proportional hazards model and extensions) and for addressing random effects (frailty models), and fully parametric methods for all of these purposes (see McNair et al. 2012 for a concise review). These statistical methods have great potential in larger studies aimed at identifying key variables associated with increased or decreased lifespans of POU filters.

Results of the KM analysis revealed that cement BSFs installed in the Artibonite Valley have very high survivorship up to 7 years of use and that the sustainability of these filters is broadly consistent with data on duration of use reported by others (Aiken et al. 2011; Duke et al. 2006; Laing et al. 2010). When compared to other POU treatment technologies, BSFs have been shown to be more sustainable over time, with high rates of continued use in the Dominican Republic (90% after 1 year), Haiti (98.1% over 1 to 5 years), and Cambodia (87.1% over 1 to 8 years) (Aiken et al. 2011; Duke et al. 2006; Liang et al. 2010). The present study is the first to document filters still in use after 12 years. Taken together, results of the present and previous field studies of BSF use provide strong evidence for the sustainability of BSF technology.

While other studies have reported the mean years of BSF use, we caution that the mean is not an appropriate measure of central tendency for filter lifespan unless the complete lifespan of every filter is known (Duke et al. 2006; Liang et al. 2010). Because many of the filters we visited were still in use (for these, all that is known is that the lifespan is greater than the current duration of use at the time of sampling), we reported the median lifespan as a more appropriate representation of filter sustainability.

High rates of *E. coli* removal and turbidity reduction show that little or no decline has occurred in filtration efficacy over long-term use of the filters. These results also compare well with similar BSF field studies around the world (Aiken et al. 2011; Duke et al. 2006; Earwaker 2006; Fiore et al. 2008; Kaiser et al. 2002; Lee 2001; Liang et al. 2010; Sobsey et al. 2008; Stauber et al. 2006; Stauber et al. 2012; Vanderzwaag 2008). While flow rates were lower than those recorded in 2005, many users did not seem to mind and continued to clean and use their filters regularly, even though clogging was reported as leading to disuse in some filters (Sisson et al. 2012).

Filtered water was found with higher *E. coli* concentrations than source water in three instances. The cases with the highest contamination levels occurred in homes using hand dug wells within river alluvium as source water which may exhibit large fluctuations of E. *coli* levels on a day-today basis. However this can only be confirmed from further investigation. Time and logistic constraints in this study made it necessary to compare filtered water to source water contamination from the same day, though in actuality the filtered water was derived from source water used in the previous dosing. The majority of previous field studies of BSFs have employed a similar study design for the same reason (Duke et al. 2006; Fiore et al. 2008; Sobsey et al. 2008; Stauber et al. 2006). This study design assumes that source water levels of *E. coli* contamination do not change significantly from one dosing to the next. However, if source water from the previous dosing was much more highly contaminated than source water from the current dosing, then contamination could be higher in filtered water than in source water from the current dosing, even with 94% removal efficiency.

In the final case the contamination level of filtered water was still less than 10 MPN/100 mL and family noted they regularly use Aquatabs® for post filtration disinfectant. This result suggests that BSFs may not always be properly functioning, and may actually harbor and be a source of *E. coli,* although further research needs to be done to confirm this hypothesis. Other studies have also reported similar results of filters “increasing” the presence of *E. coli* in post-filtered water and note this phenomenon may also be explained by the study design (Brown et al. 2007; Fiore et al. 2010).

Many similarities were found between our data and data of Duke et al. (2006), despite our smaller sample size. It is likely that source water contamination levels of piped springs and pump wells were lower in our study because sources sampled may have been different between the studies, new wells may have been drilled since 2005 that we tested or because contamination levels may vary seasonally. The frequent use of post-filter chlorination, and in some cases pre-filter chlorination (noted only in our study), is likely explained by country-wide sanitation efforts after the outbreak of cholera in 2010 (Sisson et al. 2012). That Duke et al. (2006) found higher rates of filters still in use can possibly be explained by our KM analysis that did not show many filters going into disuse until after six years. Based on this result, had our study taken place after BSFs were installed for 1-5 years (range of filter use reported by Duke et al. 2006), it is likely that we would have found a comparably high proportion of filters still in use.

CONCLUSIONS

This study shows that BSF technology continues to be an effective and sustainable water treatment option for communities in the Artibonite Valley, Haiti. The results of 94.7% filter efficacy are broadly consistent with previous studies of field filtration efficiencies in Haiti and elsewhere but reveal that filters are effective and sustainable for longer periods than previously documented. Thus, while concerns have been expressed about prematurely scaling up BSF technology, studies continue to show that this technology is effective and sustainable in the field (Clasen 2009; Schmidt and Cairncross 2009).

This study also introduces the use of statistical time-to-event analysis as a tool for modeling BSF survivorship. This class of statistical methods should prove especially useful in larger studies aimed at identifying key variables that can be targeted to increase filter lifespans. Larger datasets with specific reasons for filters becoming inactive could be used in making the model more robust and possibly calculate probabilities for inactivity driven by those reasons. This information could prove to be influential in developing BSF implementation strategy that focuses on education and technical support in specific areas to ensure even greater efficiency, acceptability, and sustainability.

