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Lifetime and effectiveness evaluation of ceramic pot filters

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LIFETIME AND EFFECTIVENESS EVALUATION OF CERAMIC POT FILTERS

by

CARLO SALVINELLI

A DISSERTATION

Presented to the Faculty of the Graduate School of the

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In Partial Fulfillment of the Requirements for the Degree

DOCTOR OF PHILOSOPHY

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Approved

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PUBLICATION DISSERTATION OPTION

This dissertation has been prepared in publication format and consists of the following three articles that have been submitted for peer-reviewed publication as follows:

Paper I, Pages 10-29, is titled “Assessment of the impact of water parameters on the flow rate of ceramic pot filters in a long-term experiment”. It was submitted to the Journal *Water Science and Technology: Water Supply* and published in volume 15, issue 6 in 2015.

Paper II, Pages 30-49, is titled “Characterization of the relationship between ceramic pot filter water production and turbidity in source water”, and was submitted to the Journal *Water Research*.

Paper III, Pages 50-70, is titled “Ceramic Pot Filters Lifetime Study in Coastal Guatemala”, and was submitted to the *Journal of Water and Health.*

ABSTRACT

Poor water quality is a major contributing factor to disease in developing countries. Ceramic pot filters (CPFs) represent an effective and sustainable technology for poor communities, but the characterization of CPF lifetimes is on-going, and the water production seems to be the limiting factor. This dissertation describes laboratory and field investigations conducted to characterize the parameters that impact CPF effectiveness and lifetime in terms of water production and treatment efficacy, both under controlled and real use conditions.

CPF initial flow rate is the most common quality control parameter, but it may not be representative of the long-term effectiveness of the CPF since other factors, as water quality and use practices, can have a significant impact on CPF lifetime. The experimental work demonstrated that, amongst the analyzed water parameters, turbidity is the principal indicator in determining CPF lifetime in term of water production. The relationship between turbidity and average flow rate was defined and followed a negative trend with a decreasing rate of 50mLh^{-1}/NTU. A method that permits prediction of the average flow rate given the initial flow rate and the turbidity of the influent water, and determines the turbidity limit for a target average flow rate was established.

The field investigation showed that CPFs could maintain bacterial removal efficacies above standards during the first 14 months of use, and flow rates in the recommended range during the first 10 months; however, consumers were tolerant of the lower flow rates. In general, filters were well accepted by users who appreciated the aesthetic quality of the treated water, reported lower incidences of health problems, and expressed their preference of the CPFs over other household treatments.

ACKNOWLEDGMENTS

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SECTION

1. INTRODUCTION

The World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) (2014) indicate that although the drinking water target of the Millennium Development Goal (MDG) was globally met in 2010, 748 million people still lacked access to an improved drinking water source in 2012. Most of these people are poor with over 90 percent living in rural areas and almost a quarter relying on untreated surface water. According to Kallman et al. (2011) WHO's definition of "improved" water source is not based on water quality at the point of use, since people that rely on this water source may face contamination and/or recontamination problems during collection, transport, and storage. The systematic review of microbiological contamination between source and point of use described by Wright et al. (2004) indicates that the bacteriological quality of drinking water significantly declines after collection in many settings concluding that safer household water storage and treatment is recommended.

UNICEF (2008) also indicates that many of the improved sources do not provide safe water due to microbiological contamination and that water quality interventions have a greater impact when applied at the household level. According to Hunter (2009), ceramic filters are the most effective over the long-term amongst the household water treatment technologies, and Oyanedel-Craver and Smith (2008) found that the silver coated CPFs, made using primarily local materials and labor, represent a sustainable point-of-use water treatment technology for poor communities. CPFs have become a common household water treatment solution in areas where people rely on untreated surface water, or where the risk of recontamination during water distribution and storage is high. However, according to the The Ceramics Manufacturing Working Group (CMWG) (2011) further research is needed to better understand the mechanisms of effectiveness, the variables that influence filter lifespan, and the useful life of the filter under real use conditions.

1.1. REVIEW OF RELEVANT LITERATURE

An overview of the current manufacturing practices adopted by CPF factories in developing countries including 25 of the 35 operational filter factories identified in 18 countries in 2009 is presented by Rayner et al. (2013). Based on the monthly production reported by each factory, and assuming five new factories per year since 2009 with a monthly production capacity of 1000 CPFs each, van der Laan et al. (2014) estimated the total number of CPFs worldwide. Figure 1.1 shows the projection assuming an average failure rate of 12 percent (Rayner et al. 2013), and a disuse rate of 2 percent (Brown and Sobsey 2007).

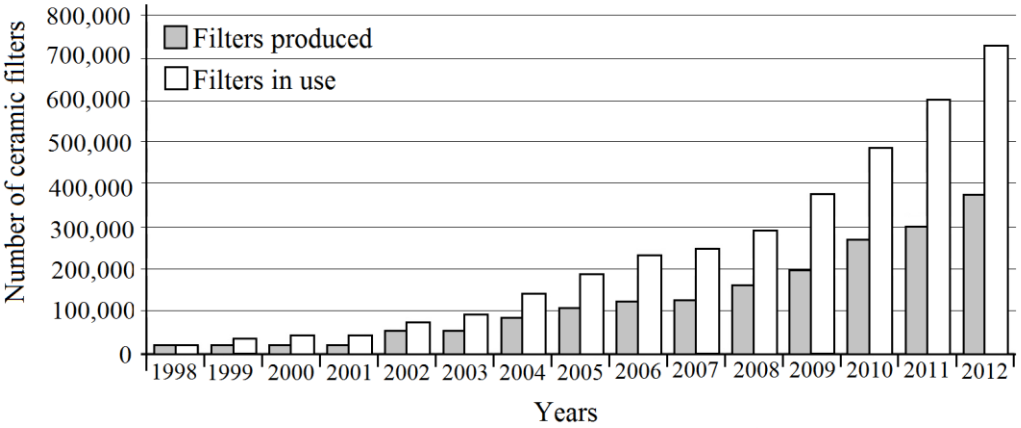

Figure 1.1 Estimation of the total number of ceramic pot filters worldwide (van der Laan et al. 2014).

The study described by Rayner et al. (2013) also shows that manufacturing processes vary widely both between and within factories posing concerns about the consistency and quality of locally produced filters due to the absence of standardized quality control procedures. The Ceramics Manufacturing Working Group (CMWG) (2011) summarizes the existing knowledge on CPF production practice and variables, identifies lessons learned by the factories, makes best practice recommendations for local manufacturing of CPFs, and suggests areas for further research.

1.1.1. ICAITI/PFP Style Ceramic Pot Filters. According to Lantagne et al. **(**2010**),** currently the most available locally-produced ceramic filters are based on a design developed in 1981 by the Instituto Centro Americano de Investigación y Tecnología Industrial (Centro American Industrial Research and Technology Institute) (ICAITI) and redesigned in the mid-1990s by the US-based non-governmental organization (NGO) Potter for Peace (PFP) . The ICAITI/PFP style CPFs are frustum-shaped porous ceramic filtering units placed in a water container (usually a five-gallon bucket) equipped with a lid and a spigot, as shown in Figure 1.2.

The filtering unit is a made of a mixture of clay-rich soil, water and a burnout material (usually saw dust) used to increase porosity. The materials are mixed until homogeneous, pressed into pot shaped moulds, air-cured, fired in a kiln, and finally coated with a suspension of silver nanoparticles. According to CMWG (2011) the silver coating bactericidal properties improve the filter capacity to deactivate pathogenic microorganisms contained within the raw water, and prevent the growth of a layer of bacteria that can form on the filter wall.

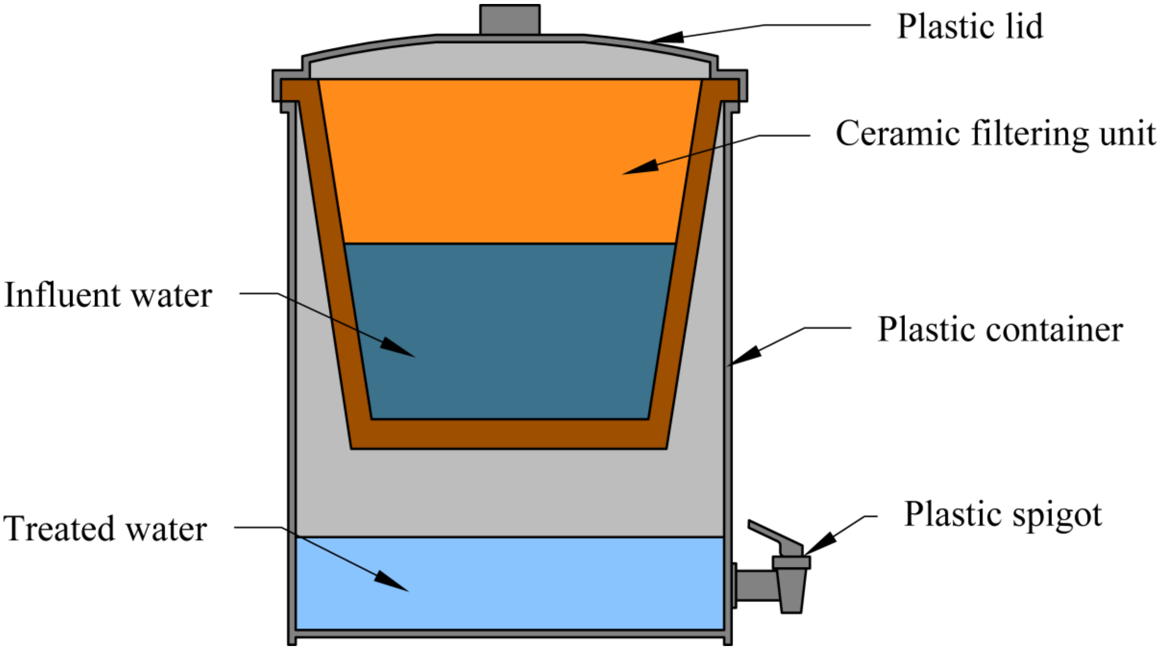

Figure 1.2 ICAITI/PFP style ceramic pot filter.

1.1.2. Effectiveness of Ceramic Pot Filters. Several laboratory studies have been conducted to assess the effectiveness of ceramic pot filters (CPFs) presenting promising results, including Oyanedel-Craver and Smith (2008), van Halem et al. (2007, 2009), Sobsey et al. (2008), Bielefeldt et al. (2009) , Lantagne et al. (2010), Mwabi et al. (2013), van der Laan et al. (2014) and others. Simonis and Basson (2011) presented an overview of fifteen studies of bacterial testing showing an average log reduction value (LRV) of 2.0 for E.*coli* that corresponds to the threshold required by WHO (2011) for a household water treatment to be considered protective against bacteria. However, the study documented a high variability in the efficacy, with LRVs ranging from 0.9 to 6.8.

1.1.3. CPFs Water Production Capacity. Flow rate is defined by CMWG **(**2011**)** as the volume of water treated by a saturated and full CPF during the first hour after production. A flow rate test is one of the most common indirect quality tests, and it can be used as an indicator of production consistency, pathogen removal efficacy, and water production capacity. The survey described by CMWG (2011) indicated that flow rates accepted by factories range from 1.0-3.0 Lh^{-1} minimum to 2.0-5.0 Lh^{-1} maximum. This variability indicates that the relationship between flow rate and pathogen removal efficacy is not well understood. The minimum acceptable flow rate is established by CMWG (2011) as 1 Lh^{-1} based on consumer needs while the maximum is calculated based on the capacity of the filtering unit which is 2.5 Lh^{-1} for 7.2-liter capacity units and 3.5 Lh^{-1} for 10-liter capacity units. Lantagne et al. (2010) conducted a study comparing flow rate behavior and coliform removal efficacy of several filter designs. A maximum flow rate of 1.7Lh-1 was established as a potential quality control measure to ensure a log reduction value (LRV) of 2 for total coliform. It was also said that a CPF's production process is considered reliable when flow rates are maintained between 1 and 2 Lh-1. However, the study indicated the need to confirm this data with long-term testing.

Although several theoretical and experimental studies have been conducted with the aim of understanding flow rate behavior of CPFs, its relation with the quantity and quality of water is not well understood. Mathematical models have been developed with the aim of describing the hydraulic characteristics of CPFs (Plappally et al., 2009; Elmore et al., 2011; Schweitzer et al., 2013; and Yakub et al., 2013). Physical properties such as porosity, pore size distribution and tortuosity have be studied by Van Halem et al. (2007), Plappally et al. (2011), and Yakub et al. (2013).

Sustainability of CPFs has been assessed by van Halem et al. (2009) considering five criteria: accessibility, water quality, water production, functionality and environmental footprint. The limiting factor was found to be the criterion of water production due to filter clogging that causes a substantial flow rate decrease during the treatment of surface water. CMWG (2011) and CPF manufacturers recommend scrubbing the filter when the flow rate reaches an unsatisfactory low level. Lantagne (2001) and van Halem et al. (2007) also show that the decrease is significant when surface water is treated and state that scrubbing the filter partially and temporarily restores the flow rate. Van Halem et al. (2007, 2009) described a long-term study of CPFs and an investigation about three possible clogging mechanisms conducted through assessment of the effects of the rehabilitation of the filters. The study concluded that neither organic nor inorganic fouling were the principal causes of failure, but rather the physical fouling by colloids were the primary cause of failure. Therefore the suggested cleaning method does not prevent long-term clogging which makes flow rate the limiting factor of CPF lifetime.

1.1.4. Field Investigations. According to Brown and Sobsey (2006), knowledge of CPF effectiveness over long periods in the field is an essential condition for successful production increases and responsible investment, but it has not been studied enough. Field investigations which can help understanding the filter behavior in real use conditions and its acceptance by the users are more difficult logistically to execute and are not as abundant in the literature relative to laboratory studies.

