

Long-Term Field Performance of Biosand Filters in the Artibonite Valley, Haiti

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Abstract. A field study assessing the sustainability and efficacy of 55 biosand filters installed during 1999–2010 was conducted in the Artibonite Valley, Haiti during 2011. Twenty-nine filters were still in use. Duration of filter use 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 showed that filter use remained high (> 85%) up to seven 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 *Escherichia coli* concentrations of < 10 most probable number of coliforms/100 mL. Recontamination of stored filtered water was negligible. Bacterial removal efficiency was 1.1 log₁₀. Comparable results from previous studies in the same region and elsewhere show that biosand filter technology continues to be an effective and sustainable water treatment method in developing countries worldwide.

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 780 million persons, approximately 11% of the world population, do not have access to safe drinking water.¹ 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.² Several studies have shown that interventions that improve water quality can reduce diarrheal disease morbidity by more than 30%.^{3–5}

As international aid organizations and government programs focus on providing adequate water resources to the millions of persons without these resources, many have turned to household or point-of-use (POU) water treatment methods and water filtration.^{1,6,7} Biosand filters (BSFs) are one of the most widely used POU treatments.^{7,8} First installed in Nicaragua in 1993, BSFs are estimated to be used by nearly 500,000 persons worldwide.⁸

Biosand filters 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,^{6,7,9} in which sustainability refers to the length of time a filter is likely to remain in use when adequately maintained. These filters have been shown to effectively remove up to 90% of viruses, > 99.9% of protozoa and helminthes, 90–98.5% of *Escherichia coli*, and up to 85% of turbidity.^{4–6,9,10} However, although BSFs use 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.^{11–13} As a result, there is currently little empirical evidence that BSF technology is effective and sustainable in the long term.

In 2005, Duke and others⁶ conducted one of the first long-term field studies of cement BSFs in the Artibonite Valley,

Haiti. During February–March 2005, 107 households with BSFs were evaluated. The filters ranged in age from one to five years and were part of a large-scale distribution of more than 2,000 filters in the region by a local hospital, Hôpital Albert Schweitzer (HAS), starting in 1999 through 2005. 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 non-randomized sample of 55 concrete BSFs distributed in the Artibonite Valley, near Deschapelles, Haiti, 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 and a novel statistical analysis. This study presents efficacy data for filters still in use up to 12 years.

METHODS

Performance data were collected from non-randomized sampling of homes located throughout the Artibonite Valley near Deschapelles, during March 2011 under Institutional Review Board protocol no. 174200. Our study area extended from Liancourt up the valley to La Chapelles (< 50 km) and encompassed 14 communities and 55 BSF installations (Figure 1). Most communities were located within 16 km of Deschapelles, and the furthest sample point was 30 km away.

The sampling design was similar to that of Duke and others⁶ in their 2005 study of the Artibonite Valley. We initially consulted HAS personnel and BSF distribution records to identify communities with several BSFs. Homes were then selected using what is known as referral sampling (snowball sampling or link-tracing), which is a non-random sampling design often used when sampling hard-to-reach or hidden populations.^{14,15} Specific homes with BSFs were selected based on information from HAS and NGO records, and by 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 (approximately four filters), and a few larger communities were assessed for a full day (i.e., Deschapelles and Petite Riviere). All visits were unannounced. This resulted in