CHAPTER IV

TESTING FIELD PRACTICE OF THE BIOSAND WATER FILTRATION SYSTEM PERFORMANCE IN THE LABORATORY

ABSTRACT

A controlled laboratory study was conducted to test field use practices of the biosand water filter (BSF). A laboratory study was designed to examine the effects of two BSF usage scenarios observed during a separate field study in Haiti; daily filtering more water than the filter media pore space without a sufficient pause period and extended pause periods of 1 to 4 weeks. Six HydrAid® BSFs, were divided into groups of three replicates each to examine both scenarios. Filters in Group 1 were dosed with 15, 20, and 30, liters of water for two week periods each to test for significant differences in filtration efficiencies. Group 2 filters were dosed daily with 15 liters for two weeks, followed by once a week dosing for four weeks. This was followed by a one month non-use period, and then 16 days of daily dosing 15 liters to test the effects on extended pause periods of filtration efficiency. Significantly lower filtration efficiencies occurred when dosing volume exceeded the filter media pore space of 15 liters (p=0.000) and extended pause periods up to one month had negative effects on filtration efficiencies (<30 %) for at least 4 days before returning to more typical efficiencies (>98%; SE = .2%). Filter manuals should more accurately reflect the scientific literature that supports these results to limit the amount of potable water per 12 hour period to 15 liters and more strongly encourage daily use of filters.

Key words: Biosand filter, pause period, biofilm maturation, water supply

INTRODUCTION

Yearly, 1.87 million children under the age of five die of diarrheal illness largely due to inadequate access to safe drinking water (Boschi-Pinto et al. 2008). Contamination of drinking water, poor sanitation and hygiene combined are a major health risk in underdeveloped countries and are responsible for 88 percent of diarrheal disease in the world (WHO 2003). In an effort to improve access to clean water, many non-governmental organizations (NGOs) and aid agencies have turned to the Biosand filter (BSF) as an effective household water filtration technology (Sobsey et al., 2008; Clasen, 2008). The BSF treats small volumes of water by removing pathogens, viruses, and turbidity through ingestion by biofilm organisms, death to influent bacteria, adsorption to sand, and mechanical filtration mechanisms to provide a household with its daily water requirements (Elliot et al. 2008; Jellison et al. 2000).

The BSF is a modified version of the centuries old slow sand filtration technology, utilizing the source water's natural ecology, intermittent use, and the difference in gravitational head to force 'dirty' water through layers of sand to filter out contaminants. The filter consists of diffuser plate (hinders disruption of media below), a top layer of fine sand, a middle layer of coarse sand, and bottom layer of drainage gravel (Figure 4.1). When water is initially poured into the filter the water level will raise above the outlet pipe, creating a difference in hydraulic head and water naturally flows through the media pore spaces and out the outlet pipe until water level returns to the level of the outlet (~3-5cm above the sand layer). As water flows through the filter, naturally occurring particulate matter and bacteria are trapped in the top layer of sand where a biological layer (biofilm) forms after a period of ripening or maturation time, typically between 2-3

Figure 4.1. Profile view of the HydrAid® Biosand Filter manufactured by Cascade Engineering, Grand Rapids, Mi. Picture adapted from HydrAid® Manual.

weeks. While the majority of filtration happens through bacteriovary within the biofilm (uppermost 3-5cm of fine sand), enhanced filtration occurs deeper in the sand as "deep-bed media aging" or maturation occurs overtime (Elliot et al., 2008; Jellison et al. 2000)

The intermittent use of the BSF is the primary difference between it and its larger scale predecessor, the slow sand filter. The time between when water stops flowing out of the filter outlet until the next time water is poured (dosed) into the filter is known as the pause period. While optimal pause periods vary with the size of the filter, it has typically been shown to be between 12-24 hours (Baumgartner et al. 2007; Stauber et al. 2008). The duration of the pause period is a semi-delicate balance between providing sufficient contact time for microbial removal processes to take place while needing to provide an adequate amount of nutrients and oxygen with the inflow from a new dosing to support the biofilm (Baumgartner et al. 2007). During the pause period water is stored in pore spaces of the media. To obtain optimal filtration efficiencies the amount of media pore space volume should be enough to hold all the water dosed to the BSF without any of it coming out of the outlet until the next dosing of water (Kubare & Haarhoff 2010). Tracer tests indicate that water flows through BSFs exhibiting the characteristics of plug flow suggesting that if the amount of media pore space is equal to the volume of water dosed to the filter the entire volume will have roughly the same amount of retention time to be filtered (Kubare & Haarhoff 2010). Some evidence by Elliot et al. 2008 showed that filtration efficiency was compromised when the dosage volume exceeded 70% of the filter media pore space volume.

Since their development in the late 1980's by David Manz at the University of Calgary, Canada, an estimated 500,000 people use BSFs world-wide (Elliott et al. 2008). While most of these filters are housed in a concrete enclosure and are built on site, a plastic version of the filter known as the HydrAid® BSF is manufactured by Cascade Engineering in Grand Rapids, MI, USA. HydrAid® filters weigh significantly less and thus are easier to distribute, are less likely to break, and distributed with the filter media as an effective way to standardize the quality of filter media and media volume pore space, as opposed to the cement versions that mine the media on location.

