Ceramic pot filters lifetime study in coastal Guatemala

C. Salvinelli, A. C. Elmore, B. R. García Hernandez and K. D. Drake

ABSTRACT

Ceramic pot filters (CPFs) are an effective means of household water treatment, but the characterization of CPF lifetimes is ongoing. This paper describes a lifetime field study in Guatemala which was made possible by a collaboration between researchers, CPF-using households, and local non-governmental organizations (NGOs). Disinfection data were collected periodically for two years using field coliform enumeration kits as were flow rate data with the assistance of NGO staff. Consumer acceptance was characterized by surveying householders in the four subject villages at the beginning and end of the study. Flow rate data showed that average CPF flow rates decreased below the recommended minimum of 1 L h^{-1} after 10 months of use; however, the survey results indicated that the consumers were tolerant of the lower flow rates, and it is reasonable to assume that the daily volume of treated water can be readily increased by refilling the CPFs more frequently. Of greater concern was the finding that disinfection efficacy decreased below the recommended bacterial reduction after 14 months of use because it would not be obvious to users that effectiveness had declined. Finally, the follow-up visits by the researchers and the NGO staff appeared to increase consumer acceptance of the CPFs.

Key words | acceptance, ceramic pot filter, drinking water, field study, Guatemala, lifetime

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INTRODUCTION

Lack of safe water, sanitation, and hygiene remains a serious world health issue. According to the World Health Organization & United Nations Children's Fund (WHO & UNICEF) (2015), 663 million people still lacked access to an improved drinking water source in 2015. Most of these people (79%) live in rural areas, and almost a quarter rely on untreated surface water. According to UNICEF (2008), water quality interventions in developing countries have a greater impact when applied at the household level. Work by Hunter (2009) also defined ceramic filters as the most effective long-term household water treatment systems. Moreover, several laboratory studies have been conducted to assess the effectiveness of ceramic pot filters (CPFs), including van Halem *et al.* (2007, 2009), Oyanedel-Craver & Smith (2008), Sobsey *et al.* (2008), Lantagne *et al.* (2010), Mwabi *et al.* (2013) and others. Although field investigations are optimum in understanding filter use, acceptance, and behavior by users in real household conditions, they are more difficult logistically to execute and are not as abundant in the literature as laboratory studies. According to Brown & Sobsey (2006), knowledge of CPF effectiveness over long periods in the field is an essential condition for successful scale-up and responsible investment, but it has not been sufficiently studied.

Lantagne (2001) described a three-week field investigation conducted in Nicaragua about the performance of CPFs distributed as an emergency response after Hurricane Mitch in October 1998. The study included water quality monitoring and a survey of filter users. It was concluded that less than 53% of the filters removed *Escherichia coli* and post-treatment contamination as a result of water storage in unclean receptacles was a major issue. It was also observed that monitoring visits to families using the filters

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are strongly correlated with continued use of the filters. A field study in Cambodia (Brown *et al.* 2009) documented a relatively low rate of abandonment of approximately 2% per month. The study also found that the log_{10} reduction value (LRV) of *E. coli* did not appear to have a strong correlation with time in use. Another field study on the effectiveness of CPFs in Cambodia (Roberts 2004) included water quality testing and user surveys and concluded that 99% of CPFs produced water meeting the WHO 'low risk' requirements and users experienced a reduction in the rate of waterborne diseases. A retrospective study of filters distributed in Cambodia described by Brown & Sobsey (2007) found that the geometric mean reduction of *E. coli* and total coliforms in filtered water was 98% and 94%, respectively. The study also found a 46% reduction of diarrheal disease incidence by CPF users. Additional work has shown *E. coli* reduction by a mean of 96% and diarrheal disease incidence reductions of 49% during the course of an 18-week field study in Cambodia (Brown *et al.* 2008). Lastly, a four-month field study in Sri Lanka (Casanova *et al.* 2013) found widely variable flow rates and concluded that water production is a limiting factor of CPFs; however, this did not seem to be negatively perceived by the users.