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 to filter users. It was concluded that less than 53 percent of the filters removed *E.coli*, and contamination post treatment from storage in unclean receptacles represented a major issue. It was also observed that monitoring visits to the families using the filters was strongly correlated with continued use of the filter. Brown et al. (2009) during a field study in Cambodia documented a rate of abandonment of approximately two percent per month after implementation and that the LRV of *E.coli* did not appear to have a strong correlation with time in use. A field study about the effectiveness of CPFs in Cambodia is presented by Roberts (2004) and included water quality testing and user surveys. It was concluded that 99 percent of CPFs produced water meeting the WHO “low risk” requirements (E.*coli* below 10CFU/100mL), and CPF users experienced a reduction of the rate of waterborne diseases. A retrospective study of filters distributed in Cambodia described by Brown and Sobsey (2007) found that the geometric mean reduction of *E.coli* in filtered water was 98 percent and of total coliforms was 94 percent. A 46 percent reduction of diarrheal disease incidence was documented in the population that used CPFs. *E.coli* reduction by a mean of 96 percent and diarrheal disease incidence reduction by 42 to 49 percent in intervention group members were documented by Brown *et al.* (2008) during the course of an 18-week field study in Cambodia. A four month field study in Sri Lanka described by 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 who in most of the cases declared that the filters produced sufficient water.

1.2. RESEARCH OBJECTIVES AND OUTLINE

The general objective of this dissertation is to characterize the parameters that impact CPF effectiveness and lifetime in terms of water production and treatment efficacy both under controlled and real use conditions with the goal of contributing to improve the quality of life of actual and future users. The dissertation includes three distinct papers which were submitted to peer-reviewed journals.

Paper I describes a long-term study of CPF flow rates under controlled conditions using three different water sources. The primary objectives of this study were to:

- Characterize the relationship between influent water parameters and CPF water production. This included the following:
    - Set-up of constant head apparatuses to maintain constant conditions.
    - Monitoring of instantaneous and daily average flow rates.
    - Characterization of chemical, physical and microbiological parameters in influent and effluent waters.
    - Comparison between water characteristics and flow rate behaviors of CPFs in the three different scenarios.
- Identify the principal parameters that impact CPF lifetime through statistical analysis.

Paper II describes a study of CPF water production capacity under controlled conditions using four different turbidity scenarios. The primary objectives of this study were to:

- Assess the relationship between influent water turbidity and CPF flow rate. This included the following:
    - Quantification of initial flow rate of each CPF.
    - Maintain a constant turbidity level in each scenario.
    - Monitoring of average daily flow rates and turbidities.

    - Comparison between water turbidity and flow rate behaviors of CPFs in the four different scenarios.
- Identify a method to predict CPF average flow rate based on the turbidity of the influent water and on the initial flow rate.
- Define the recommended turbidity limit in the influent water to avoid premature failure of the filter.
- Characterize suspended particles retained and released by the filtering unit.

Paper III describes a two year CPF field monitoring program started in January 2014 as a 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 local NGOs. The study objectives were to:

- Characterize the lifetime in terms of disinfection effectiveness and water volume production under real use conditions. This included the following:
    - Selection of subject villages and households representative of the region.
    - Characterization of microbiological removal, flow rate and total volume of treated water.
    - Comparison between collected data and required/recommended parameters for quality and quantity of treated water.
- Assess CPF user acceptance and identify the main factors that impact it positively and/or negatively.

PAPER

I. ASSESSMENT OF THE IMPACT OF WATER PARAMETERS ON THE FLOW RATE OF CERAMIC POT FILTERS IN A LONG-TERM EXPERIMENT.

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ABSTRACT

Poor water quality is a major contributing factor to disease in developing countries. Silver coated ceramic pot filters (CPFs) are a relatively common form of household water treatment systems (HWTSs) representing an effective and sustainable technology for poor communities. Water production seems to be the major limiting factor of the CPF's lifetime and sustainability since low flow rates do not produce an adequate daily volume of treated water. This paper describes a long-term study of CPF flow rates under controlled conditions using three different water sources. The relationship between water characteristics and flow rate was assessed with the intent of identifying the principal parameters that impact CPF water production. The study concluded that turbidity seems to be the principal indicator in determining the CPF lifetime in terms of quantity of treated water. There is no evidence that biological activity also contributes to premature failure of CPFs and the data did not indicate that chemical precipitation is responsible for the filter clogging. Manufacturers commonly conduct initial flow rate tests using clear water as a measure of quality assurance. However, the relationship between initial flow rate and average flow rate during the lifetime of the CPF should be further studied.

Keywords: Ceramic pot filter; flow rate; lifetime; long-term study; turbidity

INTRODUCTION

The United Nations World Water Assessment Programme (WWAP) (2015) demonstrates how water resources and services are essential to achieving global sustainability and states that water is at the core of sustainable development. The World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) (2014) indicates that although the drinking water target of the Millennium Development Goal (MDG) was globally met in 2010, 748 million people still lacked access to an improved drinking water source in 2012. Most of these people are poor with over 90 percent living in rural areas and almost a quarter relying on untreated surface water. According to Kallman et al. (2011), WHO's definition of "improved" water source is not based on water quality; therefore people that rely on this water source may face contamination and or recontamination problems during water collection, transport and storage. UNICEF (2008) indicates that many of the improved sources do not provide safe water due to microbiological contamination and that water quality interventions have a greater impact when applied at the household level. A household water treatment system (HWTS) is effective if it produces sufficient safe drinking water for a family in the long-term. Hunter (2009) states that the most effective form of HWTSs in the long-term are ceramic filters, and Oyanedel-Craver and Smith (2008) concludes that silver coated ceramic pot filters (CPFs) represent an effective and sustainable technology for poor communities.

CPFs are locally manufactured porous clay pots placed in a water container equipped with a lid and a spigot. The filter is made of a mixture of clay, a burn out material (usually saw dust), and water. The mixture is pressed into pot shaped molds, air-cured, fired in a kiln, and finally coated with a suspension of silver nanoparticles. CPF's microbiological removal efficacy has been documented by Lantagne (2001), van Halem et al. (2007), Oyanedel-Craver and Smith (2008) and others. According to van Halem et al. (2009), the decrease in water production during operation is due to filter clogging. The Ceramics Manufacturing Working Group (CMWG) (2011) and CPF manufacturers recommend scrubbing the filter when the flow rate reaches an unsatisfactory low level. Lantagne (2001) and van Halem et al. (2007) show that the flow rate decrease is significant when surface water is treated and state that scrubbing the filter partially and temporarily restores the flow rate. According to van Halem et al. (2009), this cleaning method does not prevent long-term clogging which makes flow rate the limiting factor of the CPF's lifetime.

Flow rate is defined by CMWG (2011) as the volume of water treated by a saturated and full CPF during the first hour after production. A flow rate test is one of the most common indirect quality tests, and it can be used as an indicator of production consistency, pathogens removal efficacy, and water production capacity. A survey described by CMWG (2011) indicated that flow rates accepted by factories range from 1.0 to 3.0 litre per hour (Lh^{-1}) minimum to 2.0 to 5.0 Lh^{-1} maximum. According to Lantagne et al. (2010), a CPF's production process is considered reliable when flow rates are maintained between 1 and 2 Lh^{-1}. The minimum acceptable flow rate is established by CMWG (2011) as 1 Lh^{-1} based on consumer needs while the maximum is calculated based on the capacity of the filtering unit: 2.5 Lh^{-1} for 7.2-L capacity and 3.5 Lh^{-1} for 10-L capacity.

Although several theoretical and experimental studies have been conducted with the aim to understand flow rate behavior of CPFs, its relationship with quantity and quality of water is not well understood. Mathematical models have been developed with the aim of describing the hydraulic characteristics of CPFs (Plappally et al., 2009; Elmore et al., 2011; Schweitzer et al., 2013; Yakub et al., 2013). Lantagne et al. (2010) conducted a study comparing flow rate behavior and coliform removal efficacy of several filter designs, and indicated the need for long-term testing. Van Halem et al. (2007, 2009) described a long-term study of CPFs and an investigation about three possible clogging mechanisms conducted through assessment of the effects of the rehabilitation of the filters. Van Halem et al. (2009) concluded that neither organic nor inorganic fouling were the principal causes of short-term clogging, but the physical fouling by colloids were observed as a potential cause of failure.

This paper describes a long-term study of CPF flow rates under controlled conditions using three different water sources. The primary purpose of this study is to assess the relation between water characteristics and flow rate with the intent of identifying the principal parameters that impact CPF lifetime.

METHODS

A long-term performance study was conducted in the groundwater hydrology laboratory of the Missouri University of Science and Technology to collect flow rate and water quality data using production CPFs. The experiments were conducted using nine silver coated CPFs, manufactured and quality control tested by a factory near Antigua, Guatemala. There, the CPF's flow rate is tested using clear water and filters outside the range of 1 to 2 Lh^{-1} are discarded. The subject filters were selected randomly from a stock of 100 filtering units and divided into three sets of three. Each set was used to establish three different systems with the same setup and conditions, but with differing water sources. The water sources were as follows:

- Surface water (SW) collected in the Little Prairie Lake, a small fresh water body near Rolla, Missouri, USA;
- Challenge water (CW) created by mixing tap water (97 percent) and influent waste water (3 percent) from the Rolla Waste Water Treatment Plant;
- Municipal tap water (TW) from Rolla, Missouri, USA.

Figure 1 depicts the constant head apparatus used to maintain constant flow with a relatively constant head through each CPF. Each system consisted of a 1,000-L tank used to periodically collect, store, and/or mix the source water. A timer controlled pump moved the source water from the tank to a 100-L container that gravity fed the three

CPFs using float valves which maintained the water level at approximately 21 centimetres (cm) in each CPF. This kept each filter element almost completely full at a volume of 9 L. This maximized the flow rate over the time that the experiments were conducted. Once treated, the water from each CPF was collected in a calibrated container used to measure the total volume of treated water. Three constant head apparatuses were fabricated so that experiments could be conducted on all three water sources simultaneously.

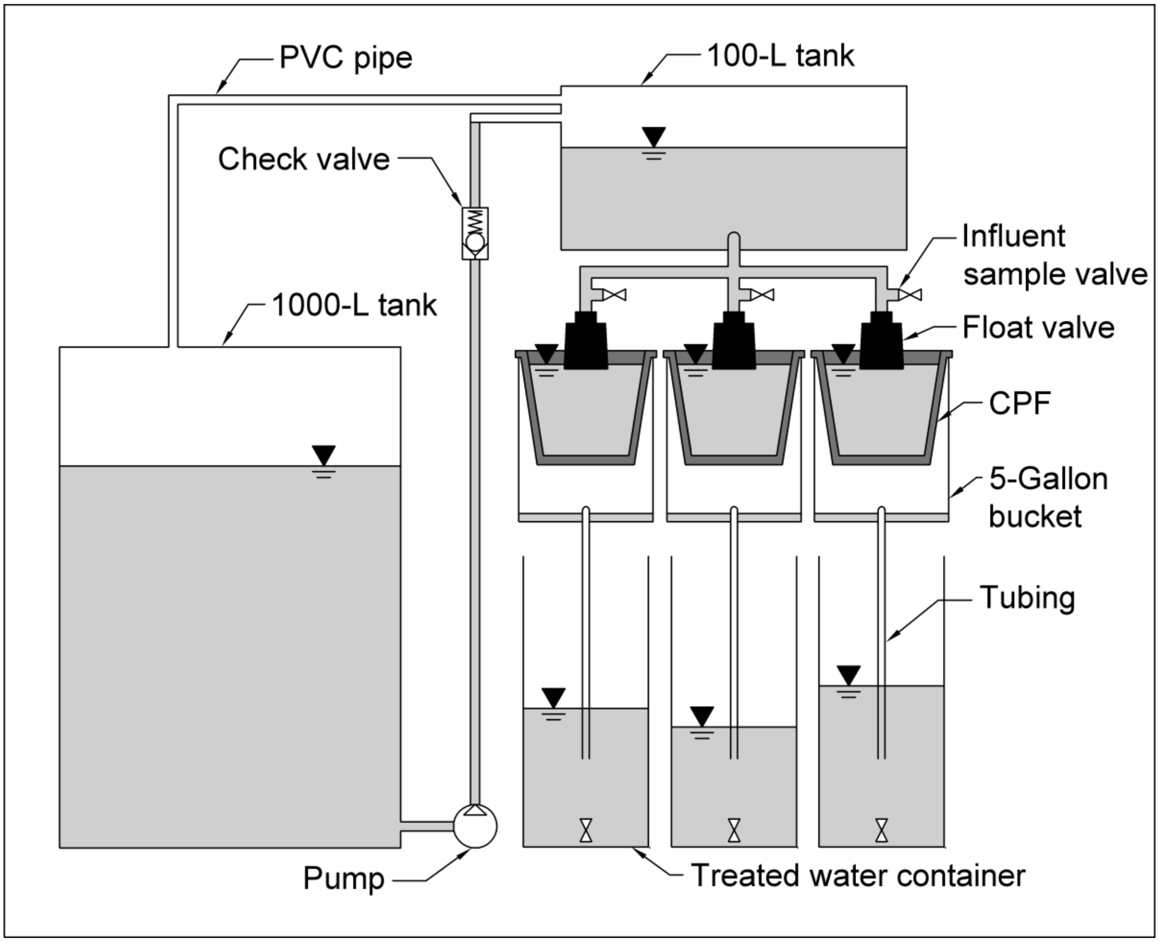

Figure 1. Constant head apparatus.

Experiments were conducted for a total of 113 days. After the first 15 days of testing, the experiments were suspended for 30 days for logistical reasons, but subsequent analysis of the data did not indicate that the suspension period affected the experimental results. Therefore, all the data were subsequently considered in the study. According to van Halem et al. (2009) long-term clogging is not prevented by scrubbing the CPFs; therefore, the CPFs were not cleaned in order to avoid cross contamination. However, at the end of the experiments, the CPFs were cleaned following the manufacturer's instructions and tested for 6 additional days to confirm that the lack of cleaning did not affect the study.

During the performance study the filter flow rate was measured daily using two different methods: (1) measuring the discharge in a graduate cylinder for a period of 1 hour (instantaneous flow rate) and (2) dividing the total volume of treated water by the number of hours (on average 23 hours) that had passed since the previous measurement, (daily average flow rate). The daily average flow rate was compared to the commonly used instantaneous flow rate in order to assess the flow rate variability between measurements.

Influent and effluent water was tested one day after the source water tank was filled and the day before it was refilled (on average every twelve days) for the following parameters: turbidity (Hach 2100P Turbidimeter), hardness (Hach Hardness, Iron, and pH Test Kit HA-62), free chlorine (Hach Free and Total Chlorine Test Kit CN-70), temperature, pH, conductivity, and total dissolved solids (TDS) (YSI 556 Multiparameter System), total and fecal coliforms (IDEXX Colilert Quantitray 2000). All the parameters were measured in duplicate and the data were averaged for analytical purposes. Influent water samples were taken from the ball valves installed upstream the float valves and immediately analyzed. Effluent water samples for microbiological, chlorine, turbidity and hardness analyses were taken from the 5-gallon buckets and collected in disinfected containers used for the instantaneous flow rate test. The maximum residence time of the sample in the receptacle was one hour. The rest of the tests were conducted using effluent water samples collected in the treated water containers with a maximum residence time of 24 hours.