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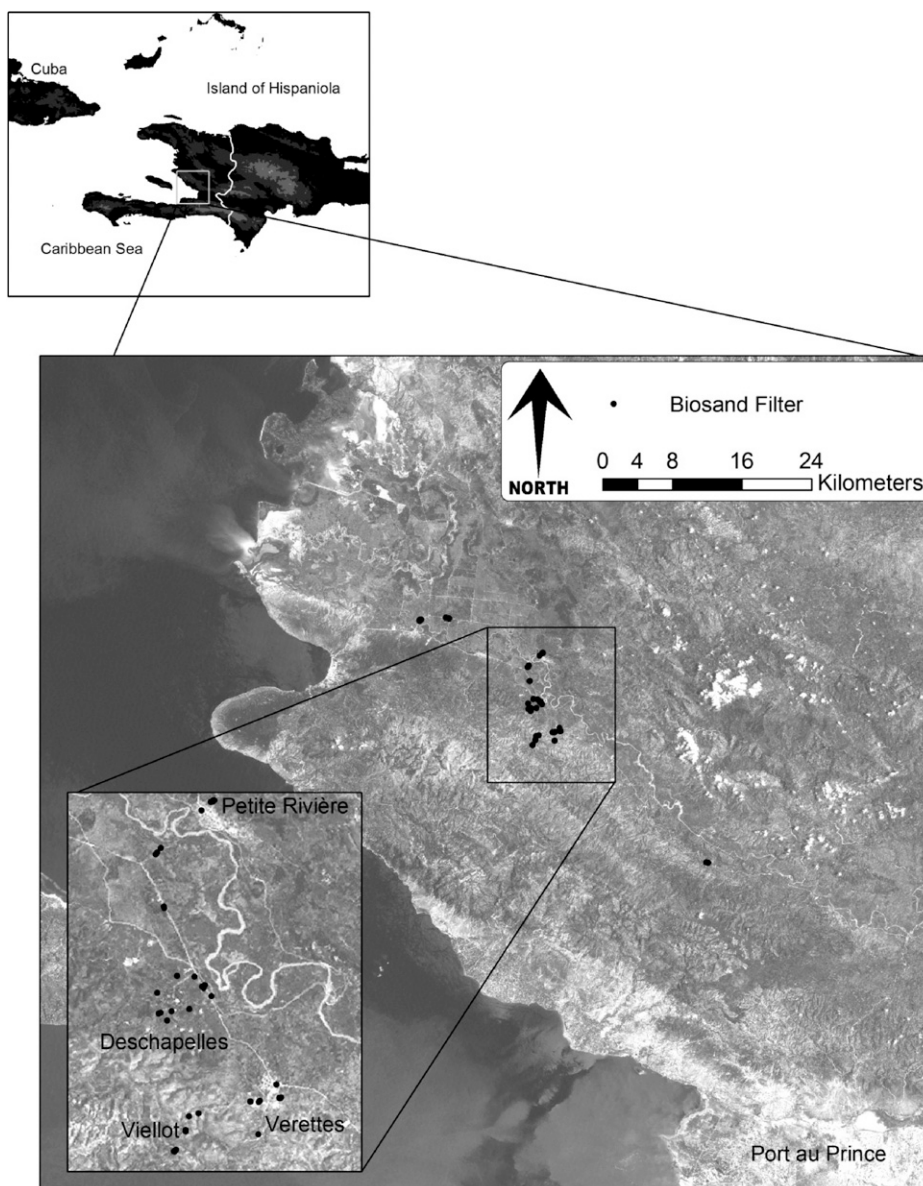


FIGURE 1. Map of the study area in Artibonite Valley, Haiti, showing locations of households with Biosand filters visited March 7–21, 2011.

55 total BSFs assessed, which fell into two categories, filters that were still in use and filters that were no longer in use. Duration of use for filters that were still in use is equivalent to the date of study minus the date of installation. Installation dates were primarily found by using HAS installation records ($n = 41$), NGO information ($n = 9$), and in some cases filter user reporting ($n = 5$). For filters that were not in use, the duration of filter use was calculated as the reported year in which use ended minus the installation year. The main source of uncertainty was the reported end date, which depended on user recall. Global positioning system locations were taken for each BSF by using a hand-held Garmin GPSMAP 76Cx (Garmin, Olathe, KS).

Our team included a microbiologist, a geologist, and a filter installation technician from HAS as an interpreter. The 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 and others.⁶ Water quality, microbial analysis, and filter flow rates were evaluated at each functioning filter. Flow rates were measured by collecting the volume of water through each filter in the initial minute after being dosed.

Water quality and microbial analysis. Three water samples were taken at each BSF location: one from the user's primary water source, one from the initial one liter of BSF-treated water immediately after dosing, 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 by using the IDEXX Colilert Quanti-Tray System (IDEXX Laboratories, Westbrook, ME). All water samples were collected in sterile Whirl-Pak[®] bags (NASCO, Atkinson, WI) 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 medium

was added directly to samples in Whirl-Pak[®] bags and then incubated in sealed Quanti-Trays for 18–24 hours at $35 \pm 0.5^\circ\text{C}$. For purposes of quality assurance, sterile water blanks containing purchased bottled water were tested with each batch of 10 samples. Blanks also were mixed with medium in sterile Whirl-Pak bags[®] and tested along with all water samples. Results of quality assurance tests were always negative for *E. coli* contamination and in only one case were positive for total coliform. Positive results for total coliform alone do not indicate outside contamination of water samples by *E. coli*.