The main CPF manufacturing company in Guatemala, which is located near the city of Antigua, has been in operation for more than 20 years, and the company owners report that more than 250,000 filters have been distributed throughout the country through 2015. The filters made by this company are the ICAITI/PFP type, described by Lantagne *et al.* (2010), and consist of a frustum-shaped (i.e., flower-pot shaped) porous clay filtering unit placed in a plastic bucket equipped with a lid and a spigot. The filtering unit is made of a mixture of clay, sawdust, and water. The mixture is pressed into pot-shaped molds, air-cured, fired in a kiln, and finally coated with colloidal silver. Untreated water is poured into the filtering unit, and treated water is collected in the bucket where it is available for use via the spigot. According to the manufacturer's instructions, the filtering unit should be scrubbed every three months with a brush and treated water, and should be replaced every two years. Most of the CPFs were distributed in the central highlands, the Pacific Coast area, and around Guatemala City. In the Atlantic Coast department of Izabal, the CPFs were first distributed in several rural villages by non-governmental organizations (NGOs) as a part of an emergency response following a major earthquake in May 2009. Although it was reported that the CPFs were well-received by the local families over the short term, this new technology was not permanently adopted by the inhabitants. A second effort to introduce CPFs by several NGOs in the region included follow-up visits to characterize the CPF's performance and to increase consumer acceptance of the technology.

This study describes a two-year CPF field monitoring program started in January 2014 as part of a collaboration between the Missouri University of Science and Technology (Missouri S&T), CPF users from four rural villages of the department of Izabal, Guatemala, and the following local NGOs: Alianza de Derecho Ambiental y Agua (ADA2), Asociación Programas de Gestión Ambiental Local (ASOPROGAL), Asociación Maya Pro Bienestar Rural del Área Sarstun (APROSARSTUN), and Red Cross Santo Tomas de Castilla. The goals of the study were to assess CPF-user acceptance and characterize lifetime in terms of disinfection effectiveness and water volume production under real use conditions.

METHODS

The study was carried out in four rural villages in the department of Izabal shown on Figure 1. The CPFs were distributed by three NGOs – ASOPROGAL, Comitato Internazionale per lo Sviluppo dei Popoli (CISP), and

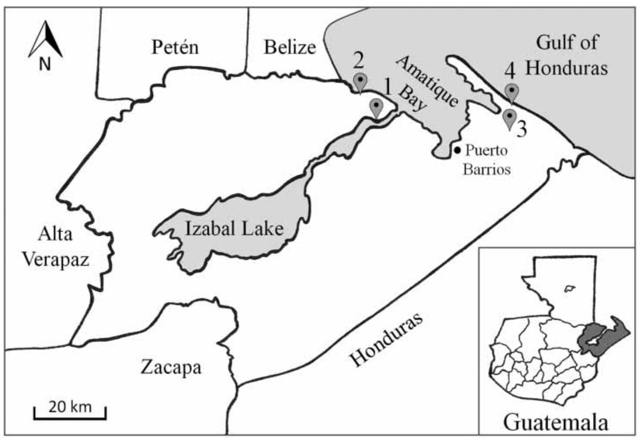

Figure 1 | Location of villages participating in the study.

Fondazione SIPEC – beginning in 2012. The first CPF was donated to every household and additional units were partially subsidized. The characteristics of the villages are listed in Table 1.

At the beginning of the study period, families from villages 1 and 2 were already familiar with CPFs and were changing the filtering units according to the manufacturer's instructions, while families from villages 3 and 4 did not have CPF experience. Five families in each village volunteered to participate in the study for a total of 20 families. All the CPFs were made in the manufacturing plant near Antigua, Guatemala, and belong to different production batches. Households in Villages 1, 2, and 4 received CPFs produced in 2014 identified as Production Year 2104 (PY14), and Village 3 received CPFs produced in 2015 (PY15).