Flow rate and water quality measurements from the three systems were then compared with the aim to assess how the different water parameters impact the flow rate behavior. The data analysis was performed using the statistical software MINITAB 15.0.

RESULTS AND DISCUSSION

The statistical information that describes the flow rate data of the three systems is summarized in Table 1. The average of the three CPFs associated with each set was used for each flow rate measurement. It is important to note that the mean value of both SW and CW is below the lower limit value of the recommended flow rate range (1 to 2 Lh^{-1}) while the mean value of TW is almost at the upper limit. The higher standard deviation in TW reflects the higher variability with respect to the other systems.

Instantaneous and daily average flow rate data, as well as the differences between their paired measurements were tested for normality and in all tests the null hypothesis that the data are normally distributed was rejected. Therefore, non-parametric test procedures for the statistical data analysis were employed.

Table 1. Statistical summary of flow rate data.

	SW		**CW**		**TW**	
Variable	**Inst. flowrate**	**Daily avg flowrate**	**Inst. flowrate**	**Daily avg flowrate**	**Inst. flowrate**	**Daily avg flowrate**
N	113	113	113	113	107	107
Minimum (L/h)	0.40	0.38	0.35	0.33	1.40	1.25
Median (L/h)	0.65	0.56	0.62	0.57	2.15	1.98
Maximum (L/h)	1.76	1.67	1.76	1.82	3.18	2.96
Mean (L/h)	0.74	0.68	0.72	0.68	2.12	2.01
St. Dev. (L/h)	0.35	0.32	0.32	0.30	0.36	0.37

The Wilcoxon signed-rank test was used to assess the flow rate variability between measurements. This test allowed for the analysis of the difference between the paired observations resulting from the two different measurements (instantaneous and daily average flow rate) and the determination if they come from the same population, as described in Helsel and Hirsch (1992). The test was conducted for all filters and in all cases the null hypothesis that the median difference between paired observations equals zero was rejected with p-values equal to 0.000. Therefore, the test shows that there is a statistically significant difference between the two methods and that flow rate variability exists between measurements. The average percent differences between instantaneous and daily average flow rate was 9.4 percent for SW, 7.9 percent for CW, and 5.5 percent for TW. In order to reduce the effect of this variability, the instantaneous flow rate data were discarded and the daily average flow rate measurements were used for further flow rate analysis. Figure 2 shows the flow rate behavior for the three systems by depicting the 10-day averaged flow rate versus time.

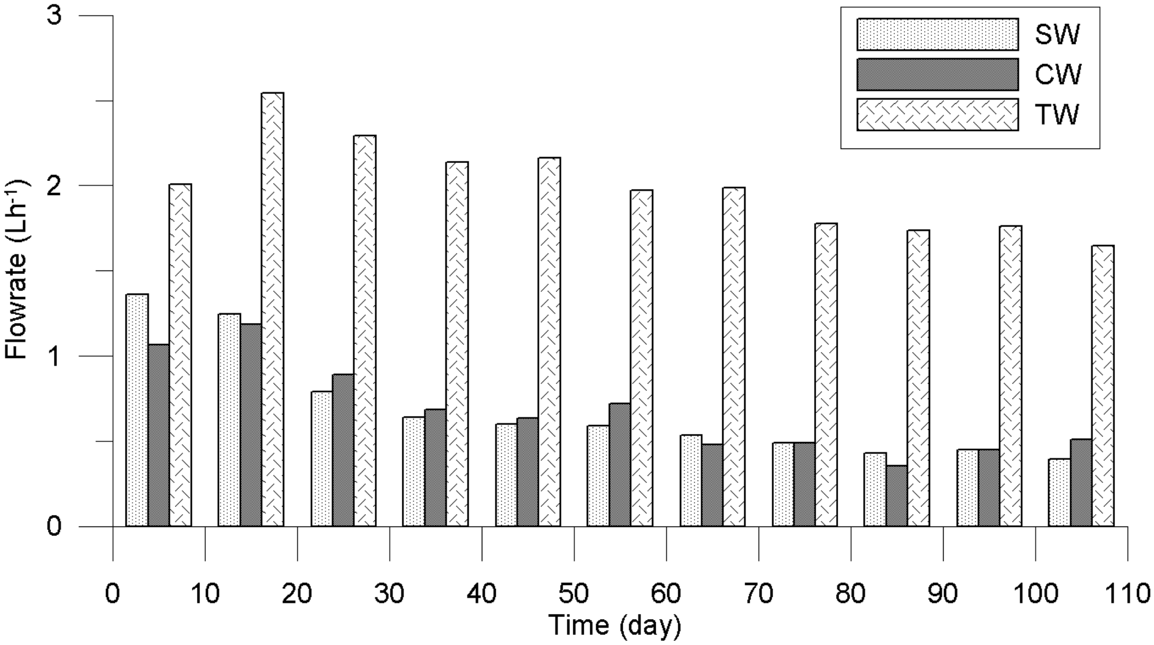

Figure 2. Flow rate data from laboratory experiments.

Inspection of the time series makes evident the similarity between SW and CW flow rate behavior, while TW presents higher values. All three data sets showed a decreasing trend in flow rate with time. However, individual flow rates were not always lower than the immediately preceding flow rate.

The similarity between SW and CW and their difference with TW were tested using the non-parametric two-sample Wilcoxon rank sum test (Mann-Whitney test). The pair combinations of the three systems (SW-CW, SW-TW, and CW-TW) were tested to determine whether the two groups come from the same population. The null hypothesis was that the probability to have one group's flow rate greater than the other group is equal to 0.5 (same median). SW-CW yielded a p-value of 0.8951 (null hypothesis not rejected) while both SW-TW and CW-TW rejected the null hypothesis with a p-value of 0.0000. In addition, the difference in variance between the paired groups was tested using the non-parametric Levene's test, described by Ryan (2007), with the null hypothesis that the variances' difference is equal to zero. Also in this case SW-CW did not reject the null hypothesis (p-value of 0.901) while both SW-TW and CW-TW rejected the null hypothesis with a p-value of 0.0000. Therefore, it can be stated that there is no statistically significant difference between SW and CW, while TW presented a statistically different flow rate behavior.

The water analyses were conducted before and after filtration to characterize treatment efficacy. The average and standard deviation are summarized in Table 2. Measured concentrations at or below detection limits were assumed to be one-half of the detection limit for the purpose of calculating average and standard deviation. If the calculated average value was below detection limits the standard deviation was not calculated. The Missouri Department of Natural Resources (MoDNR) (2015) states that no microbiological contaminants were detected in the calendar year of 2014 in the municipal tap water from Rolla, Missouri. Therefore, the microbiological analyses for TW were limited to a monthly present-absence test to check for cross contamination in the laboratory, which resulted negative for total and fecal coliforms. These results are not included in Table 2. The relatively high variability of coliform counts in both raw SW and CW shown in Table 2 is attributed to die-off of the microorganisms. However, coliform samples were collected from the influent and effluent at the same time so that treatment efficacy calculations were not impacted by the die-off phenomenon.

The TW turbidity values were significantly lower than the turbidity values measured for the raw water from the other two sources. SW and CW showed very similar levels in both influent and effluent water. According to Sawyer et al. (2003) turbidity may be caused by a wide variety of suspended materials that range in size from colloidal to coarse and include both organic and inorganic substances. Turbidity removal was significant in all the systems: in TW's effluent it was lower than the regulatory standard limit presented by the U.S. Environmental Protection Agency (EPA) (1999) while in SW and CW it was just slightly higher. These results are consistent with the flow rate behavior of the three systems analyzed above demonstrating that turbidity is an indicator that suspended particles do impact CPF's flow rate.

The microbiological analysis showed a higher concentration of coliform, especially fecal, in CW than in SW, which reflects a higher biological activity in CW. This is confirmed by the low concentration of dissolved oxygen found in CW. According to EPA (2012) wastewater from sewage treatment plants, such as that used to create CW, often contains organic materials that are decomposed by microorganisms. This causes an increase in the biochemical oxygen demand (BOD) and a decrease in the concentration of dissolved oxygen. Natural organic matter (NOM) is described by Crittenden et al. (2012) as a variety of complex matrix of organic chemicals originating from a water body due to biological activity, including secretion from the metabolic activity of microorganisms and algae. It was hypothesized that the higher CW biological activity would result in a higher potential for biological fouling and a corresponding decrease in the flow rate. However, since there is no significant difference between the measured SW and CW flow rates, that hypothesis does not appear valid.

Percent differences between influent and effluent water in hardness, conductivity, and TDS were not significant in any of the systems. Similar levels were reported in CW and TW, while SW presented lower values, as expected. According to Sawyer et al. (2003) hardness is caused by multivalent cations capable of reacting with anion and precipitate. These results are not consistent with the flow rate behavior demonstrating that inorganic fouling is not responsible for the change in flow rate.

No free chlorine was detected in the influent water of SW and CW while TW showed an average concentration of 0.28 part per million (ppm). Free chlorine concentration in effluent water was below detection limits in all the systems. According to EPA (2013), the maximum residual disinfectant level for chlorine is 4 ppm, fourteen times higher than the maximum detected concentration. Therefore, the measured free chlorine concentrations were considered too low to impact CPF’s behavior. Temperature and pH measurements were consistent between the influent and effluent for all three water sources. In general the results described above agree with the performance study and rehabilitation experiments described in van Halem et al. (2007, 2009).

Table 2. Water quality testing data.

Water property	Raw SW		Treated SW	
	Average	**Std dev**	**Average**	**Std dev**
Turbidity (NTU)	3.26	2.15	0.33	0.09
Hardness (gpg CaCO3)	5	0.5	5	0.4
Conductivity (mS/cm)	0.125	0.009	0.133	0.006
TDS (g/L)	0.082	0.006	0.086	0.004
pH	6.96	0.16	6.80	0.10
Temprature (C)	22.27	0.93	20.67	0.39
Free Chlorine (mg/L)	ND(0.02)	N/A	ND(0.02)	N/A
DO (mg/L)	6.26	0.59	6.24	0.33
Total Coliform (MPN/100 mL)	457.2	723.6	2.1	5.1
Fecal Coliform (MPN/100 mL)	0.4	0.8	0.0	0.0

Water property	Raw CW		Treated CW	
	Average	**Std dev**	**Average**	**Std dev**
Turbidity (NTU)	3.53	4.12	0.37	0.09
Hardness (gpg CaCO3)	16	0.8	17	1.1
Conductivity (mS/cm)	0.513	0.030	0.501	0.028
TDS (g/L)	0.333	0.019	0.325	0.019
pH	6.80	0.23	7.12	0.17
Temprature (C)	21.98	0.35	20.64	0.36
Free Chlorine (mg/L)	ND(0.02)	N/A	ND(0.02)	N/A
DO (mg/L)	4.26	1.74	6.07	0.18
Total Coliform (MPN/100 mL)	1089.7	1068.2	43.4	64.0
Fecal Coliform (MPN/100 mL)	315.8	532.1	0.6	1.4

Water property	Raw TW		Treated TW	
	Average	**Std dev**	**Average**	**Std dev**
Turbidity (NTU)	0.66	0.43	0.23	0.07
Hardness (gpg CaCO3)	16	1.4	17	1.0
Conductivity (mS/cm)	0.502	0.016	0.485	0.052
TDS (g/L)	0.326	0.011	0.323	0.012
pH	6.81	0.40	7.02	0.09
Temprature (C)	21.96	0.37	20.85	0.28
Free Chlorine (mg/L)	0.28	0.18	ND(0.02)	N/A
DO (mg/L)	5.82	1.00	6.11	0.20

In order to compare the flow rate trends of the systems, flow rate was plotted versus the total volume of treated water in Figure 3. All three data sets showed that early time flow rates increase, and after a stabilization period all three flow rates begin decreasing with an almost linear trend. The flow rate growth during the first phase is consistent with other flow rate observations documented by Lantagne et al. (2010), Hubbel and Elmore (2012), Hubbel et al. (2015), and others. According to Lantagne et al. (2010), this initial increase could be due to the washing of combustible material trapped in the CPF during the production process. The total volume of treated water was 1,759 L in SW, 1,758 L in CW and 4,961 L in TW. All the filters passed the quality test at the production location, and thus should have an initial clear water flow rate in the range of 1 to 2 Lh^{-1}. This is true for all the systems, but the graph shows a change in flow rate behavior after the first 400 L more or less have been treated. The vertical line in Figure 3 depicts the separation between this first phase when the flow rate increases, and the second phase when the flow rate stabilizes prior to gradually declining.

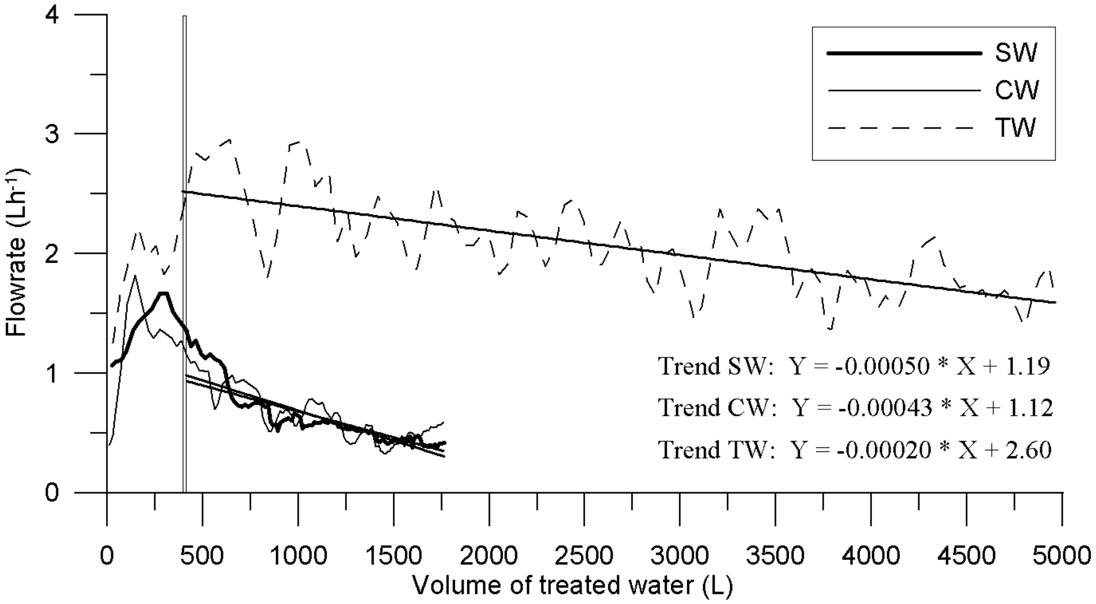

Figure 3. CPF’s flow rate trend analysis.