Numerous field and laboratory studies have been undertaken to improve the design, evaluate BSF efficacy, and understand the mechanisms actively at work removing water contaminants. Such studies have analyzed the effective removal and reduction of *Escherichia coli* (*E. coli*) and other fecal coliform, protozoan parasites (*Cryptosporidium* oocysts and *Giardia* lamblia), viruses (Hepatitis A virus and echovirus 12), organic and inorganic toxicants, heavy metals, and turbidity (Bauer et al. 2011; Collin 2009; Duke et al. 2006; Earwaker 2006; Lee 2001; Lukacs 2001; Muhammad et al. 1997; Ngai 2003; Palmateer et al. 1999; Stuaber et al. 2006). A small summary of some of these studies and others can be found at the Center for Affordable Water and Sanitation Technology website (http://www.cawst.org/). However, conclusions of many controlled laboratory studies are limited in that they do not incorporate actual field use conditions. Operator practices may impact BSF functionality and efficiencies of filters used under sub-optimal field conditions; such as prolonged pause periods (>24 hrs) and regular dosing volumes greater than filter media pore space volume. Studying filters in the field over a long period of time also has limitations, due to the ability to control some variables such as consistency of use by the filter user once they realize they are being monitored. In order for laboratory experiments to more accurately represent field conditions, study protocols need to replicate the operational practices observed in home instillations in developing countries (Baumgartner et al. 2007; Stauber et al. 2006).

BSF distributing organizations typically train users on optimal usage patterns such as: daily use, avoiding frequent stop and re-start usage patterns, and often supply them with user manuals (CAWST 2010a; Hydraid 2010). However, during a field study of the BSF in Haiti during March 2011, filters were observed being used contrary to recommended protocols with pause period longer than one week and dosing volumes as much as 56 L/day. BSF users, noted that having to use the filter daily did not always work well with their lifestyle, which at times required them to be gone for a week or more and would require restarting the biolayer maturation process again. In other instances, filter users with larger families needed more than 15 liters of water in a day and would filter several buckets. Mathematical modeling and some laboratory studies have shown optimal parameters pertaining to pause periods and filter dosing; however, research that has examined the effects of pause periods beyond 36 hours on filtration efficiencies has not been conducted. In addition, questions still remain about the effect of dosage volumes in excess of a filter's media pore space. As a result, this study was designed to examine the effects of two common BSF usage scenarios observed in Haiti; routine filtering in excess of the filter media pore space and extended pause periods (1- 4 weeks). Using HydrAid® BSFs (Triple Quest Group, Cascade MI, USA), the experimental design was used to test if:

H_1: Daily filtering a greater volume of water than 15 liters (Experiment 1) will force breakthrough of bacterial contamination levels in the effluent water higher than influent water levels

H_2: Daily use of a BSF followed by an extended absence or non-use period of one week and one month (Experiment 2) will negatively impact filter performance and require a two week maturation period to re-establish a viable biofilm to and return optimal filtration potential.

METHODS

Prior to the start of the study six replicate HydrAid® BSFs were constructed according to recommended guidelines (HydrAid 2010). Filters were numbered 1-6 and dosed with roughly 60 liters of deionized water (when filtered water ran clear). Filters 3-6 had been used one year prior in a preliminary study and stored wet until this study. At the start of this study all filter flow rates were measured using the initial one liter of water through the filter from a full 15 liters dosing of deionized lab water. Similar flow rates between filters were obtained by adding or removing sand to each filter while maintaining 3-5cm of standing water (Table 4.1). Filters were kept in a small incubation room maintained at 26 °C.

Table 4.1. Filters categorized by group and hypothesis being tested. Initial filter flow rates measured for each filter using the first one liter of water through the filter from a full 15 liters dosing of deionized lab water.

Group	Filter	Initial Flow Rate (L/min)
Group 1 (H_1)	Filter 1	0.77
	Filter 2	0.76
	Filter 3	0.77
Group 2 (H_2)	Filter 4	0.72
	Filter 5	0.72
	Filter 6	0.68

In order to test multiple hypotheses, retain a reasonable sample size, and still allow for the determination of statistically valid effects, the study was conducted in three successive stages over a 12 week period. The stages consisted of a biofilm establishment stage, an experimental stage, and a final recommended use stage for each of two groups of three filters. All six filters were dosed daily with 15 liters of water for two weeks during the initial biofilm establishment stage (Figure 4.2). During the experimental stage, filters 1, 2, and 3 (Group 1) were run for two weeks and daily dosed with 15 liters of water, followed by two weeks of 20 liter daily dosages, followed by two weeks of 30 liter daily dosages. Because the HydrAid® filter only can be dosed with 15 liters at a time, water was added roughly every 10 minutes during 20 and 30 liter dosing volumes to maintain a relatively constant hydraulic head throughout the run.