The microbiological disinfection effectiveness was annually assessed by Missouri S&T geological engineering undergraduate and graduate students by counting the number of colony forming units (CFU) of *E. coli* and total coliforms in the raw (influent) and treated (effluent) water. The influent sample was collected from the container used by the individual household to fill the CPF and the effluent sample was collected directly from each CPF's plastic container via the spigot. Samples were analyzed using a Coliscan Plus Easygel Kit (Micrology Laboratories LLC, Goshen, IN, USA) following the manufacturer's instructions. Coliform growth media was mixed with water samples (1, 3, or 5 mL depending on a pretesting estimate of the influent water quality), placed in a Petri dish, sealed, and incubated at 35.5 °C for 24 hours. The *E. coli* and other coliform colonies were counted and reported as CFU/100 mL. Samples were duplicated, and the results were averaged for analytical purposes. Influent and effluent samples were also tested for turbidity using a Hach 2100P portable turbidimeter (Loveland, CO, USA).

The water production capacity of CPFs was characterized approximately every two months through falling head flow rate tests by employees of local NGOs who received training during S&T field visits. The plastic container was emptied, the filtering unit was filled, and after 1 hour the treated water was measured using a 2 L graduated cylinder. In addition, the date, time, and volume of water poured in the filter were recorded on a log sheet by the users.

In order to evaluate the potential adoption and acceptance of the filters, evaluations of the filter performance were obtained by interviewing CPF users during Missouri S&T visits at the beginning and end of the program. Free and informed consent of the participants or their legal representatives was obtained, and the study protocol was approved by the Campus Institutional Review Board at Missouri S&T, MO, USA, on April 3, 2014. A community meeting was initially organized to obtain a general idea of the users' satisfaction, and then the families participating in the study were interviewed individually. The data

Table 1 | Characteristics of subject villages

	Village 1	**Village 2**	**Village 3**	**Village 4**
Name	La Angostura	San Juan	Creek Grande	San Francisco del Mar
Number of families	23	35	32	73
Ethnic group	Q'eqchi'	Q'eqchi'/Mestizos	Q'eqchi'/Mestizos	Mestizos
Main water source	Creek	Shallow well (10 m)	Shallow well (2 m)	Rain
Initial CPF exposure	Sep-12	Sep-12	Feb-15	Jul-14
Study period	Jan-14 to Jan-16	Jan-14 to Jan-16	Mar-15 to Jan-16	Jan-15 to Jan-16
Main occupation	Fishing / farming	Fishing	Farming	Fishing / farming
Access to electricity	No	No	No	100% (PV)
Literacy	15%	20%	32%	80%
Health care	20%	20%	12%	20%
Sanitation	No	Latrines (37%)	Latrines (70%)	Latrines (90%)

PV, photovoltaic.

collection team determined the state of each CPF (that is, were all parts intact and functional) and whether the filter was in current use (was the ceramic filtering unit completely saturated). Then a questionnaire was administered to the primary caregiver for the household who was usually an adult female. Data on basic household demographics, water handling and use, CPF use and cleaning practices, advantages and disadvantages of using the filter, and perceived changes in the family health conditions were collected. All survey instruments were prepared in English and Spanish before use in the study. When necessary, the questions were translated to Q'eqchi' by a native speaker with experience in community work. The content of the English version of the survey is shown in Table 2.

The total number of monitoring activities conducted in each village is shown in Table 3.

Table 2 | List of question contained in the survey

What is the family name? Who is the principal care keeper for the household and CPF?
How many people use the water from the filter in your household? How many children and adults?
Where do you source the water that you pour in the filter?
Do you use your filter every day? How many times per day do you refill the filter?
Does the filter provide enough water for your family? If not, how much more water is needed?
Do you clean the filter and if so, how?
How long have you been using CPFs/ this filter?
Since using the filter have you noticed an improvement in your family's health?
What do you like and dislike about the filter?
What do other families think about the filter?
Do you think the filter is needed?
Since using the filters what has changed in your daily activities?