The equations of the linear trend of the second phase data were calculated to allow for comparison of the slopes. SW and CW showed a similar slope significantly steeper than TW.

SW and CW failed, in terms of water production, after the first 400 L since the flow rate dropped below the lower limit of 1 Lh^{-1} during the second phase. The TW flow rate was above the manufacturer's specification of 2 Lh^{-1} during the first 3,000 L, but below the upper limit of 3.15 Lh^{-1} published by CMWG (2011). Using the CMWG criterion, the TW result can be considered valid and the lifetime can be estimated. The lifetime in terms of water production capacity was calculated adding the volume of water treated during the first phase (400 L) and the second phase. The latter was calculated using the trend line slope with acceptable flow rates inside the range of 1-3.15 Lh^{-1}. The result for TW was a total volume of treated water equal to 8,000 L before it reached the expiration flow rate. Similar estimates could not be calculated for CW and SW because their flow rates were too low.

CONCLUSIONS

Considering the results of both the flow rate experiments and water quality analysis, it can be concluded that turbidity seems to be the principal indicator in characterizing the CPF's lifetime in terms of quantity of treated water. Indeed, the results of the study show how an increase in water turbidity impacts both the average flow rate and the rate at which it decreases. Estimates of the CPF's lifetime with water having different turbidity levels showed that the total volume of treated water before failure can range between 400

L and 8,000 L. However, further research is required to identify the relationship between turbidity and flow rate, and to characterize the suspended particles responsible for clogging.

There is no evidence that biological activity also contribute to premature failure of CPFs and the data did not indicate that chemical precipitation is responsible for the filter clogging.

Flow rate is a powerful indicator of CPF's performance since it readily provides information about water production capacity and performance of the filter in terms of removal efficacy, but its behavior has to be better understood. This study indicates that the results from the initial flow rate tests that are commonly conducted by the manufacturers as quality test using clear water could be non representative of the average flow rate during the lifetime of the CPF.

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II. CHARACTERIZATION OF THE RELATIONSHIP BETWEEN CERAMIC POT FILTER WATER PRODUCTION AND TURBIDITY IN SOURCE WATER.

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ABSTRACT

Ceramic pot filters represent a common and effective household water treatment technology in developing countries, but factors impacting water production rate are not well-known. Turbidity of source water may be principal indicator in characterizing the filter's lifetime in terms of water production capacity. A flow rate study was conducted by creating four controlled scenarios with different turbidities, and influent and effluent water samples were tested for total suspended solids and particle size distribution. A relationship between average flow rate and turbidity was identified with a negative linear trend of 50mLh^{-1}/NTU. Also, a positive linear relationship was found between the initial flow rate of the filters and average flow rate calculated over the life of the experiment. Therefore, it was possible to establish a method to estimate the average flow rate given the initial flow rate and the turbidity in the influent water source, and to back calculate the maximum average turbidity that would need to be maintained in order to achieve a specific average flow rate. However, long-term investigations should be conducted to assess how these relationships change over time. CPFs rejected fine suspended particles (below 75µm), especially particles with diameters between 0.375µm and 10µm. The results confirmed that ceramic pot filters are able to effectively reduce turbidity, but pretreatment of influent water should be performed to avoid premature failure.

Keywords: ceramic pot filter; drinking water; flow rate; particle size; suspended solids; turbidity

1. Introduction

Ceramic pot filters (CPFs) have become a common household water treatment solution in areas where people rely on untreated surface water, or where the risk of recontamination during water distribution and storage is high. According to Hunter (2009), CPFs are the most effective over the long-term among various household water treatment technologies, and Oyanedel-Craver and Smith (2008) found that the silver coated CPFs, made using primarily local materials and labor, represent a sustainable point-of-use water treatment technology for poor communities. The most widely available locally-produced CPF is the ICAITI/PFP type described by Lantagne (2010) which has been adopted in over twenty countries. However, a study of the current practices in CPF manufacturing in developing countries described by Rayner et al. (2013) shows that manufacturing processes vary widely both between and within factories posing concerns about the consistency and quality of locally produced filters due to the absence of standardized quality control procedures. In addition, variability in characteristic of the influent waters, and in use and cleaning practices makes it difficult to predict the quantity of water that a CPF will produce over its lifetime.

Several studies have been conducted both in the laboratory and in the field to better understand CPFs behavior and assess their effectiveness in terms of removal efficacy of microorganisms, suspended particles, and water production capacity. Simonis and Basson (2011) presented an overview of fifteen laboratory and field studies of bacterial testing showing an average log reduction value (LRV) of 2.0 for E.*coli* that corresponds to the threshold required by the World Health Organization (WHO) (2011) for a household water treatment to be considered protective against bacteria. However, the study documented a high variability in the efficacy, with LRVs ranging from 0.9 to 6.8. Bielefeldt et al. (2010) described the particle removal performance of six CPFs made in Nicaragua using water engineered with natural particles (with a turbidity of 40NTU) and kaolin clay particles (with a turbidity of 3NTU) from 2μm to 100μm, and with fluorescent microspheres (0.02-10μm) to simulate microorganism removal efficacy. The 40NTU scenario presented an average LRV of turbidity slightly below 2.5. Larger microspheres were preferentially removed with average LRVs from 1.5 (0.02μm particles) to 3.2 (10μm particles). The smallest particles (0.02-0.1μm) were partially washed out from the CPF when clean water was filtered after the experiments, and similar results of contamination of clean water treated after spiked tests have been observed with E.*coli* by Bielefeldt et al. (2009). A long-term investigation described by Salvinelli and Elmore (2015) showed that flow rates decrease over time and that turbidity negatively affects both the average flow rate and the rate at which it decreases. According to Lantagne (2001) and van Halem et al. (2007), flow rate decrease is significant when surface water is treated, and scrubbing the filter, as recommended by manufacturers and the Ceramic Manufacturing Working Group (CMWG) (2011), partially and temporally restores the flow rate. Van Halem et al. (2009) concluded that a potential cause of failure is the physical fouling by colloids, and that neither organic nor inorganic fouling are the principal causes of clogging. Therefore cleaning the filtering unit provides a temporary benefit but does not prevent long-term clogging, thus the flow rate is the limiting factor of CPFs' lifetime and sustainability.

Mihelcic et al (2009) stated that turbidity has a negative impact on many water treatment processes in different ways, including clogging filters and therefore reducing their effectiveness. They also concluded that turbidity is easily measurable in the field with the use of a turbidity tube, and that the pretreatment turbidity limit for ceramic filters is between 15NTU and 20NTU. 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. The models do not include the effect of turbidity and filter clogging over time, and a quantitative description of how turbidity affects filter hydraulic performance is suggested as future work. According to Salvinelli and Elmore (2015), turbidity seems to be the principal indicator in characterizing CPF lifetime in terms of water production capacity, but its relationship with CPF flow rate is not well understood. It was also concluded that initial flow rate is a powerful indicator of CPF performance, but it is unclear how it can be representative of the average flow rate.

This paper describes a study of CPF water production capacity under controlled conditions using four different turbidity scenarios. The primary purpose of this study is to assess the relation between turbidity and flow rate with the intent of identifying a method to estimate CPF average flow rate. The secondary objective is the characterization of the suspended particles retained and released by the filter in order to better understand the clogging mechanisms and identify possible pretreatments that could enhance the filter lifetime.

2. Material and methods

An experiment was conducted in the ground water hydrology laboratory of the Missouri University of Science and Technology (Missouri S&T) to assess how turbidity impacts CPF flow rate. Twelve ICAITI/PFP type filtering units manufactured and quality tested by a CPF factory located near Antigua, Guatemala were selected from a stock shipped to

Missouri S&T. The quality control test in the factory consists of three consecutive one-hour falling head flow rate tests conducted using clear water and the calibrated T-device described by CMWG (2011). Only filtering units producing between $1Lh^{-1}$ and $2Lh^{-1}$ at least in two tests are accepted. All the filters used in the study passed the quality test at the factory, but their flow rates were not recorded and provided to the authors. First, the twelve filters were soaked in deionized (DI) water for one day and a 24-hours constant head flow rate test was conducted in order to establish a baseline daily average flow rate for each individual filter, called initial flow rate (Qi). Then the filters were divided into four sets of three, and each set was used to establish four different systems with the same setup and conditions except for the turbidity of the untreated water. Three different engineered waters were created mixing municipal tap water from Rolla, Missouri, USA, and alluvial soil from a local river called Little Piney Creek. The fourth water source was tap water from the Rolla, Missouri municipal system. The soil was collected, dried at 105°C for 24 hours, crushed using a soil mortar and pestle, sieved through a 200-mesh (0.075mm) test sieve (Soiltest Inc.) using a portable sieve shaker (CE Tyler RX-24), and added to the tap water in three different concentrations: 125mg/L for the Low Turbidity (LT) system, 250mg/L for the Medium Turbidity (MT) system, and 375mg/L for the High turbidity (HT) system.

In order to maintain constant conditions and to maximize the flow rate of each filter over the time that the experiment was conducted, constant head apparatuses similar to the one described by Salvinelli and Elmore (2015) were used. With the goal of reducing the sedimentation of suspended particles and therefore maintaining the turbidity level relatively constant in the water sources, a compressed air distribution system was added to the original design for the three systems using engineered water, as shown in Figure 1. Likewise, the pump timer frequency was increased and the water was recirculated every fifteen minutes.

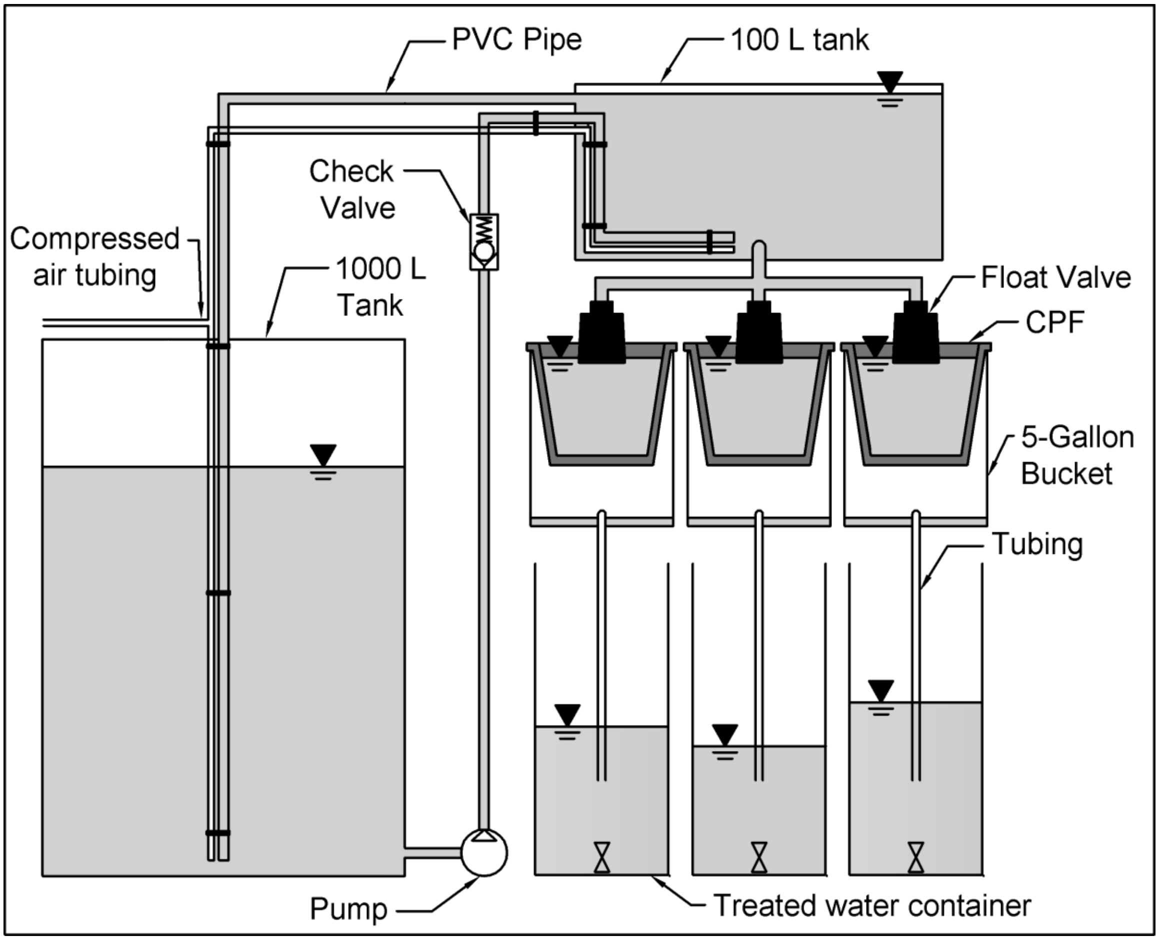

Figure 1. Constant head apparatus with air mixing (after Salvinelli and Elmore 2015).

Experiments were conducted over a 23 day period. The daily average flow rate (Q) was measured by dividing the volume of treated water by the number of hours (on average 23 hours) that had passed since the previous measurement, and recorded as Lh^{-1}. Turbidity (T) of the influent water was also measured every day for each filter using a Hach 2100P

Turbidimeter and recorded in NTU. Influent water samples were taken from the float valves outflow and immediately analyzed in duplicate.