Statistical analysis. Based on BSFs with installation dates ranging between 1999 and 2010, a Kaplan-Meier (KM) estimate of the survivor function for duration of filter use was computed by 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 (i.e., event times known to exceed a particular value but whose exact values are not known).^{16–18} 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.¹⁹ In the present case, it provides a statistically sound estimate of the relationship between the probability that a BSF is still in use and the time (years) since it was installed, properly accounting for BSFs that were still in use when the data were collected (so the duration of use is censored). Output is produced 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. The median BSF lifespan and point-wise 95% confidence intervals for the survivor function were also computed.

The years in which filters were installed were known, but the years in which filter use ended were based on recall by residents. To determine whether recall error is likely to have seriously reduced accuracy of the estimated survivor function and median duration of use, we conducted a Monte Carlo simulation to assess the degree of uncertainty in these estimates caused by recall error. Because we considered it likely that recalled event times were accurate to within ± 1 year, we generated perturbed data sets by adding -1 , 0 , or $+1$ with equal probability to each observed event time. Two exceptions were necessary to avoid creating impossible perturbed event times. For real event times of 1 year, 0 or $+1$ was added with equal probability. For real events occurring in the study year, -1 or 0 was added with equal probability. Once a perturbed data set was generated, the KM survivor function was estimated, and the median duration of filter use was computed. This procedure was repeated 4,000 times. The 5th and 95th percentiles of the 4,000 survival probabilities for each duration of filter use (1, 2, 3, ..., 12 years) were computed and plotted along with the KM estimate of the survivor function for the original data, and the relative frequency distribution of the medians was computed and plotted. The 5th and 95th percentiles of the 4,000 survivor functions for the perturbed data sets provide an uncertainty envelope for the original KM estimate, and give a good sense of the degree of uncertainty caused by recall error in the original estimate. Similarly, the distribution of the 4,000 medians gives a good

TABLE 1

Characteristics of Biosand filters visited in the Artibonite Valley, near Deschapelles Haiti, March 2011*

Characteristic	Value
No. BSF visited	55
% BSF in use	53
Median BSF lifespan, years	10
Oldest working, years	12 (n = 3)
Newest working, years	< 1 (n = 2)
Average maintenance (times/year)	3.4
Average no. persons served per household	5.5

*BSF = biosand filter.

sense of the uncertainty in the original estimate of the median duration of use.

RESULTS

The 55 filters visited in 2011 had been installed by three organizations: HAS (n = 41), Faith in Action International (FAI) (n = 9), and the Agency for Technical Cooperation and Development (ACTED) (n = 5). These organizations started installing filters in 1999, 2006, and 2010 respectively. Only 53% of the filters were still in use (Table 1). Functioning filters ranged from < 1 to 12 years of age. 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.

The KM analysis showed that the probability of a filter still being in use exceeded 80% up to 5 years after installation and was nearly 40% at 12 years (Figure 2), with the median duration of use being 10 years (Table 1). Our assessment of uncertainty in the estimated survivor function caused by recall error showed that the uncertainty envelope around the original KM estimate is much narrower than the point-wise 95% confidence intervals (Figure 3, left panel). The distribution of medians in the uncertainty assessment shows a range of 9–11, with nearly 90% of the 4,000 perturbed data sets having the same median (10) as the original data (Figure 3, right panel).

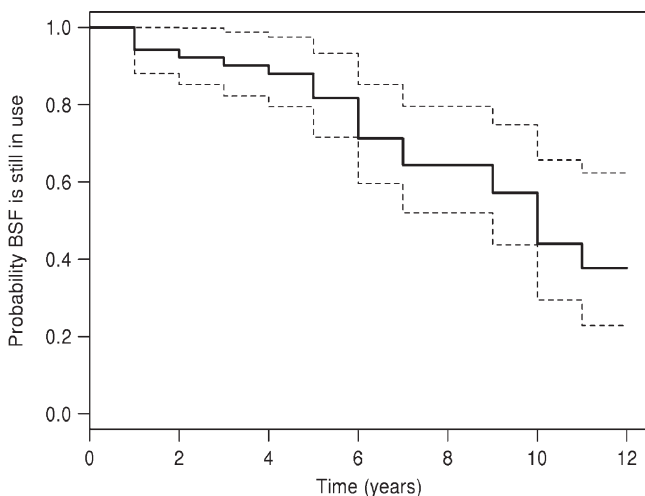


FIGURE 2. Kaplan-Meier estimate of the survivor function (solid line) and pointwise 95% confidence intervals (dashed lines) for Biosand filters (BSFs) in the Artibonite Valley, Haiti. The survivor function indicates the probability that a Biosand filter is still in use as a function of time since installation. The fate of filters still in use after 12 years is unknown.