Table 3 | Summary of monitoring activities

	Village 1	Village 2	Village 3	Village 4
Flow rate	23	30	19	7
Effectiveness	11	12	10	4
Turbidity	7	9	3	4
Interviews	11	11	3	4

RESULTS AND DISCUSSION

The aggregate data collected during the field visits are summarized in Figure 2. Samples that did not have any colonies were assumed to have a concentration equal to one-half of the detection limit which varied according to the volume of water sampled. The detection limit for a 1 mL sample was 100 CFU/100 mL, 33 CFU/100 mL for a 3 mL sample, and 20 CFU/100 mL for 5 mL samples. It is noted that these detection limits make these results inappropriate for comparison to drinking water standards, but the results can be used in a comparative analysis. A total of 37 samples were analyzed for total coliforms presence, 24 for *E. coli* and 23 for turbidity. Such small numbers of samples cannot provide the basis for a definitive characterization of CPF performance, but analysis of the results can provide an indication of general behavior.

As seen in Figure 2, the CPF use resulted in a reduction of all the measured parameters. *E. coli* was not found in any of the effluent samples, and there were no coliforms (total) detected in 57% of the effluent samples. In addition, more than 75% of the effluent samples present turbidity levels lower than one nephelometric turbidity unit (NTU).

Microbiological removal effectiveness

Historically, total coliform testing has been performed to characterize the potential for a water supply to support the growth of fecal pathogens even if the direct indicator *E. coli* is not present. The Centers for Disease Control and Prevention (2010) stated that in the absence of *E. coli*, total coliforms can be used to characterize disinfection efficacy. The LRVs of total coliforms in treated versus untreated water were calculated as standard measures of technology performance and were computed as $\log_{10}$ (influent concentration/effluent concentration). In order to understand the trend of performance of CPFs during their lifetimes, LRVs were plotted against the time that the CPFs were in use as shown in Figure 3. Measured concentrations below detection limits were assumed to be one-half of the detection limits for the purpose of calculating LRVs. In 8% of the samples collected from households in the four villages, both influent and effluent

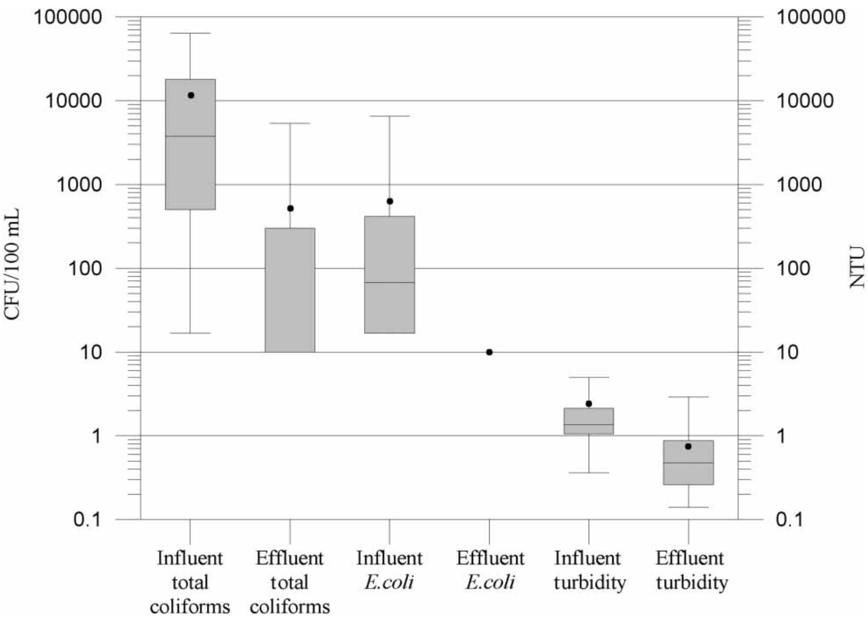

Figure 2 | Summary of microbiological contamination and turbidity in all influent and effluent samples.