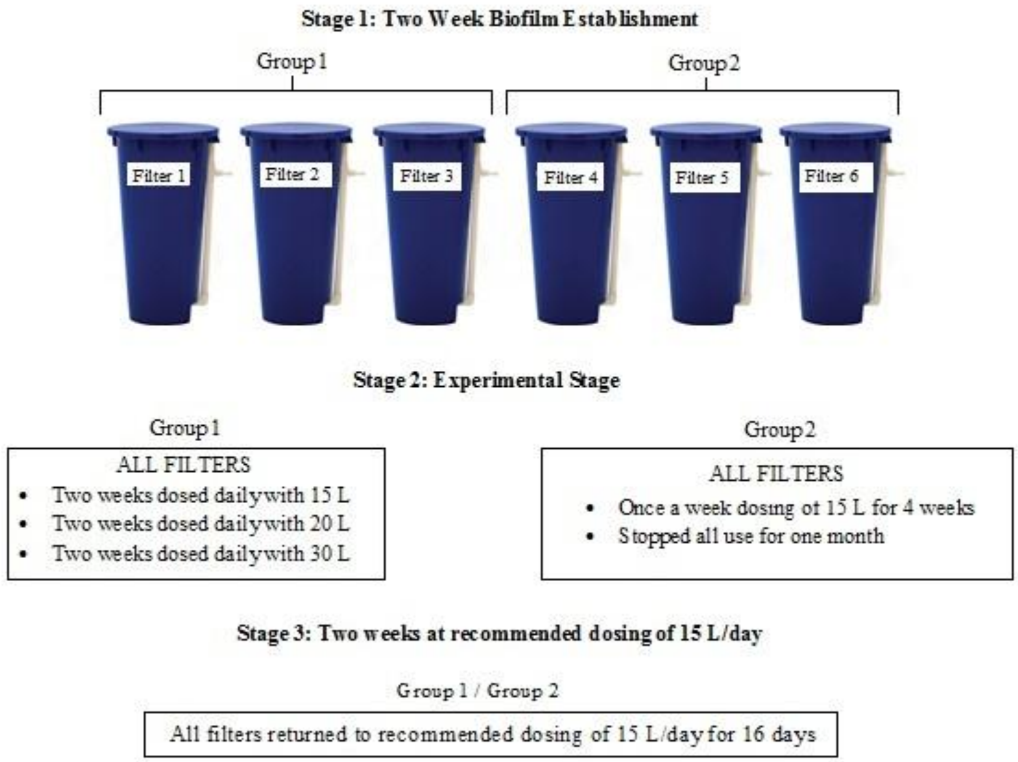

Figure 4.2. Study design using two groups of three replicate HydrAid® Biosand filters. All three filters underwent the same experimental treatment within their respective groups. All stages of the study simultaneously followed each other.

The experimental stage for filters 4, 5, and 6 (Group 2) consisted of dosing 15 liters once, weekly for four weeks. After the fourth weekly dosing these filters were not used again for one month. Immediately following both groups experimental stages, all six filters were returned to the recommended dosing of 15 liters daily for 16 days. The initial two weeks and final two weeks in this stage represent baseline filtration efficiencies for Group 1 filters. Because it takes longer to filter greater volumes of water, pause periods varied slightly throughout the study. During 15 liter dosing pause periods were roughly 22.5 hours; for 20 liters dosing, 22 hours and for 30 liters dosing, 21.5 hours.

Throughout the duration of the study samples of influent (prefilter) water and effluent (filtered) water from each filter was tested every other day for *E. coli*. Quality control was monitored by running a single laboratory blank each day samples were taken.

Microbiology and Filter Charging

In order to mimic the ecology that filters would develop from natural water, sources, water for all filter dosing was collected from mesotrophic Muskegon Lake (Muskegon County, MI. USA). Water was periodically pumped directly from the lake into a 500 gallon holding tank inside the Grand Valley State University Lake Michigan Center Field Station. From this storage tank, one-hundred liters was collected in a large Rubbermaid bin and transferred to the lab (140 liters of water was collected while testing Experiment 2 to account for the greater volume needed). Periodic 100mL samples of source water were tested for background *E. coli* contamination levels. These samples ranged from 0-7 MPN/100 mL. Source water temperatures ranged from 21-27 °C.

An artificially prepared spike of *E. coli* was used in an attempt to eliminate natural variances in source water source water *E. coli* levels. A prepared stock of *E. coli* was used to inoculate the 100 liters (140 L during stage 2) of water within the collection bin. Spiking methods followed the similar procedure as described by Stauber et al. 2006. *E. coli* strain B extracted from pure plate cultures was incubated at 35 °C in sterile tryptic soy broth contained in 10mL vials and grown to log phase overnight. From this overnight culture, 100 µl was pipetted into a new sterile 10 ml vial of tryptic soy broth and incubated for 1 hr at 35 °C. Next, between 276 and 500 µl of this culture was used to spike the 100 and 140 liters of Muskegon Lake water respectively, in attempt to obtain a source *water E. coli* level testable by the Idexx Colilert-18© (IDEXX Laboratories, Westbrook, ME). *E. coli* enriched "influent water" was dosed to each filter as prescribed above.

The microbial analysis utilized 100 mL water samples from the prefiltered influent water and each filter to analyze for *E. coli* contamination using the Idexx Colilert-18© method immediately after collection. This method has successfully been used to study drinking water contamination in previous investigations in Bangladesh and the Dominican Republic providing accurate results, without dilutions from 0-2418 MPN/100 mL (Fricker et al. 1997;Sobsey et al. 2002; Stauber et al. 2009). Water samples for microbial analysis of source water were collected after spiking of *E. coli* occurred and the entire bin of water was thoroughly stirred with a clean, large metal spoon. Effluent water from each filter was collected in individual 20 L buckets. Once the filters had stopped flowing, one 100 mL sample was collected from each bucket after thoroughly mixing the water. When more than 20 liters was dosed per filter two buckets were used and then thoroughly mixed back and forth between the buckets before a sample was taken for microbial analysis. All samples were collected in sterile Whirl-Pak® bags (NASCO: Atkinson, WI, USA).

Statistical Analysis

Colilert trays were enumerated manually for *E. coli* and filtration efficiency was calculated by comparing prefilter influent to post filtration effluent *E. coli* levels and reported as a percent removal. All statistical analyses were conducted using R statistical software, version 2.13.2 (R Development Core Team, 2011). Filtration efficiencies for Group 1 were not normally distributed, so a Friedman rank test was utilized to test for significant differences in filtration efficiencies based on experimental dosing volumes:15

L before, 20 L, 30 L, and 15 L after. A Friedman test was used as the non-parametric version of the random block design repeated measures 1-way ANOVA were the dosing volumes were considered blocks, the filter number (1, 2, or 3) was the treatment, and filtration efficiency was the dependent variable to test the null hypothesis that the distributions between filter efficiencies are the same across dosing volumes (α = 0.05). Post hoc analyses were conducted as paired Wilcox tests with correction for multiplicity (http://www.r-statistics.com). A repeated measures Friedman test was conducted to test for differences in filtration efficiencies between filters in group 2.