At day 8 and 11 the systems were stopped and, once empty, the filters were rinsed with two litres of (DI) water to collect the particles retained by the filtering unit. Then, a sample of influent water taken from ports installed between the 100 L tank and each float valve, the DI water used to rinse the filters, and the water collected in the 5-gallon bucket were analyzed for turbidity, total suspended solids (TSS) and particle size distribution (PSD) in order to quantify and characterize the particles retained and released by the filters. The TSS tests were conducted according to the American Society for Testing and Materials standard test method D5907-13. The PSD was tested in triplicate using a laser diffraction particle size analyzer (Beckman Coulter LS200) in the paleoclimatology laboratory at the University of Missouri-Kansas City (UMKC). Prior to the PSD analysis, 5mL of a 5 percent solution of sodium hexametaphosphate was added to the 100mL samples that were then mixed with a magnetic stirrer for 15 minutes in order to avoid grain flocculation.

The collected data were then analyzed in order to evaluate any relationship between the measured parameters and to assess any impact on the CPFs flow rate. The statistical software MINITAB 15.0 was used to perform the data analysis.

3. Results and discussion

The source water turbidity data for each system collected during the duration of the experiment is summarized in Figure 2. Upper and lower points represent maximum and minimum values, boxes indicate the 25th and 75th percentile boundaries, the line within each box represents the median value, and the symbols are arithmetic means.

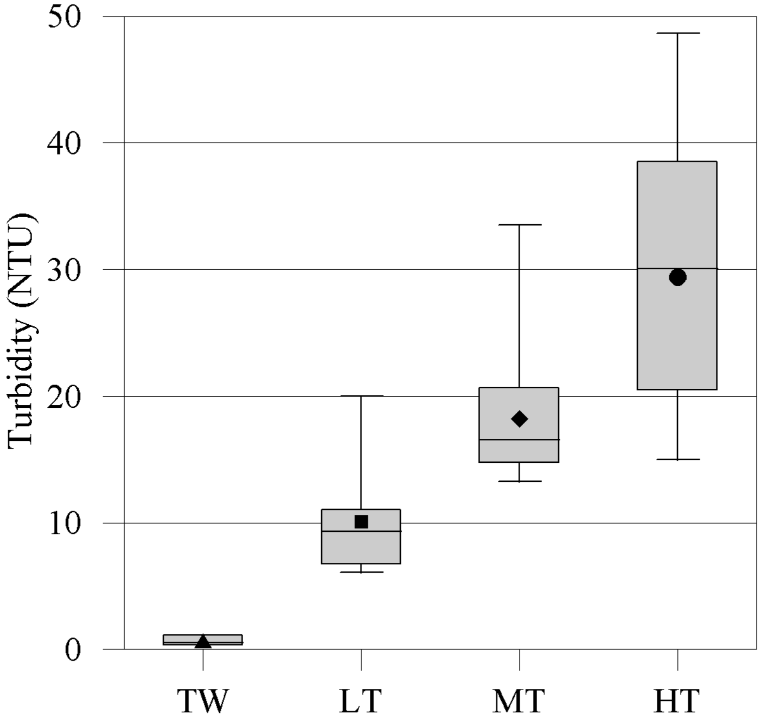

Figure 2. Box-whisker plot of the turbidity in the water sources.

The plot shows that the turbidity variability increases at higher turbidity levels. The turbidity values cover turbidity levels up to 30NTU representing the turbidity of source waters typically treated by CPFs. Lantagne (2001) reported turbidity levels before filtration ranging from 0NTU to 62NTU with an average of 10NTU in 24 homes in Nicaragua. A retrospective study of CPFs distributed in Cambodia described by Brown and Sobsey (2007) presents influent turbidities from 160 households with an arithmetic mean of 9NTU and a median of 2.5NTU. Turbidities with an average equal to 2.4NTU and a median equal to 1.4 were measured in 20 households in coastal Guatemala by Savinelli et al. (in review).

The statistical information that describes Qi and the average Q for the entire duration of the experiment (Qa) for each CPF is summarized in Table 1. These two parameters were also tested for normality. The probability plot showed that normal distributions fit both Qi and Qa with all data points falling in the 95 percent confidence intervals for each parameter. Qi presented an Anderson-Darling statistic (AD) equal to 0.229 with a p-value of 0.754 and Qa presented an AD equal to 0.213 with a p-value of 0.807. Therefore, both the Qi and Qa data are from a normally distributed population. In addition the Pearson product moment correlation coefficient was calculated to measure the degree of linear relationship between two variables. The Pearson correlation result was 0.962 and the null hypothesis that the correlation equals zero was rejected with a p-value of 0.000.

Table 1. Statistical summary of flow rate data.

Variable	**Qa (Lh^{-1})**	**Qi (Lh^{-1})**
N	12	12
Mean	1.83	1.65
SE mean	0.20	0.17
Std dev.	0.67	0.58
Minimum	0.71	0.53
1st quartile	1.24	1.22
Median	1.83	1.55
3rd quartile	2.25	2.05
Maximum	3.20	2.70

Visual inspection of the glass fiber filters used to perform the TSS tests indicated a difference in color between the particles found in the water sources, and the particles found in the treated water (collected in the 5-gallon bucket). According to the Geological Rock-color Chart (Munsell Color, 2009) the particles in the source water were dark yellowish brown (10YR 4/2) which was consistent with the color of the soil used to create the turbidity in the source water, while the particles collected from the 5-gallon bucket were moderate reddish brown (10R 4/6) similar to the color of the filtering unit's ceramic matrix. Most of the particles found in the DI water used to rinse the filters were dark yellowish brown, but also a few moderate reddish brown particles were detected. It was assumed that the reddish particles found in the bucket were ceramic particles washed out from the filtering unit and their weight was recorded as lost mass.

The relationship between Qa, average turbidity for each CPF (Ta), Qi, and lost mass are shown in Figure 3. Lost mass data for TW were not available and are not included in the scatterplot matrix.

Qa appears to be negatively correlated with Ta and positively correlated with Qi, while lost mass is positively correlated with both Qa and Qi. This indicates that CPFs with a high Qi lose a bigger amount of mass and this causes an increase in Qa. The variability of Qa in each turbidity scenario appears to be related to the differences between the CPFs' initial flow rates.

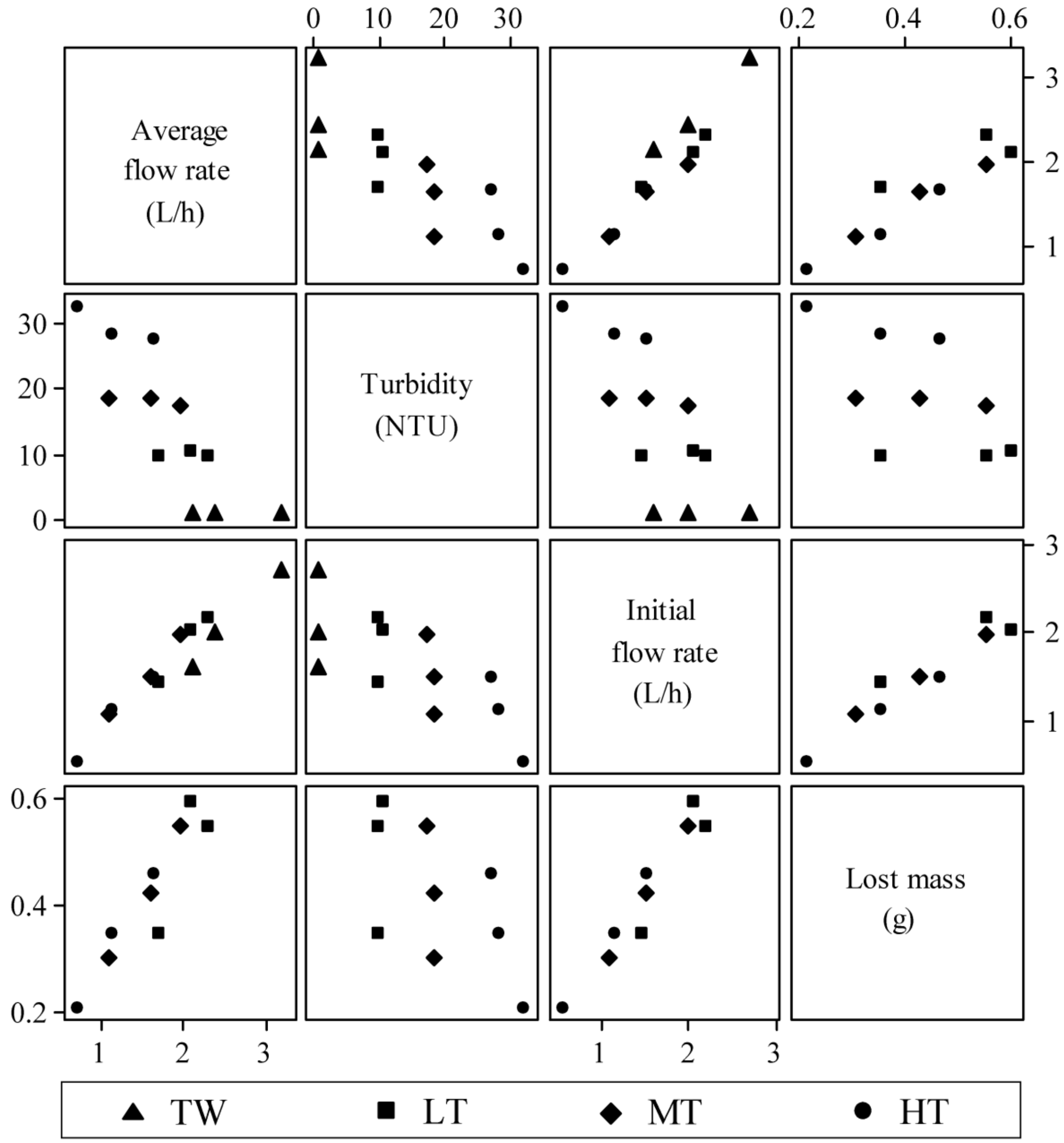

Figure 3. Scatterplot matrix for average flow rate, turbidity,
initial flow rate, and lost mass.

In order to characterize the impact of turbidity in the water source on the filter production capacity, the average flow rate of the three CPFs associated with each system (Qas) was plotted against the average turbidity of each scenario (Tas), as shown in Figure 4.

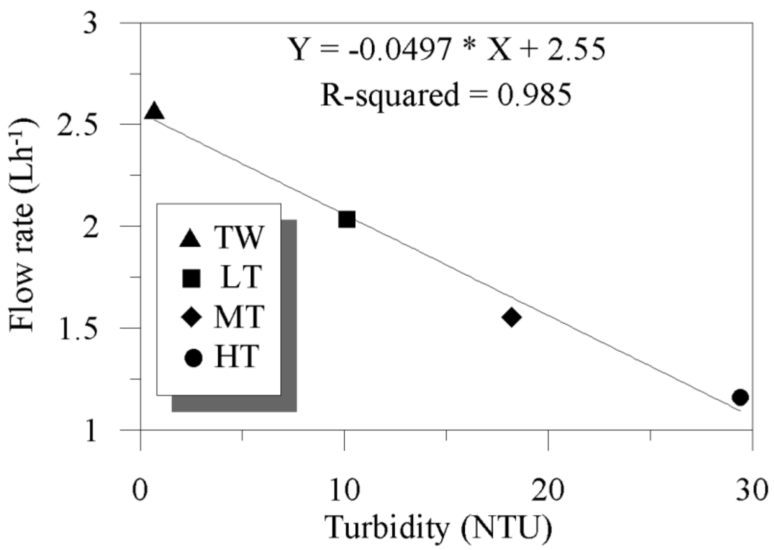

Figure 4. Relationship between system average flow rate and average turbidity.

The graph shows that the water production decreases with higher turbidity levels. Qas data fit a negative line with a decreasing rate of almost 50mLh^{-1} per NTU and an R-squared value of 0.985. In addition the Pearson product moment correlation coefficient was calculated with a result of -0.993. The null hypothesis that the correlation equals zero was rejected with a p-value of 0.007.

Initial flow rate and turbidity are easily measurable parameters and have an opposite impact on average flow rate. The ratio of those values was used to predict the average flow rate as shown in Figure 5. The three values of Qa measured for each system were plotted against the Qi/Ta ratio. In order to show the results at the lowest turbidity level (TW), the X axis has a break from 0.3Lh^{-1}/NTU to 2.3L/h^{-1}/NTU, but no data fell in that range. The Figure 5 lines were fit through the origin, and the resulting R^2 values were relatively high.

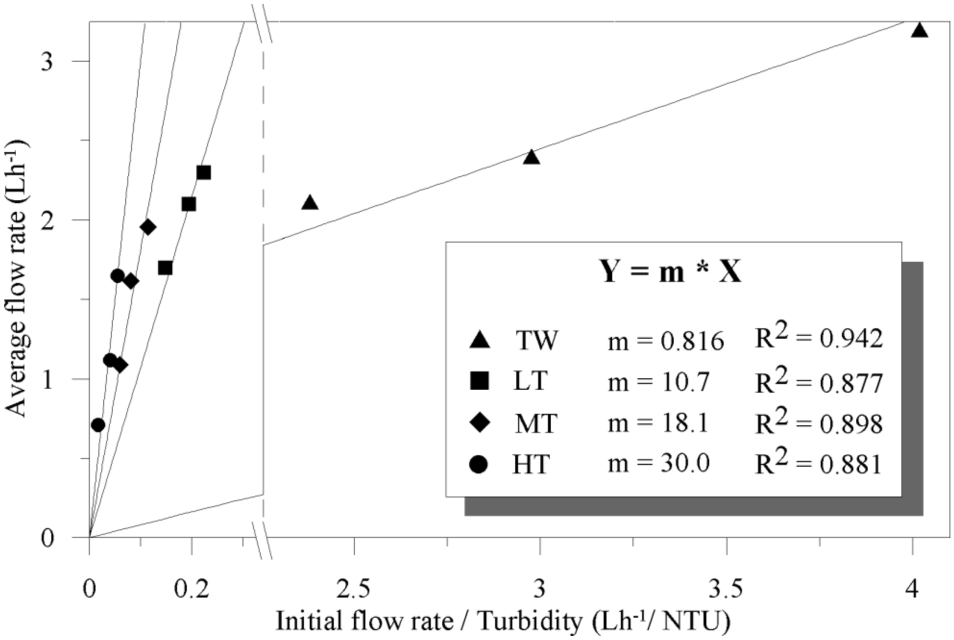

Figure 5. Relationship between average flow rate and
initial flow rate/turbidity ratio for each CPF.