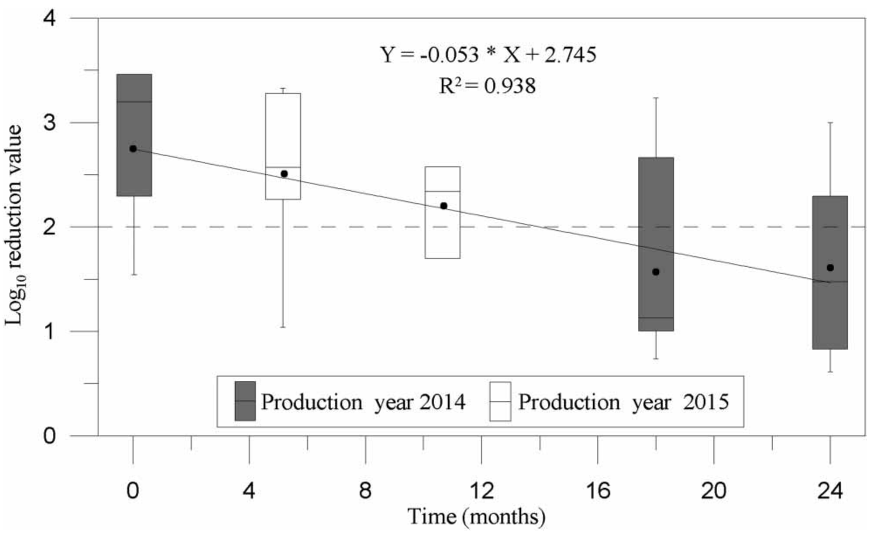

Figure 3 | LRV of total coliforms by time of usage of the CPF.

results were below detection limits, and those results were not included in Figure 3.

Inspection of the time series makes evident that the bacterial removal capacity of CPFs decreases over time and the average LRVs follow a linear negative trend with an R^2 value of 0.938. Brown & Sobsey (2007) found that LRV is a valuable measure of technology performance; however, reduction is a function of influent water characteristics and low LRVs do not necessarily indicate poor performance. Lantagne *et al.* (2010) established a LRV of bacteria equal to two as the criterion for effective removal when it is not possible to spike samples with bacteria and the water is not contaminated enough to document a higher LRV. The performance requirements for small-scale and household drinking-water treatment defined by WHO (2011) indicate that two is the minimum LRV of bacteria for a technology to be considered protective. The dashed line in Figure 2 at LRV = 2 shows that on average the CPFs used during the study were able to achieve the recommended bacterial reduction during the first 14 months of usage.

Water production capacity

Flow rate results for the two different production years of CPFs are represented in Figure 4. Both data sets showed a decreasing trend in flow rate with time, but with different behaviors. Flow rates of PY14 filters presented an initial increase, and after reaching the maximum, started to decline until the end of the study, while in PY15 the filter flow rate started decreasing initially and followed an almost linear trend. CPF flow rate behavior in PY14 is consistent with other flow rate observations documented by Lantagne et al. (2010), Hubbel & Elmore (2012), Salvinelli & Elmore (2015), and others. The initial increase could be due to the removal of combustible material trapped in the CPF during the production process, and the decline is possibly