RESULTS

All blanks run for quality control were negative. Friedman rank analysis of group 1 showed a significant difference in filtration efficiencies between filter dosing volumes (Table 4.2; *p*=0.000). Post hoc multiple comparisons showed a significance increase in filtration efficiency occurred over time between 15 liter dosing before and after the experimental 20 and 30 liter dosing periods (Figure 4.3; Table 4.3). Multiple comparisons test also showed that no significant difference in filtration efficiency occurred between 20

Table 4.2. P-values for mulitple comparisions tests shows significant differences in *E. coli* filtration efficiencies of filters in Group 1 based on the volume of water dosed without a pause period (α =0.05). Overall Freidman test was significant at p-value was 0.000.

	20 Liters	30 Liters	15 After
15 Before	0.295	0.011*	0.003**
20 Liters	-	0.543	0.000**
30 Liters	-	-	0.000**

and 30 liters but both filtered significantly less efficiently than 15 liters. Comparisons between the 15 liter efficiencies before and after show that higher efficiencies are coupled with less variation over time.

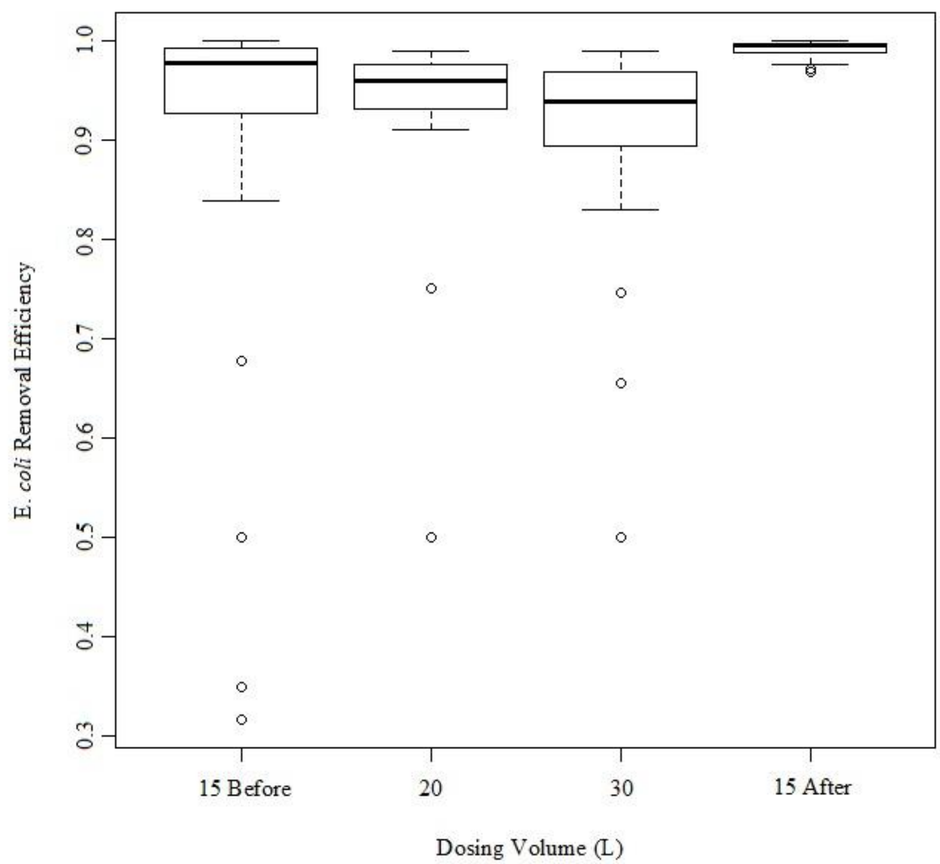

Figure 4.3. Group 1, HydrAid® Biosand filtration efficiencies of *E. coli* based on 2 week charging peroids at 15 liters before and after 20 and 30 liter dosing volumes.

Table 4.3. Summary statistics of Group 1, HydrAid® Biosand filtration efficiency boxplot Figure 4.3.

	15 Before	**20 Liters**	**30 Liters**	**15 After**
Minimum	0.839	0.910	0.830	0.976
Lower Quartile	0.926	0.931	0.894	0.987
Median	0.977	0.959	0.938	0.994
Upper Quartile	0.992	0.975	0.969	0.997
Maximum	1.000	0.989	0.988	1.000
Outliers	0.677, 0.5, 0.349, 0.317	0.75, 0.5, 0.5	0.747, 0.656, 0.5	0.971, 0.968

Filtration efficiencies in Group 2 filters were statistically similar (p=0.54) and differences in *E. coli* removal efficiencies were negligible between the initial dosing after the non-use period (Figure 4.4). No change in filtration efficiencies were seen after week one and four pause periods. Source water *E. coli* contamination for weeks two and three were too numerous to count so no filtration efficiencies were calculated. After the experimental pause periods, filtration efficiencies dropped substantially at days 2 and 4, and then recovered to similar pre-stoppage efficiencies by day 6 of the restart period. Filtration efficiencies for the 10 days prior to the extended pause periods averaged 99.9% (SE = 0.04%) and 99.1% (SE = 0.2%) for the10 days post extended pause periods starting at day 6 after re-start.