The degree of linear relationship between Tas values and the slope values was measured resulting in a Pearson coefficient of 1.000 with a p-value of 0.000. The initial flow rate of a CPF and the turbidity level of the source can be used to calculate the Qi/T ratio and then the appropriate Figure 5 trend line slope can be used to estimate the average flow rate. It is noted that the Figure 5 slope values approximate the average turbidity used with each set of three CPF's, so it appears that average flow rate of a CPF can be predicted solely from the Qi value.

The analysis was repeated using the averaged values for each 3-CPF system. Qas was plotted against the Qis/Tas ratio, and the result is shown in Figure 6. It should to be noted that the X axis is presented in a logarithmic scale.

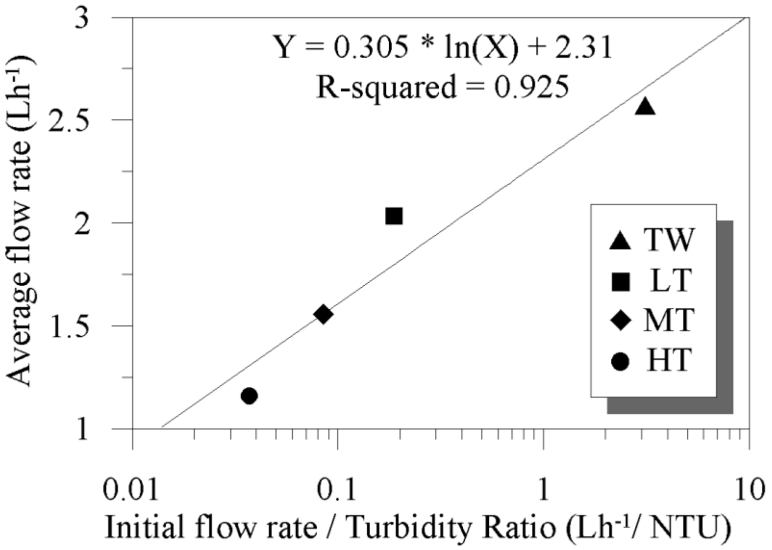

Figure 6. Relationship between average flow rate and initial flow rate/turbidity ratio for each system.

From the graph it is possible to identify a logarithmic relationship between Qas and the ratio between Qis and Tas. The graph also shows that Qas is more sensitive to changes in Qis for high turbidities. This approach allows initial flow rate and source water turbidity to be used to predict the average long-term flow rate of a group of CPFs. Using the trend line equation, it is also possible to back calculate the maximum average turbidity that needs to be maintained in order to achieve a specific average flow rate. For example, given the mean initial flow rate of the 12 CPFs used in this study (1.65Lh^{-1}), and the maximum recommended flow rate (2.00Lh^{-1}), the resulting Qi/Ta ratio is 0.36. The Figure 6 graph predicts that an average turbidity of 4.5NTU should to be maintained.

Samples for PSD analysis were collected from the soil used to engineer the water source, the influent water collected immediately before entering each CPF, CPF rinsate, and rinsate from the buckets used to collect the treated water. Figure 7 shows the PSD curves of the cumulative volume percentage corresponding to each particle size, and Table 2 summarize the statistical information of each sample set.

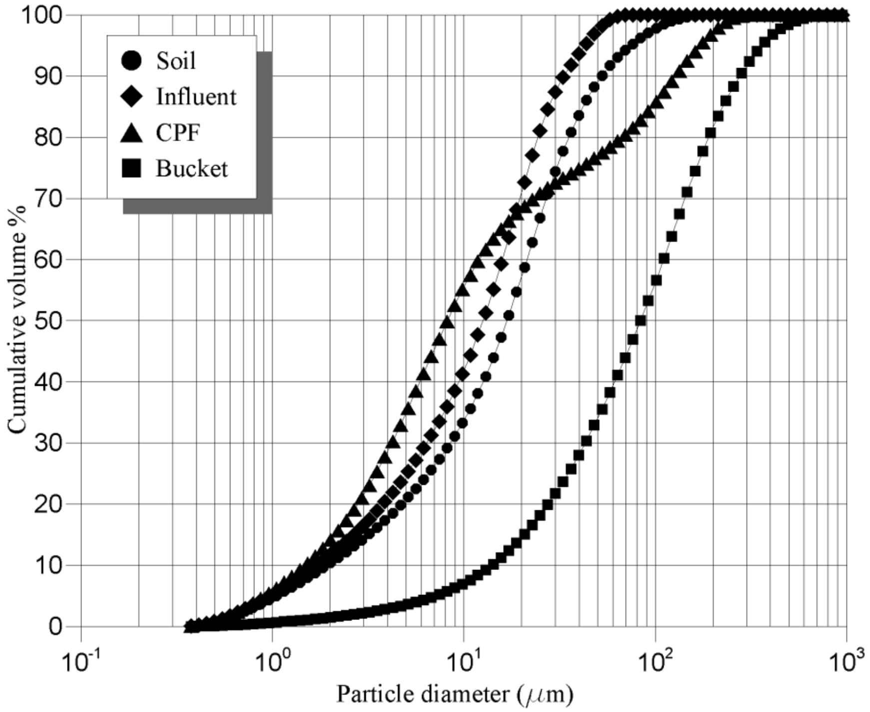

Figure 7. Size distribution curves of suspended particles at four different stages of the experimental procedure.

Table 2. Statistical summary of the results of the PSD analysis

Variable	**Soil**	**Influent**	**CPF**	**Bucket**
Mean (μm)	25.77	16.91	39.89	131.1
Median (μm)	18.46	13.81	9.430	92.06
D[3,2] (μm)	5.718	4.909	4.316	25.19
Mode (μm)	23.81	21.69	7.083	140.1
Std. dev.(μm)	27.2	14.3	60.04	128.7
Var. (μm^2)	739.6	204.6	3804	16555
Skewness	2.259	1.237	1.951	1.815
Kurtosis	6.763	1.428	3.040	4.087
d10 (μm)	2.109	1.847	1.642	15.42
d50 (μm)	18.46	13.81	9.430	92.06
d90 (μm)	57.38	36.57	137.8	304.3

The modes or peaks of the particle size distribution frequency for the soil sample and the influent water sample were similar, but the influent water sample particles were generally smaller. This is due to the sedimentation of the larger particles in either the 1000L or 100L tanks. Bucket rinsate results are from samples collected during the first eight days of experiment. After that time, there was an insufficient mass of suspended solids to permit particle size analysis. The Figure 7 size distribution graph shows that the particles in the bucket rinsate were larger than the particles in the influent water which supports the theory that the filters were retaining the suspended soil particles while releasing ceramic particles. In addition, the Table 2 size distribution statistics present values remarkably different from the influent water samples (mean size and d-values 6.7 to 7.8 times higher).These results are consistent with the visual inspection of the color of the particles retained on the TSS fiber glass filters. The distribution of the CPF rinsate particles was bimodal. The first peak corresponded to a smaller particle size than the peaks of the soil particles and influent water particles. The CPFs rejected suspended particles with a diameter between 0.375μm (particle analyzer detection limit) and 75μm, and particles between 0.375μm and 10μm were more abundant inside the filtering unit than in the influent water. This could be due to the fact that smaller particles have slower sedimentation velocities, and therefore bigger particles reach the ceramic matrix faster. The second peak corresponded to the bucket rinsate peak, and is due to ceramic particles detached from the CPF. The correspondent volume percentage gradually decreased over the duration of the experiment.

4. Conclusions

It is concluded that a relationship between CPFs average flow rate and turbidity exists, and follows a negative linear trend with a decreasing rate of $50mLh^{-1}$/NTU for a source water turbidity range from 0NTU to 30NTU. A positive relationship between initial and average flow rate was also found. Based on these findings it was possible to identify a method that permits estimation of the average flow rate given the initial flow rate and the turbidity of the influent water. Conversely, the same relationship can be used to establish the turbidity limit for a target average flow rate. Since the initial flow rate test is the most common quality control parameter used by CPF manufacturers, this method is easily applicable. However, long-term investigations should be conducted to assess how these relationships change over time.

Ceramic particles detached from both sides of the CPF matrix, but this phenomenon gradually decreased over time. The mass of the ceramic particles washed out from the filtering unit was positively related to both the initial and average flow rates. CPFs rejected fine suspended particles (below 75µm), especially particles with diameters between 0.375µm and 10µm. In general the CPFs used in this investigation were effective at reducing turbidity since no suspended particles were detected in the treated water. However, to avoid premature failure of the filter the turbidity of the influent water should be reduced following simple pretreatment practices including sedimentation and prefiltering through a cloth. The CPF users could visually estimate the effectiveness of pretreatment efforts because, according to Strausberg (1983), turbidity begins to become visible to the human eye at about 5NTU.

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III. CERAMIC POT FILTERS LIFETIME STUDY IN COASTAL GUATEMALA.

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ABSTRACT

Ceramic pot filters (CPFs) are an effective means of household water treatment, but the characterization of CPF lifetimes is on-going. 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 CPF acceptance was characterized by surveying householders in the four subject villages at the beginning and conclusion of the study. Flow rate data showed that the average CPF flow rate dropped below the recommended minimum of 1 Lh^{-1} after 10 months of use; however, the survey results indicated that the consumers were tolerant of the lower flow rates. 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 dropped below accepted standards 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.

Keywords: acceptance; ceramic pot filter; drinking water; field study; Guatemala; lifetime

INTRODUCTION

Lack of safe water, sanitation and hygiene remains a serious world health issue. According to the World Health Organization (WHO) and the United Nations Children's Fund (UNICEF) (2014) 748 million people still lacked access to an improved drinking water source in 2012. Most of these people are poor with over 90 percent living in rural areas and almost a quarter relying on untreated surface water. According to UNICEF (2008), water quality interventions in developing countries have a greater impact when applied at the household level, and Hunter (2009) defined ceramic filters as the most effective long-term household water treatment systems. Several laboratory studies have been conducted to assess the effectiveness of ceramic pot filters (CPFs) presenting promising results, including Oyanedel-Craver and Smith (2008), van Halem *et al.* (2007, 2009), Sobsey *et al.* (2008), Lantagne *et al.* (2010), Mwabi *et al.* (2013) and others. Field investigations which can help understanding the filter behavior in real use conditions and its acceptance by the users are more difficult logistically to execute and are not as abundant in the literature relative to laboratory studies. According to Brown and Sobsey (2006), knowledge of CPFs effectiveness over long periods in the field is an essential condition for successful scale-up and responsible investment, but it has not been studied enough.

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 to filter users. It was concluded that less than 53 percent of the filter removed *E.coli*, and contamination post treatment from storage in unclean receptacles represented a major issue. It was also observed that monitoring visits to the families using the filters was strongly correlated with continued use of the filter. Brown *et al.* (2009) during a field study in Cambodia documented a rate of abandonment of approximately 2 percent per month after implementation and that the $\log_{10}$ reduction value (LRV) of *E.coli* did not appear to have a strong correlation with time in use. A field study about the effectiveness of CPFs in Cambodia is presented by Roberts (2004) and included water quality testing and user surveying. It was concluded that 99 percent of CPFs produced water meeting the WHO “low risk” requirements, and CPF users experienced a reduction of the rate waterborne diseases. A retrospective study of filters distributed in Cambodia described by Brown and Sobsey (2007) found that the geometric mean reduction of *E.coli* in filtered water was 98 percent and of total coliforms was 94 percent. A 46 percent reduction of diarrheal disease incidence was documented in the population that used CPFs. *E.coli* reduction by a mean of 96 percent and diarrheal disease incidence reduction by 42 to 49 percent in intervention group members were documented by Brown *et al.* (2008) during the course of an 18-week field study in Cambodia. A four months field study in Sri Lanka described by Casanova *et al.* (2013), found widely variable flow rates and concluded that water production is a limit of CPFs; however, this did not seem to be negatively perceived by the users that in most of the cases declared that the filter produce enough water.

The main CPF manufacturing company in Guatemala which is located near Antigua has been in operation for more than twenty 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). Most of the CPFs were distributed in the central highlands, in the Pacific Coast area, and around Guatemala City. In Izabal, the Atlantic Coast department, CPFs were first distributed as a part of an emergency program conducted by non-government organizations (NGOs) to help several rural villages affected by a major earthquake in May 2009. The filters were reportedly well-received by the local families over the short term but the technology which was new to the inhabitants was not permanently adopted. After that first intervention, NGOs continued distributing filters in the region without characterizing the CPFs' effectiveness and consumer acceptance.

This study describes a two year CPF field monitoring program started in January 2014 as a 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 local NGOs called 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 study objective is to assess CPF user acceptance, and to characterize the 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 where CPFs were distributed by the NGOs ASOPROGAL, Comitato Internazionale per lo Sviluppo dei Popoli (CISP) and Fondazione SIPEC beginning in 2012. The first CPF was donated in every household, while the change of filtering unit was partially subsidized. Table 1 lists the characteristics of the villages.

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 (10m)	Shallow well (2m)	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)
Alphabets	15%	20%	32%	80%
Health care	20%	20%	12%	20%
Sanitation	No	Latrines (37%)	Latrines (70%)	Latrines (90%)

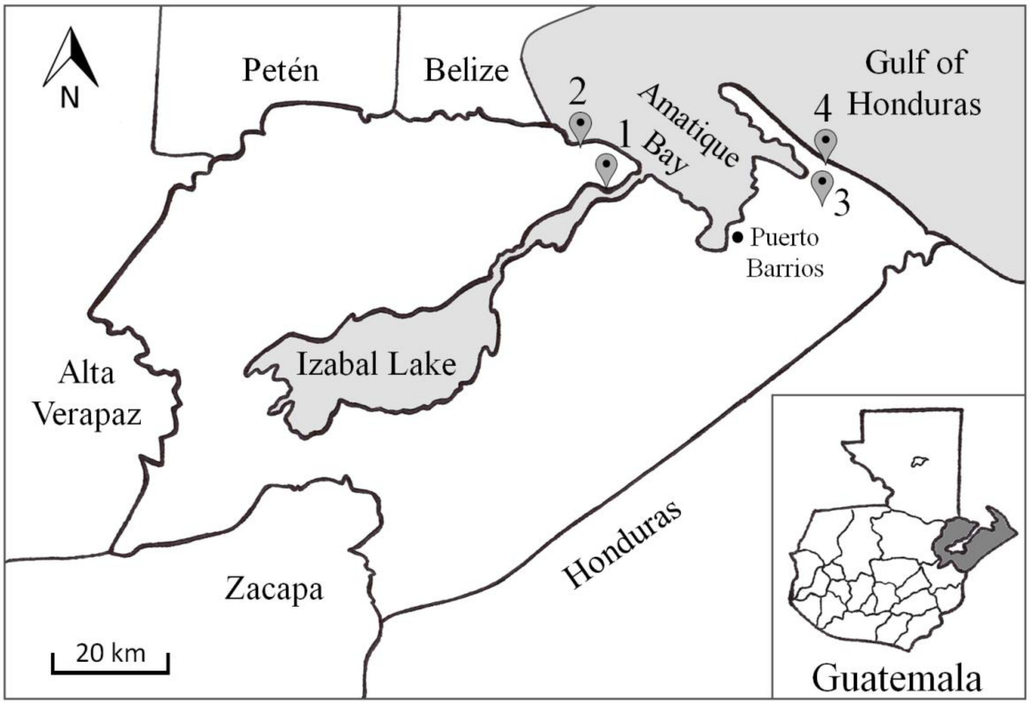

Figure 1. Location of villages participating in the study.