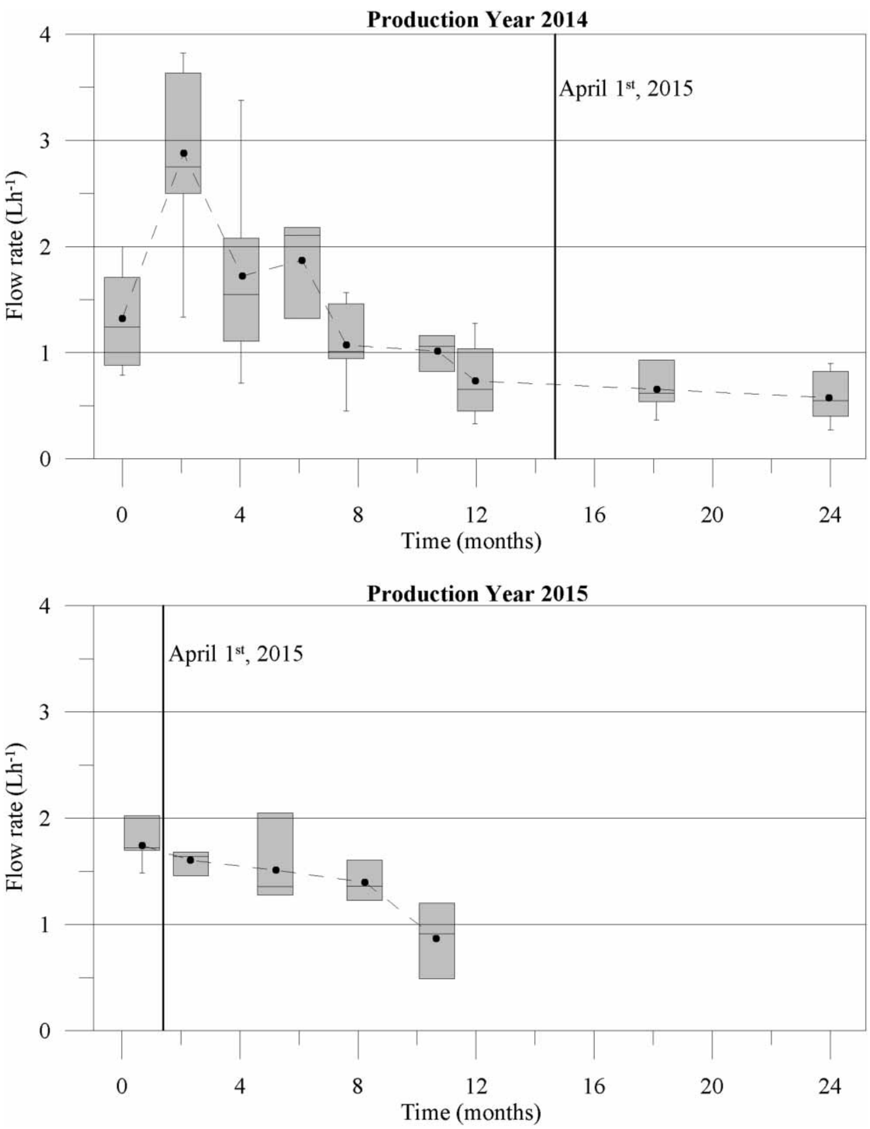

Figure 4 | CPF's flow rate by time of usage for two different production years.

caused by suspended material in the water source or other mechanisms that gradually clog the pores. Salvinelli & Elmore (2015) concluded that turbidity seems to be the principal indicator in characterizing the CPF's lifetime with regard to water production capacity. The turbidity range of the influent water treated by the PY14 filters was 0.36 to 4.47 NTU, similar to the PY15 influent turbidity range of 0.9 to 5 NTU. Likewise, the PY14 influent total coliforms range of 17 to 46,200 CFU/100 mL was similar to the PY2015 range from 17 to 64,000 CFU/100 mL. Therefore, it appears that the difference in flow rate behavior is most likely the result of manufacturing differences. This is a reasonable assumption given that the authors have visited the CPF factory at least annually since the beginning of the program, and have observed that the kiln-operating (firing) sequence is routinely modified in an effort to improve the number of filters that pass quality control testing.

According to The Ceramics Manufacturing Working Group (CMWG) (2011), the flow rate test can be used as an indicator of production consistency, pathogen and suspended solids removal efficacy, and water production capacity. Uniform flow rates are expected from a standardized manufacturing process while high flow rates could compromise the quality of treated water and low flow rates may not result in water quantities sufficient for consumer needs. The flow rate test is the most common quality control test performed by the manufacturers, but there are differences between the factory-established acceptable flow rates. Historic work by Rayner *et al.* (2013) found that the quality control flow rate ranges vary from a minimum of 1 to 3 $L\,h^{-1}$ to a maximum of 2 to 5 $L\,h^{-1}$. Lantagne *et al.* (2010) stated that a production process should be considered reliable if the quality control flow rate range at the factory is 1 to 2 $L\,h^{-1}$, while CMWG (2011) established an acceptable range between 1 and 3.5 $L\,h^{-1}$. The company that manufactured the CPFs used in this study accepts filters with flow rates between 1 and 2 $L\,h^{-1}$. The PY14 CPFs initially met the manufacturer's requirements, exceeded the 2 $L\,h^{-1}$ threshold around the second month of use, and then returned to the expected range prior to dropping below 1 $L\,h^{-1}$ at the end of the study. The PY15 filters presented more consistent values and maintained a flow rate between 1 and 2 $L\,h^{-1}$ during the study. On average, the water production of CPFs decreased below 1 $L\,h^{-1}$ after approximately 10 months of use.