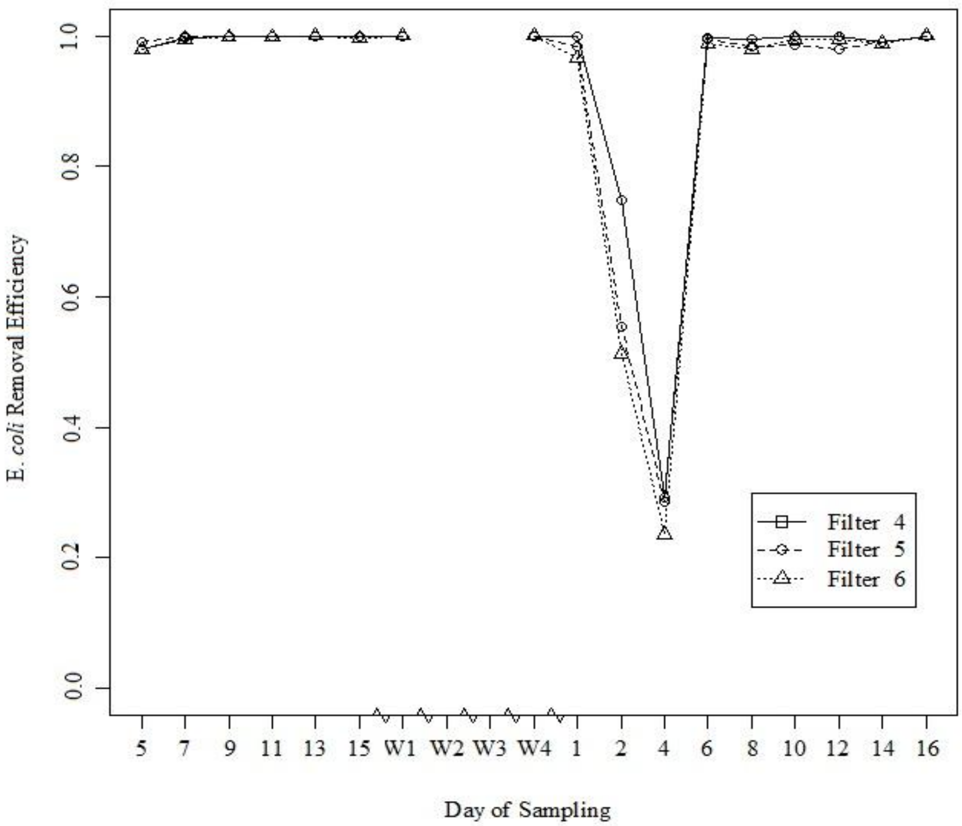

Figure 4.4. Group 2 filtration efficiencies of the HydrAid® Biosand filter during 10 days of use at 15 liters/per 22 hour pause period (typical use) interrupted by 4-one week pause periods with subsequent *E. coli* testing, followed by a one month pause period. After experimental pause periods, filters were returned to typical use for 16 days. Days 1- 6 indicate restart period.

DISCUSSION

A significant increase in filtration efficiency and reduced filtration variability before and after 20 and 30 liter experimental dosing volumes suggests that the biofilms had not fully developed by the start of the experimental period. This factor may also explain why the initial 15 liter dosing was not significantly different than at 20 liters but was at the 30 liter dosing. However, because the ending 15 liter efficiencies were significantly higher than for 20 and 30 liters, it is likely that biofilm maturation did occur, but only after an additional two weeks of filtration to the initial two week biofilm establishment period (total ~ 4 weeks). Although, only 5-14 days are stated as necessary for full biofilm maturity and effectiveness to be reached by the HydrAid® manual and to chlorinate effluent water before use during this time, our results and previous studies (Baumgartner et al. 2007; Elliot et al. 2008; Stauber et al. 2006; Tellen et al. 2010) suggest that filters may take up to four weeks or more for deep-bed ripening of the media to occur, that will increase and stabilize filtration efficiencies.

The high level of significance found between the ending 15 liter and 20 and 30 liter dosing volumes did not support the hypothesis that dosing greater volumes of water than the filter media pore space would force breakthrough of bacterial contamination levels in the effluent water higher than influent. However, the results do suggest that the filters capacity to remove *E. coli* decreases substantially when as little as 30% more water is dosed than the filter media pore space. A similar study by Elliot et al. (2008) found that removal of *E. coli* was compromised when the dosage volume exceeded 70%. Baumgartner et al. (2007) suggested that similar results between 10 and 20 liter sampling points were a factor of the greater hydraulic head from a larger dosing volume increasing the flow rate and thereby decreasing the amount of exposure to the biofilm and sand for filtration. However, their use of a Danvor BSF with a slightly larger design than the HydrAid® allowed them to dose the full 20 liters into the filter at one time, whereas the HydrAid® filter only can be dosed with 15 liters at time. As a result, the conclusion that the difference in hydraulic head may explain the significant decrease in filtration efficiency between 15, 20, and 30 liters in our study likely does not have a significant affect. Rather, it is more likely that decreases in filtration efficiency are due to the additional water, beyond the first 15 liters, that did not have an adequate time for the biological filtration mechanism to significantly reduce the *E. coli* levels.

Similarities of Group 2 filtration efficiencies before and after the non-use period suggest that the filter's biofilms had matured by the time of the non-use period (~2 week). Filters 4, 5, and 6 previously were used in an experiment a year prior to this study and stored wet. This group of filers had a faster maturation time with little variation in filtration efficiency. Rather than perceiving the two-week maturation time shown by these filters as typical for biofilm establishment, it is more likely a result of deep-bed ripening from the prior year reestablishing itself. Therefore, a more typical time to establish a viable biofilm is shown by the Group 1 filters and similar to times suggested by others (Baumgartner et al. 2007; Stauber et al. 2006).