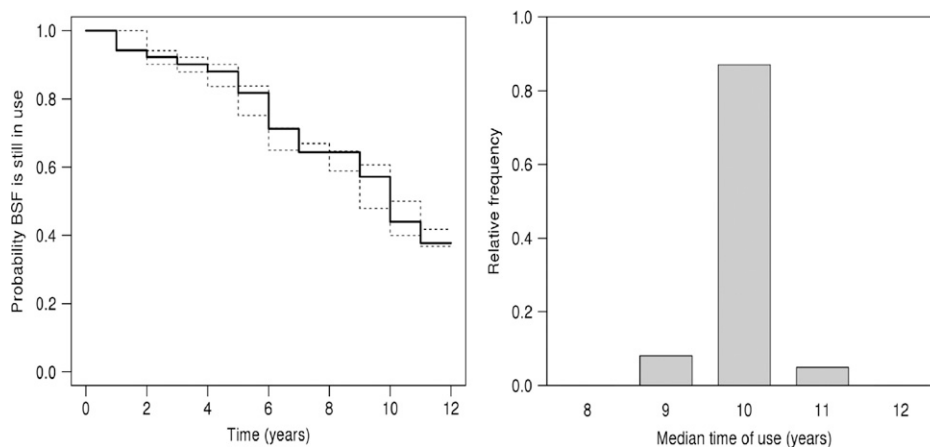


FIGURE 3. Assessment of uncertainty in the Kaplan-Meier survivor function and the median duration of Biosand filter (BSF) use caused by error in recalling the year of filter termination. The left panel shows the original Kaplan-Meier survivor function (solid line) bracketed by the 5th and 95th percentiles of 4,000 Kaplan-Meier survivor functions computed for random perturbations of the original data (dashed lines). The right panel shows the relative frequency distribution of the 4,000 medians computed for these same perturbed data sets. The median duration of filter use in the original data set is 10 years.

Both of these uncertainty results suggest that recall error had only a minor effect on the original KM analysis.

User source water types included undeveloped open springs, developed capped or piped springs, shallow hand-dug wells, and hand pump wells (Table 2). Hand-dug wells/open springs had the highest level of *E. coli* contamination for source water with a geometric mean of 87 most probable number of coliforms (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 < 10 MPN/100 mL (Table 2). Recontamination of stored filtered water was negligible. In 11 cases, source water and filtered water had no detectable *E. coli*. These data were not included in overall removal efficiency calculations because there were 0 MPN in the pre-filtered source water and a 0 MPN in BSF filtered water. Therefore, calculating removal efficiencies for these 11 filters and including them in the overall efficiency data was not meaningful. The overall bacterial removal efficiency (1.1 log₁₀ or 92%) was based on the remaining 18 filters, including the data of three filters that had higher concentrations of *E. coli* in filtered water than in

source water (Table 3). No stored water buckets had *E. coli* concentrations > 10 MPN/100 mL. In 41% of the households, chlorination was used in conjunction with the BSF. Flow rates ranged from 3 to 64 liters/hour, and filtration reduced turbidity by 82% (Table 2).

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 ceasing to use a BSF are numerous and include ant infestation, bad tasting water, filter clogging, and incompatibility of the technology with a user's lifestyle.²⁰ Thus, the fact that a BSF was no longer in use does not 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 used 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.¹⁸ To our knowledge, the present study is the first to use 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), semiparametric methods for assessing potential fixed effects of categorical and continuous covariates (e.g., Cox proportional hazards model and extensions) and for addressing random

TABLE 2

Biosand filter statistics and source water quality data collected in the Artibonite Valley, near Deschapelles Haiti, collected in March 2011*

Characteristic	Value
Flow rate (liters/hour)	
Range	3–64
Average	25.1
<i>Escherichia coli</i> levels	
Hand-dug well/open spring	87†
Piped spring/deep well	7
% Filtered water 0–10 MPN/100 mL	86
% Stored filtered water % > 10 MPN/100 mL	0
Overall bacterial removal efficiency	1.1 log ₁₀ or (92%)‡
Turbidity (NTU)	
Average source water	4.7
Average filtered water	0.9
% Reduction	82
Regularity of post-chlorination	41%

* *E. coli* levels of source water are calculated as geometric means. MPN = most probable number of coliforms; NTU = nephelometric turbidity units.

† Includes one well with 2,419 MPN/100 mL that was too numerous to count or > 2,419.