User acceptance

A total of 25 families with an average of 5.6 people per household participated in the interviews. Other than visually verifying that the CPFs were in use (by examining the brim for complete saturation), there was no mechanism for verifying the veracity of participants' responses. The main water sources were reported to be rainwater collected from rooftops and stored in tanks for 28% of the families, surface water (streams) for 18%, and shallow wells (defined here as $\leq$10 m in depth) for 54%. All the families participating in the study were using the filter daily at the time of the follow-up and reported filling the filter an average of 2.1 times per day, with a maximum of 4 times per day and a minimum of once a day. According to the manufacturer's instructions, the filtering unit should be cleaned every three months using just-treated water. Most of the families reported to be familiar with the recommended cleaning process, and 20% of them reported cleaning the filtering units using bleach or soap. However, 63% of the families stated that they preferred to clean the filter more frequently than quarterly. According to Salvinelli & Elmore (2015) and van Halem *et al.* (2009), the water production capacity seems to be the major limiting factor of the CPF's lifetime and sustainability. Nevertheless, 76% of the families reported that the filters produced sufficient drinking water, but it is important to note that 20% of them owned two CPFs and a single CPF would not have produced a sufficient quantity of treated water. A high percentage (88%) of the respondents reported that the use of the filter had positive consequences on the health condition of family members, especially children, by reducing the perceived frequency of disease symptoms including diarrhea, fever, nausea, and vomiting. Most of the positive comments about the CPFs referred to the water quality, which was stated to be clear, fresh, safe, and with a better taste than boiled and chlorinated water. In addition, users who previously drank boiled water were satisfied about saving the time and energy required to gather firewood and prepare a fire. The most common CPF disadvantages were identified as the slow filtration rates and the fact that the CPFs are fragile and can easily break.

Interactions at community meetings also demonstrated satisfaction among the users and the positive impact of the follow-up visits seemed to extend beyond the five volunteer households in each village. In January 2014, 57% of families in village 1 and 63% of families in village 2 changed the filtering units and covered a portion of the costs. Furthermore, in January 2016, these families had achieved up to 3.5 years of continuous CPF use. These results are consistent with Lantagne (2001), who concluded that continued use of the filter was strongly correlated with monthly visits to the household by the local NGO or community leaders.

Daily water production

The total volume of treated water was recorded daily during the first two months of use by five families using the PY14 filters and three families using the PY15 filters. The PY14 filters produced an average volume of 12.3 L day^{-1} and the PY15 filters yielded an average volume of 10.0 L day^{-1}. Schweitzer *et al.* (2013) presented two hydraulic models, for paraboloid- and frustum-shaped CPFs that can be used to predict water level in the filter, instantaneous volumetric flow rate, and cumulative volume of water produced. These models permit prediction of how variables such as filter shape or frequency of filling impact the water production capacity. The model for the frustum-shaped CPF was adapted to the geometry of the filters used in this study and the hydraulic conductivity was calculated for each production year based on the average of the first two flow rate measurements which correspond approximately to the first two months of use. For PY14, the average flow rate was 2.43 L h^{-1} and for PY15 the average flow rate was 1.7 L h^{-1}. Figure 5 shows the predicted daily volume of water produced by the two production years considering four different filling frequencies.

The daily filling frequencies reported by the users were an average of 2.5 times per day for the PY14 filters and 2.0 times per day for the PY15 filters. As shown in Figure 5,