Substantial decreases in filtration efficiencies for up to four days after re-starting the filters suggest that the biofilm viability was compromised during the non-use period and required replenishment of oxygen and nutrients to return viability and 'typical' filtration efficiencies. Contrary to the initial hypothesis of two week being required, this process only took between 4-6 days.

Interestingly, no change in filtration efficiency was seen from the initial day of re-starting the filters and as far as I know, no other published data has ever noted this. This observation may be because the first 15 liters of filtered water collected on day 1 of the re-start had been sitting in the filter for the duration of the non-use period and therefore filtration efficiency was similar to typical filtration. As a result the impact of the non-use period was not noticeable until a second 15 liters is dosed or at day two. Therefore filtration efficiencies from the second 15 liters through the filters are more representative of how the biofilms were compromised from non-use periods. This also is the most probable reason why no change in filtration efficiencies was noticed when testing at week 1 and week 4 of the weekly non-use periods.

CONCLUSIONS

The results from Group 1 filters illustrate the importance of both allowing BSFs to fully mature for at least 3-4 weeks before considering water as potable and only dosing the volume of water which can be held within the filter's media pore space. If additional water is needed, user's should be advised not to ingest the water unless used in conjunction with other household water treatment methods (i.e. chlorination) and to allow at least a 12 hour pause period after the filter stops (Baumgartner et al. 2006) before assuming the water is potable again. Based on the observed reduction in filtration efficiencies after extended pause periods in Group 2 filters, extreme caution should be taken by users when using their BSFs after long periods when filters have not remained in continual daily use. Biosand filter distributors should continue to encourage daily use of filters, even if this requires asking a neighbor to dose the filter while the owner is away for extended periods. Distributors should also discourage drinking the water if filters have not been in use for periods up to four weeks or more without additional filtration or recommend the use of a postfiltration disinfectant.

Finally, the current BSF user instruction manuals fail to clearly convey the scientific findings previously published and described here regarding the important balance between allowing for adequate pause periods and filtering more than the media pore space volume. Both HydrAid® and CAWST manuals should more accurately note that only the initial volume of water equivalent to the media pore space can be used for drinking without additional filtration or disinfectants. They should also note that even after allowing for a minimum pause period of 12 hours only 30 liters of water/day would be optimally filtered, rather than the 40 liters suggested. Unless these manuals accurately incorporate the scientific literature into user training instructions, users may not be provided with the best service possible and may put at unnecessary health risk for drinking water they perceive as safe.

CHAPTER V

CONCULSIONS AND RECOMMENDATIONS

A large number of individuals, organizations, and governments have tried to understand the complexity of the problems facing Haitians and the greater issue of providing clean water to areas of the poorest nations of the world. Without negating many good efforts and outcomes from years of aid and development work, it is important to evaluate how much these efforts have helped and determine how their effectiveness can be improved. If done improperly or insufficiently, international development work can be more harmful than helpful, as evident from the UN relief efforts leading to a devastating Cholera epidemic in Haiti. There continues to be a data gap with only few long-term studies on the BSF, the lack of incorporating ethnographic studies, and differences in field use practices compared to controlled laboratory practices. Differences in field operator practices may impact BSF functionality and efficiencies of filters used under sub-optimal field conditions; such as prolonged pause periods (>24 hrs.) and regular dosing volumes greater than filter media pore space volume. In order to avoid implementation problems and provide access to clean water in an efficient manner, it is critical to conduct field studies that monitor the effectiveness of interventions, evaluate water treatment technologies with respect to user lifestyle, and develop new approaches to provide clean water on a sustainable basis.

In Chapter 2, we examined the long term use and sustainability of 55 BSF systems in the Artibonite Valley near Deschapelles, Haiti. Of the 55 BSFs visited, 47% were no longer in use. Interviews with BSF owners revealed problems related to intermittent filter use due to travel for employment or personal matters; broken or missing filter parts; and fears that the filter would not be effective against cholera. A review of 17 BSF field studies also was included to compare and substantiate observations made in Haiti. Together, previous field studies and our observations point toward the importance of providing culturally appropriate technologies and education materials explaining proper maintenance and operation are essential for improved filter performance and sustainability.

In Chapter 3, we assessed the *E. coli* removal efficiency of the 29 functioning BSFs studied in Haiti. Filtered water from 86% of functioning filters contained *E. coli* concentrations of less than 0-10 MPN/100 mL. Recontamination of stored filtered water was negligible and bacterial removal efficiency was 94.7% (SE = 4.8%).The duration of filter use (lifespan) ranged from <1 to 12 years. Water quality, microbial analysis, and flow rate were evaluated for each functioning filter. Kaplan-Meier analysis of filter lifespans revealed that filter usage remained high (>85%) up to 7 years after installation. Several filters were still in use after 12 years, which is longer than documented in any previous study. Comparable results from previous studies in the same region and elsewhere show that BSF technology continues to be an effective and sustainable water treatment method in developing countries world-wide.