‡ Excludes 11 filters that had no detectable *E. coli* in source water or filtered water.

TABLE 3

Biosand filters tested in the Artibonite Valley, near Deschapelles Haiti, with concentration of *Escherichia coli* (MPN/100 mL) in filtered water that exceeded of source water levels*

Source water type	Source water	Filtered water
Hand-dug well/open spring	61	387
Piped spring/pump well	0	2
Hand-dug well/open spring	24	45

* MPN = most probable number of coliforms.

effects (frailty models), and fully parametric methods for all of these purposes.¹⁹ 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 showed that cement BSFs installed in the Artibonite Valley have survivorship of > 80% up to 5 years and nearly 40% at 12 years. Thus, the durability of these filters is broadly consistent with data on duration of use reported by others.^{4,6,10} When compared with 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% for 1 year⁴), Haiti (98.1% for 1–5 years⁶), and Cambodia (87.1% for 1–8 years^{11,21}). The present study is the first one 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.

Although other studies^{6,11} 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. 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 (10 years), which is robust to censoring.

Several aspects of the sampling design potentially limit the accuracy, precision, and scope of our statistical analyses. First, we relied on user recall to determine the year in which filter use ended. To assess the degree of uncertainty in the KM survivor function and median duration of use caused by recall errors, we conducted a Monte Carlo simulation study in which we added random errors to the reported filter lifespans. The results suggest only minor uncertainty in the KM survivor function and median duration of use caused by recall error. Second, the biosand filters studied were installed by different organizations, one of which (HAS) installed nearly 75% of the filters. The numbers of filters installed by different non-HAS groups in our study are too small to permit meaningful assessment of potential installer effects, but these could be assessed in a future study using group-comparison methods of time-to-event analysis if it were possible to include a sufficient number of biosand filters installed by each of several different organizations. Third, all but one of the biosand filters in our study was of the cement type. This fact increases precision but limits applicability to biosand filters of different designs. Fourth, because of the nature of the population being sampled and constraints imposed by available resources, it was necessary to use referral sampling to select filters for inclusion in the study. We are not able to quantitatively assess the degree of bias (if any) this non-random sampling method contributed to our results, but as is typical of studies using this method, we must caution that there is no guarantee our results extend to the entire population of filters in the Artibonite Valley or elsewhere.

There was no clear indication of a decrease in filtration efficacy for *E. coli* or turbidity over long term-use of filters sampled. These results are consistent with those of similar BSF field studies worldwide.^{4,6,7,9,11–13,22–26} Although 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.²⁰

That filtered water was found with higher *E. coli* concentrations than source water in three instances was not surprising and shows that in reality, filters may not always be properly functioning. It suggests that filters may actually harbor and be a source of *E. coli*, although further research needs to be conducted to confirm this hypothesis. Other studies have also reported filters “increasing” the presence of *E. coli* in post-filtered water and note that this phenomenon may be explained by the study design.^{23,26} Time and logistic constraints in the present study made it necessary to compare filtered water to source water contamination from the same day, although in actuality the filtered water was derived from source water used in the previous dosing. Most previous field studies of BSFs have used a similar study design for the same reason.^{6,7,9,26} 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 1.1 log₁₀ (92%) removal efficiency.

Many similarities were found between our data and data of Duke and others⁶ from 2005, but there were several noticeable differences. Source water contamination levels of piped springs and pump wells were lower in our study, possibly because different sources were sampled, new wells were drilled, or contamination levels varied seasonally. The 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 2010.²⁰ The use of post-filtration chlorination may also explain why no recontamination was found in the stored buckets tested this study. That Duke and others⁶ found a much higher percentage of filters still in use is probably caused mainly by the fact that their study only included filters up to 5 years of age whereas our study included filters up to 12 years of age. We note that our KM survivor function estimated that > 80% of filters remain in use for at least 5 years, and the 95% confidence interval extends > 90%.

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 1.1 log₁₀ (92%) filter efficacy are broadly consistent with previous studies of field filtration efficiencies in Haiti and elsewhere but show that filters are effective and sustainable for longer periods than previously documented. Thus, although concerns have been expressed about prematurely scaling up BSF technology,^{8,27} studies continue to show that this technology is effective and sustainable in the field.

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 collected with random or stratified random sampling, which include specific reasons for cessation of filter use, could be used to assess the statistical significance of the various reported reasons for cessation of use. This information could prove to be useful in developing a BSF implementation strategy that focuses on education and technical support to ensure even greater efficiency, acceptability, and sustainability.

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