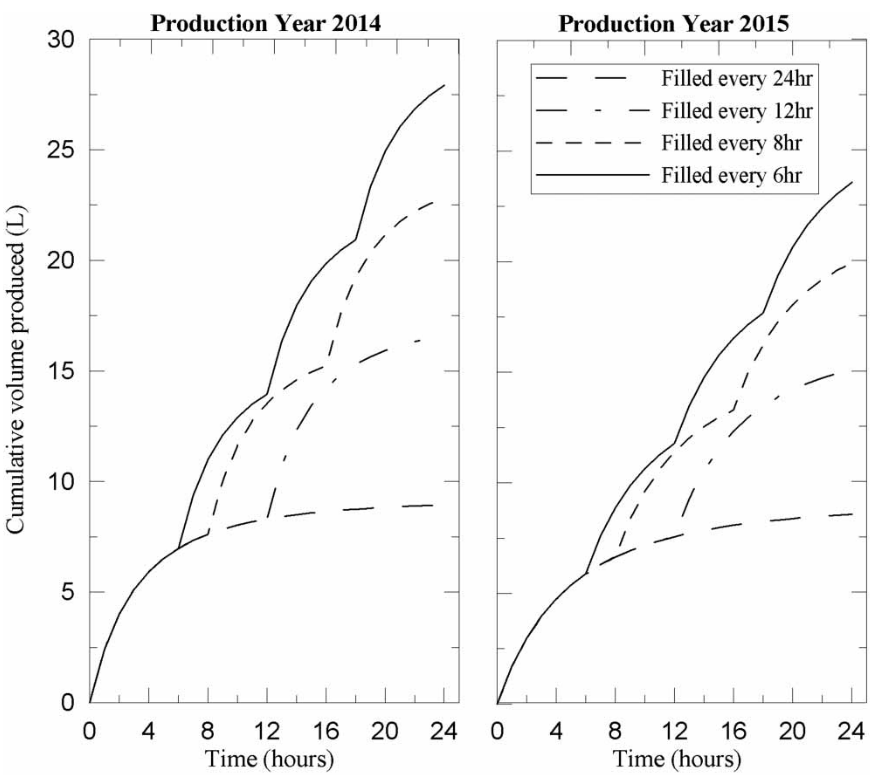

Figure 5 | Model prediction of cumulative volume of water produced, V(t), if filters are refilled once per day (every 24 h), twice per day (every 12 h), three times per day (every 8 h) and four times per day (every 6 h). After Schweitzer *et al.* (2013).

the volume of water predicted by the model (around 20 L day^{-1} for PY14 filters and 15 L day^{-1} for PY15 filters) is higher than the actual volume reported by filter users. This finding could possibly be a result of the users not filling the filters at regular time intervals. However, the model suggests that even though the water production capacity depends on the filter flow rate, the amount of available treated water could be significantly increased with frequent and constant filling intervals.

CONCLUSIONS

The relatively small number of water quality samples collected during this study and the relatively high detection limits associated with those results mean that the results should be interpreted as general characterizations of CPF performance as opposed to the more definitive results that could be generated by a laboratory study. The field data show that the CPFs used in this study had the ability to provide good quality water by treating highly contaminated waters with total coliform LRVs greater than 2. A negative correlation between filter disinfection efficacy and time in use was observed, and after 14 months disinfection efficacy dropped below the WHO requirements for bacterial removal. This could be a concern because consumers would not readily be aware of the increased risk. However, further studies with a larger number of samples and more accurate microbiological testing procedures should be conducted to confirm these results.

The CPF flow rates were maintained in the recommended range of 1 to 2 L h^{-1} during the first 10 months of use. The water production capacity was reported to be sufficient for most of the users during the entire 24 months of the study, and modeling results show that the production could be increased by filling the filters more frequently.

In general, the filters were well accepted by users who appreciated the esthetic quality of the treated water, reported lower incidences of health problems especially among children, and expressed their preference for CPFs over other treatments such as boiling or chlorinating drinking water. Unlike previous experiences with CPFs in the region, locals who participated in the field investigation have continued to use the filters for 3.5 years. It is postulated that the presence of an ongoing monitoring program increases the acceptance rate and yields an improvement in use and maintenance practices.

Field data are more difficult to collect from a logistical perspective relative to laboratory data. This study successfully illustrates how a synergistic collaboration between university researchers, local NGOs, and water consumers can generate data that can be used to characterize the real-life performance of CPFs in a field setting. There is potential that this type of collaborative effort could also include governmental organizations and CPF manufacturers in the future, and thus provide even more detailed information regarding the health conditions of target and control groups during future studies.

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