Finally in Chapter 4, we conducted controlled laboratory experiments to analyze filtration efficiencies of the HydrAid® BSF using two field use practices observed while in Haiti that differed from recommended BSF practice: daily filtering more water than the filter media pore space without a sufficient pause period and extended pause periods of 1 to 4 weeks. Six HydrAid® BSFs, were utilized in two groups of three replicates each to examine both scenarios. We found significantly lower filtration efficiencies occurred when dosing volume exceeded the filter media pore space of 15 liters and extended pause periods up to one month had negative effects on filtration efficiencies for about 4 days before returning to normal. Recommendations were made that filter manuals should more accurately reflect the scientific literature that supports these results to limit the amount of potable water per 12 hour period to 15 liters and more strongly encourage daily use of filters without extended pause periods. My research demonstrates that the BSF technology continues to be an effective and sustainable water treatment option for communities in the Artibonite Valley, Haiti. The results of 94.7% filter efficacy (Chapter 3) are broadly consistent with previous studies of field filtration efficiencies in Haiti and world-wide. While concerns have been expressed about prematurely scaling up BSF technology, studies continue to show that this technology is effective and sustainable in the field. Therefore, in the following recommendations I do not try to rewrite how BSF distributors implement their projects. Rather, I aim to summarize the research presented here into practical guidelines that will hopefully enhance BSF manuals and increase long-term BSF sustainability, filter functioning efficiency, and protect against failing BSF implementation projects.

RECOMMENDATIONS

Insights gained through the literature review and field and lab studies indicate four areas that should be reinforced in current BSF project areas and implemented in future BSF projects to increase filter longevity and provide the greatest benefit to users:

1) Distributors should provide educational and technical support upon distribution and throughout a project's lifetime and should include:
   - Standardized recommended usage instructions should be designed and implemented for use by all BSF distributors.
   - Educational materials in native languages with pictorial depictions for illiterate populations.
   - The importance of daily usage and proper cleaning practices over long-term use.
   - The importance of the initial 3-4 week start-up period for more complete biofilm maturation and proper combined usage with Clorox disinfectant powder.
   - Information regarding the decreased water quality with dosing volumes beyond the filter's media pore space. This should be made clear to users and use of this water for drinking purposes should be done only in conjunction with additional disinfection.
   - The importance of allowing at least a 12 hour pause period after the filter stops, before assuming the water is potable again.
   - Educating users to take caution when using their BSF after long periods of inactivity.
2) Distributors continually should seek a better understanding of geographic region, changing societal needs, cultural beliefs, and lifestyle habits in relation to BSF suitability and sustainability in a given area.
   - Assess family lifestyle needs to provide most appropriate technology

- Seek individual and household understanding and beliefs of safe water, hygiene, and sanitation practices regarding illness and disease contraction.
- Study water resources from an ecological, biological, geological, and anthropological context by region.
- Develop an adaptable distribution plan that can meet the individual needs of all the families in a community and provide the most appropriate and sustainable solution to meet clean water needs.

3) BSF distribution should be done through collaborative partnerships with established community groups, local governments, and other organizations working in similar regions.
    - This could help maintain long-term finical and technical support sustainability.
    - Rely more on a community empowerment model utilizing the community's assets and strengths rather than an emergency relief model of giving and leaving.
4) Use of statistical time-to-event analysis as a tool for modeling BSF survivorship and possible transfer to other POU technologies.
    - A time-to-event analysis has considerable potential for use in larger studies aimed at identifying key variables that to target for increased filter lifespans.
    - Information gathered from larger datasets using this statistical approach could prove to be influential in developing focused BSF implementation

strategies in specific areas to ensure even greater efficiency, acceptability, and sustainability.

While these recommendations address BSF sustainability and distribution on a general and practical level, they do not adequately substantiate the importance of understanding the culture of group being served from an ethnographic perspective. This represents an essential framework that needs to be more clearly understood before effective strides forward can be made. Personal ethnographic observations not presented here, regarding water, sanitation and hygiene practices in the Artibonite Valley indicate poor infrastructure and the "deaf ear" to the voice of the Haitian people by the international aid community. Inadequate sanitation services and infrastructure point toward historical collapse and turmoil at a higher societal level than individuals. The lack of an effective government is evident in all aspects of the Haitian society. The current state of Haitian water, sanitation, and hygiene requires a stabilized government and a national water and sanitation board that will work at providing and maintaining infrastructure for decades, which to note has only recently started and is making impressive strides (DINEPA). Currently, open canals, which collect sewage and trash and pollute rivers as well as connect individual health problems in smaller towns to larger regions still, are common place. While infrastructure, improved sanitation and water systems are a necessary portion of the equation to providing a safer environment and life for Haitians, a more bottom-up approach also needs to be taken.

In my travels to Haiti, I have realized that while many Haitian's are faced with the same problems, have similar histories, beliefs, and culture; each person has a different perspective. Conversations with both rural mountainous and semi-rural valley dwelling

Haitians revealed discrepancies in their understanding of the connection between safe water, improved sanitation and hygiene practices. As a result, aid efforts should focus on a combination of education and intervention with this segment of Haitian society. Assistance needs to be provided at both individual and community levels which can be replicated regionally and nationally. By promoting group discussions that allow Haitian communities to share what they believe; how they perceive a situation or topics such as water and sanitation; and how they think changes should be made, the role of aid workers changes from doing the work for Haitians or to Haitians to empowering, encouraging and enabling Haitians to seek solutions themselves; promote education about safe drinking water; and practice improved sanitation and hygiene techniques. Giving ownership of the change to Haitians, rather than transitory international aid workers, will facilitate growth of individual, community and national pride. Only this approach will lead to long lasting and sustainable solutions to inadequate water, sanitation, hygiene and the many other challenges that Haiti faces. It is often apparent that development work has been attempted without utilizing the best assets of Haiti, its people. If this continues, I am concerned that lasting improvements will remain unrealized and that aid will continue be applied like a temporary Band-Aid to a wound that will fall off before the healing process is effective.

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