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 twenty 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 the Coliscan Plus Easygel kit (Micrology Laboratories LLC, Goshen, IN) following the manufacturer’s instructions. Coliforms growth media were mixed with water samples (1, 3, or 5 mL depending on a pretesting estimate of the influent water quality), plated in a Petri dish, sealed, and incubated at 35.5°C for 24 hours. The *E.coli* and other coliforms colonies were counted and reported using the unites of CFU/100mL. 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).

The CPF’s water production capacity was characterized approximately every two months through falling head flow rate tests by employees of local NGOs that received trainings 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 2L graduated cylinder. In addition, the date, time and volume of water poured in the filter were recorded on a log sheet by the users every time that the CPF was filled.

In order to evaluate the potential adoption and acceptance of the filters, evaluations of the filter performance were obtained by interviewing CPF users during S&T visits at the beginning and at the 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, by the Missouri S&T, MO, USA, April 3, 2014. First a community meeting was organized to obtain a general idea of the users' satisfaction, and then the families participating in the study were interviewed individually. The data 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 question were translated to Q'eqchi' by a native speaker with experience in community work. Table 2 shows the content of the English version of the survey. The total number of monitoring activities conducted en 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 other family 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 is summarized in Figure 2. In all box-whisker plots of this paper, upper and lower points represent maxima and minima, boxes indicate 25th and 75th percentile boundaries, the line within each box represents the median value, and the points are arithmetic means. 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/100mL, 33 CFU/100mL for a 3 mL sample, and 20 CFU/100mL for 5 mL samples. A total of 37 samples were analyzed for total coliforms presence, 24 samples were analyzed for *E.coli*, and 23 for turbidity.

Figure 2 shows that 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 percent of the effluent samples. In addition, more than 75 percent of the effluent samples present turbidity levels lower than one Nephelometric Turbidity Unit (NTU).

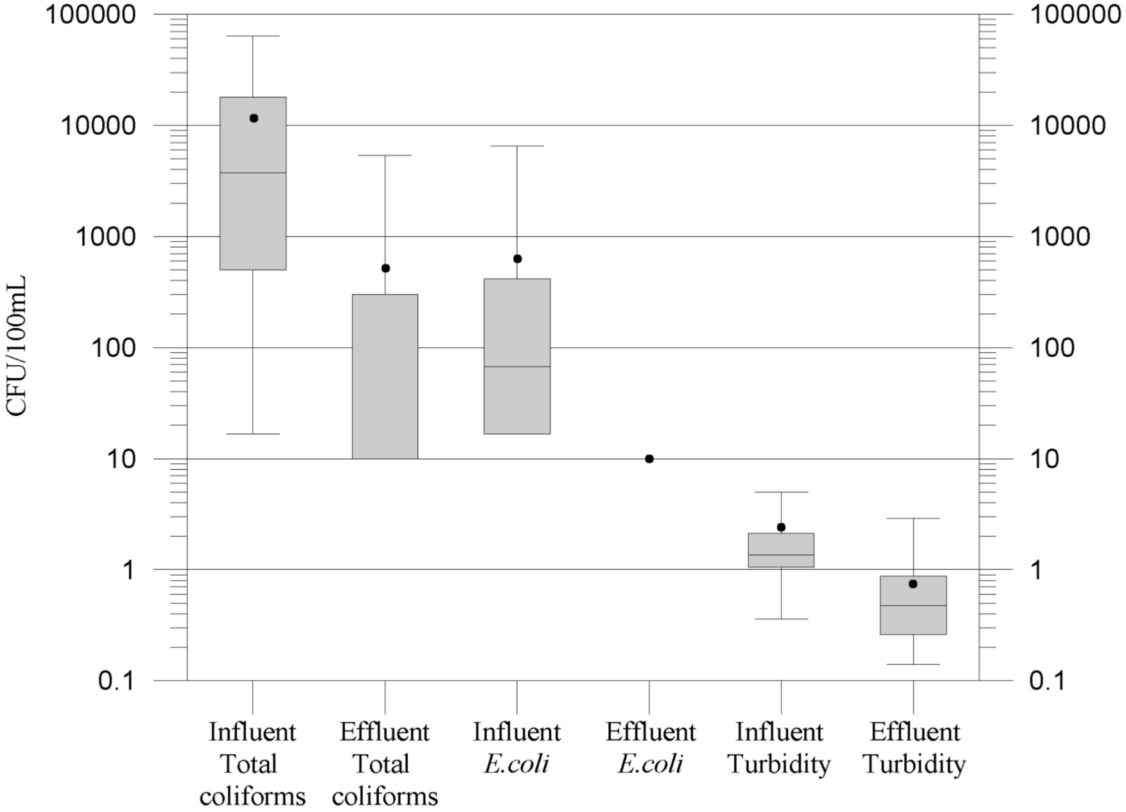

Figure 2. Summary of microbiological contamination and turbidity in all influent and effluent samples.

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*, was not present. The Center 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 the CPF's performance during its lifetime, 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 eight percent of the samples collected from households in the four villages, both influent and effluent results were below detection limits, and those results were not included in Figure 3.

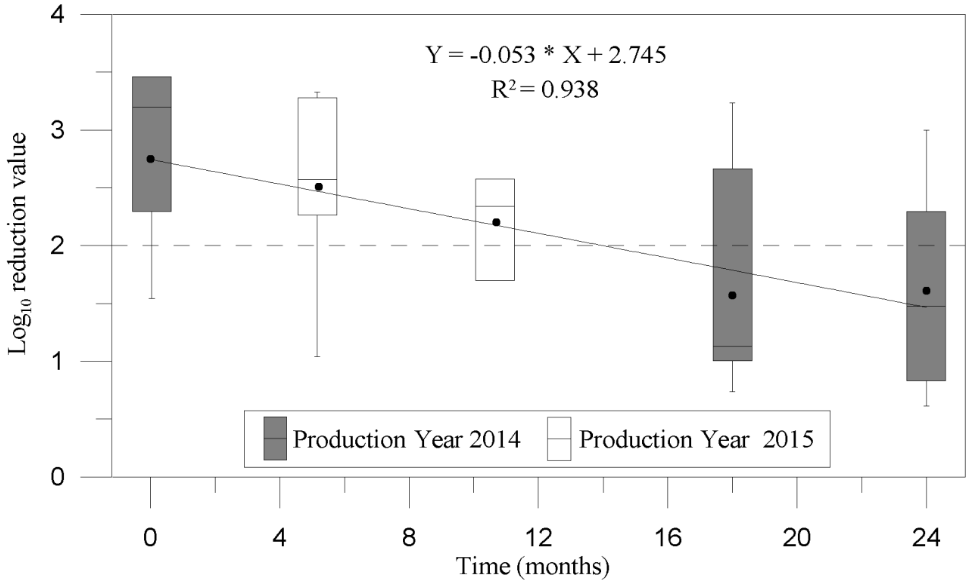

Figure 3. LRV of total coliforms by time of usage of the CPF.

The time series shows that the CPFs bacterial removal capacity decreases over time and the average LRVs follow a linear negative trend with an R-squared value of 0.938. Brown and Sobsey (2007) stated that LRV is a valuable measure of the technology performance, however, reduction is a function of influent water 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) indicated 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.

Flow rate results for the two different production years are represented in Figure 4. Both data sets showed a decreasing trend in flow rate with time, but with different behaviors. Flow rates in PY14 presented an initial growth, and after reaching the maximum, started to decline until the end of the study, while in PY15 started decreasing since the beginning and followed an almost linear trend. Flow rates behavior in PY14 is consistent with other flow rate observations documented by Lantagne *et al.* (2010), Hubbel and Elmore (2012), Salvinelli and 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 caused by suspended material in the water source or other mechanisms that gradually clog the pores. Salvinelli and 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 NTU to 4.47 NTU which was similar to the PY15 influent 0.9 NTU to 5 NTU. Likewise, the PY14 influent total coliforms range of 17 CFU/100mL to 46,200 CFU/100mL was similar to the PY2015 range from 17 to 64,000 CFU/100mL. Therefore, it appears that the difference in flow rate behavior is most likely the result in 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.

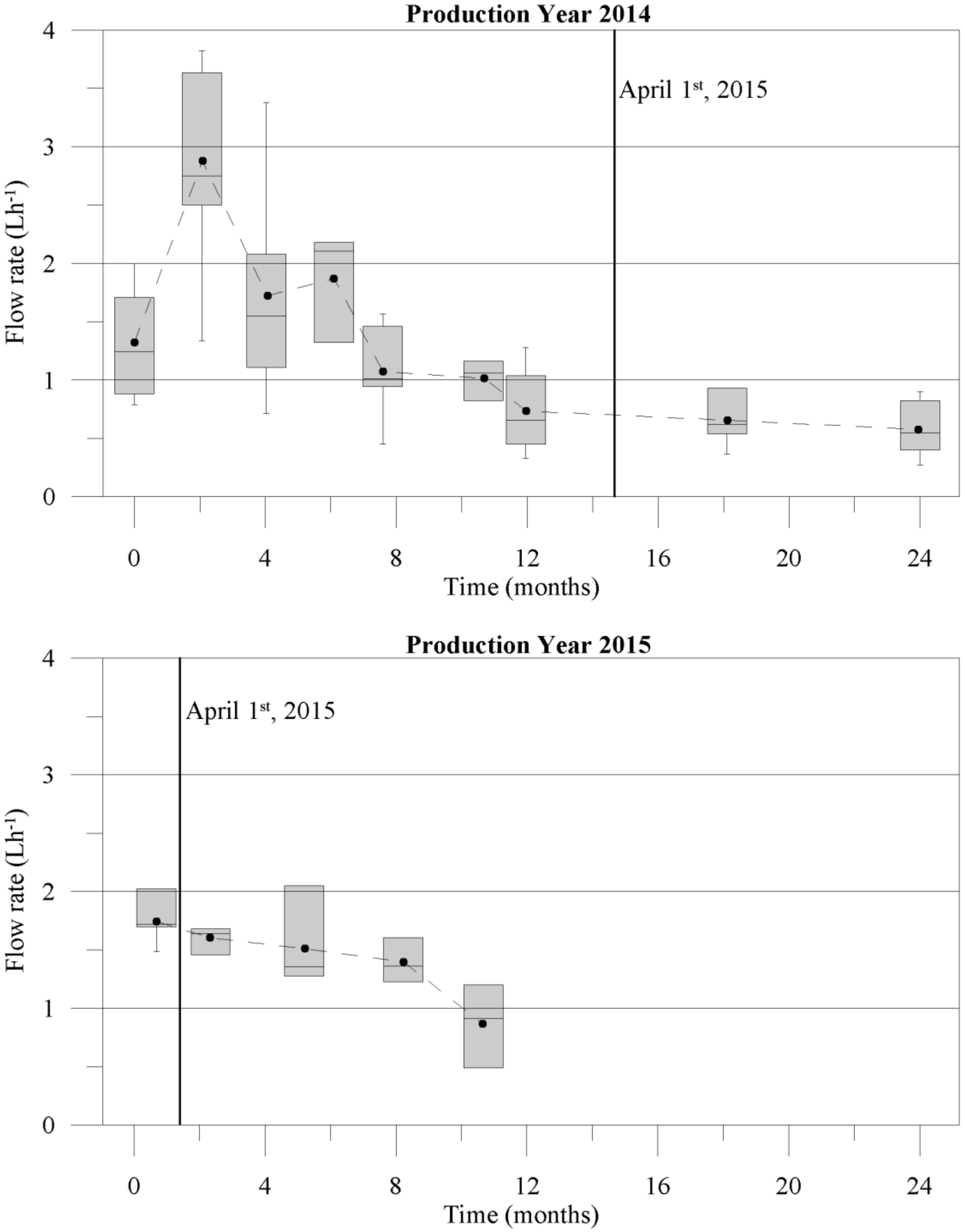

Figure 4. CPF’s flow rate by time of usage for two different production years.

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, 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. Rayner *et al.* (2013) stated that the quality control flow rate ranges vary from a minimum of 1 Lh^{-1} to 3 Lh^{-1} to a maximum of 2 Lh^{-1} to 5 Lh^{-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 Lh^{-1} to 2 Lh^{-1}, while CMWG (2011) established an acceptable range between 1 Lh^{-1} and 3.5 Lh^{-1}. The company that made the CPFs used in this study accepts filters with flow rates between 1 Lh^{-1} and 2 Lh^{-1}. PY14 CPFs initially met the manufacturer's requirements, exceeded the 2 Lh^{-1} threshold around the second month of use, and then went back to the expected range prior to dropping below 1 Lh^{-1} at the end of the study. PY15 filters presented more consistent values and maintained the flow rate between 1 Lh^{-1} and 2 Lh^{-1} during the study. On average, the CPFs production dropped below 1 Lh^{-1} after approximately 10 months of use.

A total of 25 families with an average of 5.6 people per household participated in the interviews. The main water source was reported to be rain water collected from rooftops and stored in tanks for 28 percent of the families, 18 percent relied on surface water (streams), and 54 percent used shallow wells (defined here as ≤10 m in depth). 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 instruction, 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 just 20 percent of them reported cleaning the filtering units using bleach or soap. However, 63 percent of the families declared that they preferred to clean the filter more frequently than quarterly. According to Salvinelli and 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 percent of the families reported that the filters produced sufficient drinking water, but it is important to note that 20 percent of them owned two CPFs and a single CPF would not have produced a sufficient quantity of treated water. A high percentage, 88 percent, of the respondents reported that the use of the filter had positive consequences on the health condition of the family members, especially the 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 declared to be clear, fresh, safe and with a better taste than boiled and chlorinated water. In addition users that previously used to drink boiled water were satisfied about saving the time and energy previously required to gather firewood and prepare the fire. On the other side, the most common CPF disadvantages were identified as the slow filtration rates and the fact that the CPFs are fragile and can easily break.

The community meetings also showed satisfaction between the users, and the positive impact of the follow-in visits seemed to extend beyond the five volunteer households in each village. In January 2014, 57 percent of families in village 1 and 63 percent of families in village 2 changed the filtering units covering part of the cost and reaching, in January 2016, up to three years and half of continued use of CPFs. These results are consistent with Lantagne (2001), which concluded that continued use of the filter was strongly correlated with monthly visits to the household by the local NGO or community leaders.

The total volume of treated water was recorded daily during the first two months of use by five families using PY14 filters, and three families using PY15 filters. PY14 produced an average of 12.3 Lday^{-1} and PY15 10.0 Lday^{-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. This permits to predict how variables like 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 subject of this study and the hydraulic conductivity was back calculated for each production year based on the average of the first two flow rate measurements, corresponding approximately to the first two months of use. For PY14 the average flow rate resulted 2.43 Lh^{-1} and for PY15 1.7 Lh^{-1}.

Figure 5 shows the predicted daily volume of water produced by the two production years considering four different filling frequencies.

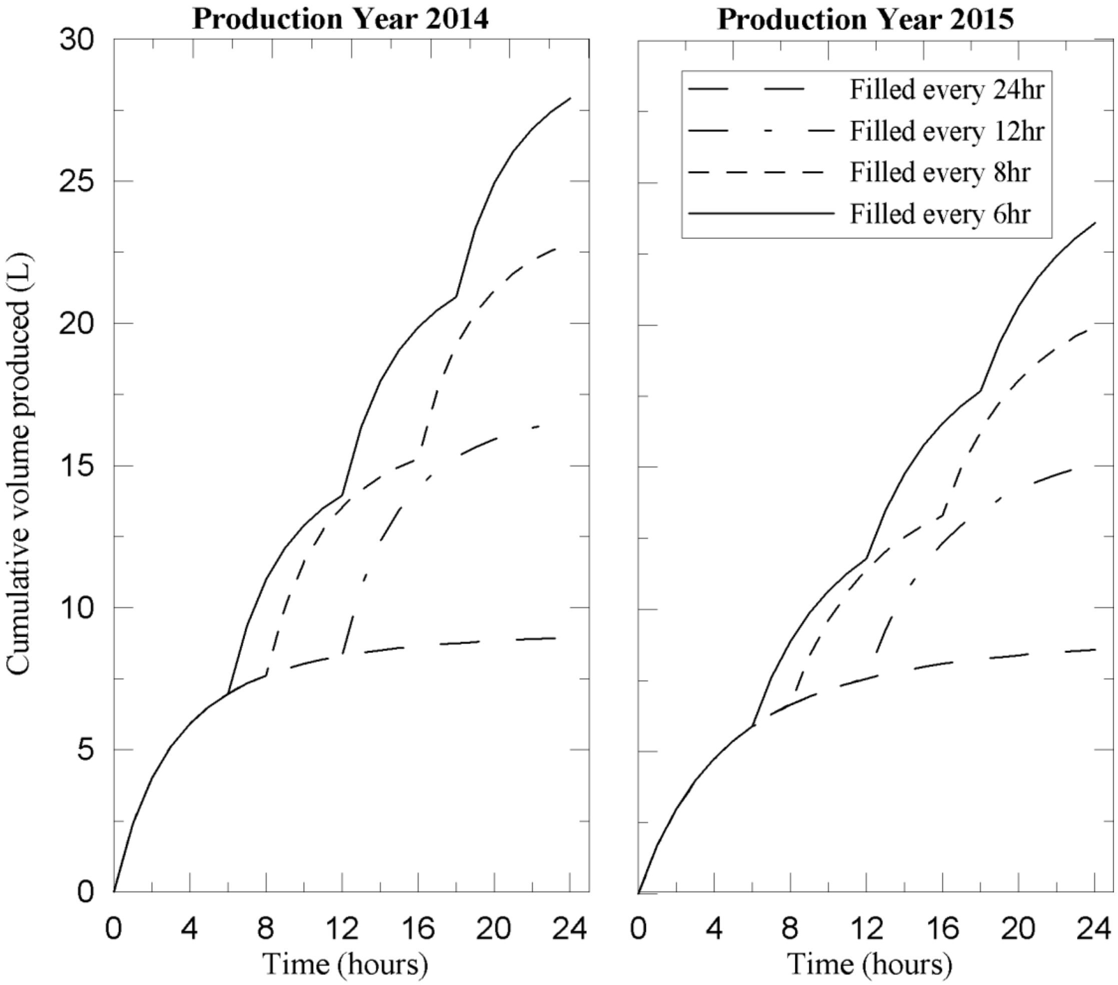

Figure 5. Model prediction of cumulative volume of water produced, V(t), if filters are refille once per day (every 24hr), twice per day (every 12hr), three times per day (every 8hr) and four times per day (every 6hr). After Schweitzer *et al.* (2013).

The daily filling frequencies reported by the users were an average of 2.5 for PY14 and 2.0 for PY15. Figure 5 shows that the volume of water predicted by the model (around 20 Lday^{-1} for PY14 and 15 Lday^{-1} for PY15) is higher than the volume reported by the filter users. This could be because the user did not fill 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 field data shows 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. However, a negative correlation between filter disinfection efficacy versus time in use was observed, and after 14 months treatment dropped below the standards. This could be a concern because consumers would not readily be aware of the increased risk.

The CPF flow rates were maintained in the recommended range of 1 Lh^{-1} to 2 Lh^{-1} during the first ten months of use. However, 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 filling the filters more frequently.

In general, filters are well accepted by users who appreciated the aesthetic quality of the treated water, reported lower incidences of health problems especially among children, and expressed their preference of the CPFs over other treatments like boiling or chlorinating. Unlike previous experiences with CPFs in the region, users that participated in the field investigation have been using the filter during up to three years and half. It can be concluded that presence of an ongoing monitoring program seemed to increase the acceptance rate and to cause an improvement in use and maintenance practices.

Field data is more difficult logistically to collect relative to laboratory data. However, this study illustrates how a synergistic collaboration between university researchers, local NGOs and water consumer can generate data that can be used to characterize the real-life performance of CPFs. There is the potential that this type of collaborative effort could include governmental organizations and CPF manufacturers, and provide more detailed information regarding health conditions of target and control groups during future studies.

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SECTION

2. SUMMARY OF RESULTS

2.1. RESULTS FROM PAPER I

A statistically significant difference was found between instantaneous (1 hour) and daily average flow rate measurements (on average 23 hours). This indicates that flow rates varied between daily measurements despite the fact that a relatively constant head was maintained through each CPF. All three data sets showed that early time flow rates increase and, after a stabilization period around 400L of treated water, start decreasing with an almost linear trend. Surface water (SW) and challenge water (CW) systems presented similar flow rate behaviors and average flow rates below the recommended threshold of 1Lh^{-1}. Flow rates in the tap water (TW) system showed higher variability, slower decrease, and an average value of 2.12 Lh^{-1}.

All the CPFs effectively reduced microbiological contamination and turbidity, while hardness, conductivity, total dissolved solids (TDS), and pH were similar in influent and effluent waters. Influent CW presented higher biological activity with high coliform and low dissolved oxygen concentrations. SW and CW showed similar and higher average turbidities, while hardness, conductivity and TDS were similar and higher in CW and TW.

Comparing data from the flow rate tests and the water quality analysis illustrated that biological and inorganic fouling does not seem to be responsible for the change in flow rate. On the contrary, average turbidity levels are consistent with the flow rate behaviors demonstrating that turbidity do impact CPFs flow rate and lifetime.

2.2. RESULTS FROM PAPER II

The turbidity values in the four scenarios covered turbidity levels up to 30NTU representing the turbidity of source waters typically treated by CPFs, with an increase in variability at higher turbidity levels. Both the average (Qa) and initial (Qi) flow rate data from each CPF resulted in a normal distribution, and correlated with a Pearson correlation coefficient of 0.962 and p-value of 0.000. Also, Qa appeared to be negatively correlated with the average turbidity (Ta) for each CPF. Ceramic particles washed out from the filtering unit were found in the treated water bucket. Their weight was recorded as lost mass, and it resulted in a positive correlation with both Qa and Qi. The average flow rate of the three CPFs associated with each system (Qas) and the average turbidity of each scenario (Tas) resulted highly correlated with a Pearson coefficient of -0.993 and a p-value of 0.007. Qas data fit a negative slope line with a decreasing rate of almost 50mLh^{-1} per NTU and an R-squared value of 0.985.

The ratio between initial flow rate and influent water turbidity was used to predict the average flow rate. When the average values for each system (Qis, Qas, Tas) were considered, a logarithmic relationship between Qas and the ratio between Qis and Tas was found. Given the mean initial flow rate of the 12 CPFs used in this study (1.65Lh^{-1}), and the maximum recommended flow rate (2.00Lh^{-1}) the resulting Qi/Ta ratio was 0.36, and an average turbidity of 4.5NTU should be maintained.

Particle size distributions of the soil used to engineer the water sources, and from the influent water were similar, but the influent water sample particles were generally smaller due to sedimentation of the larger particle in the tanks. The particles in the bucket rinsate were larger than the particles in the influent water which supports the theory that the filters were retaining the suspended soil particles while releasing ceramic particles. The distribution of the filtering unit rinsate particles was bimodal. The first peak (6.76µm) corresponded to a smaller particle size than the peaks of the soil particles (23.81µm) and influent water particles (21.69µm). The CPFs rejected suspended particles with a diameter between 0.375µm (particle analyzer detection limit) and 75µm, and particles between 0.375µm and 10µm were more abundant inside the filtering unit than in the influent water. The second peak (133.7µm) corresponded to the bucket rinsate peak (140.1µm), and is due to ceramic particles detached from the CPF. The correspondent volume percentage gradually decreased over the duration of the experiment.

2.3. RESULTS FROM PAPER III

The aggregated data for influent and effluent water samples showed that 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 percent of the effluent samples. In addition, more than 75 percent of the effluent samples present turbidity levels lower than one NTU. The CPFs bacterial removal capacity decreased over time and the average LRVs followed a linear negative trend with an R-squared value of 0.938. On average the CPFs were able to achieve the recommended bacterial reduction (LRV ≥ 2) during the first 14 months of usage. CPFs produced in different years (2014 and 2015) presented a difference in flow rate behavior, but all of them showed a similar decreasing trend of flow rate with time. On average, the CPFs production dropped below the recommended threshold of $1Lh^{-1}$ after approximately 10 months of use. The recorded volume of treated water was on average $12.3Lday^{-1}$ for 2014-CPFs and $10.0Lday^{-1}$ for

2015-CPFs. The volume of water predicted by the model presented by Schweitzer et al. (2013) resulted in 20Lday^{-1} for 2014-CPFs and 15Lday^{-1} for 2015-CPFs. The model also showed that the water production could be increased with frequent and constant filling intervals.

From a total of 25 interviewed families, 28 percent relied on rainwater stored in tanks, 18 percent on surface water, and 54 percent on shallow wells (≤10m). The reported CPF filling frequency was on average 2.1 times per day. Most of the respondents declared to be familiar with the recommended cleaning process. However, 20 percent of them reported to clean the filtering unit with bleach and soap, and 63 percent to clean the filter more than quarterly. A large percentage (76 percent) of the families reported that the filters produced sufficient drinking water (20 percent of them owned two CPFs), and 88 percent reported that the use of the filter had positive consequences on the health condition of family members, especially the 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 that previously drank boiled water were satisfied about saving the time and energy previously required to gather firewood and prepare the 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. Unlike previous experiences with CPFs in the region, users that participated in the field investigation have been using the filter up to 3.5 years.

3. CONCLUSIONS

CPF initial flow rate is the most common quality control parameter used by manufacturers, and it can be a powerful indicator of production consistency, pathogen removal efficacy, and water production capacity. However, it may not be representative of the long-term effectiveness of the CPF since other factors, such as water quality and use practices, can have a significant impact on CPF water production and lifetime.

The experimental work demonstrated that, among the analyzed water parameters, turbidity is the principal indicator in characterizing the CPF lifetime in terms of quantity of treated water. Also, there is no evidence that biological activity contributes to premature failure of CPFs, and the data did not indicate that chemical precipitation is responsible for filter clogging.

It was possible to conclude that a relationship between CPF average flow rate and turbidity exists, and follows a negative linear trend with a decreasing rate of $50mLh^{-1}$ per NTU for influent water turbidity ranging from 0NTU to 30NTU. Initial flow rate and turbidity are easily measurable parameters and have an opposite impact on average flow rate. The ratio of those values can be used to predict the average long-term flow rate and to back calculate the turbidity limit for a target average flow rate. CPFs were effective at reducing turbidity and retaining fine suspended particles. Ceramic particles detached from both sides of the CPF matrix, but this phenomenon gradually decreased over time. CPFs with a high initial flow rate lose a larger amount of mass and this causes an increase in average flow rate.

The field investigation showed that CPFs could maintain flow rate in the recommended range during the first 10 months of use. In addition it was demonstrated that CPFs have the ability to provide good quality water, but the bacterial removal efficacy decreases over time, and after 14 months of use treatment drops below the standards. Therefore it was demonstrated that water production is the limiting factor of CPF lifetime. However, the volume of treated water 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. Of greater concern was the finding that disinfection efficacy dropped over time and consumers would not readily be aware of the increased risk. In general, filters were well accepted by users who appreciated the aesthetic quality of the treated water, reported lower incidences of health problems especially among children, and expressed their preference of the CPFs over other household treatments.

Finally, the field study illustrates how a synergistic collaboration between university researchers, local NGOs and water consumer can generate reliable data that can be used to characterize the real-life performance of CPFs. In addition it can be concluded that follow-up visits with users seem to have a positive impact on CPF acceptance and maintenance practices that extends beyond the volunteer households that actively participated in the study.

3.1. ORIGINAL CONTRIBUTION

The research presented in this dissertation analyzed the parameters that impact CPF effectiveness and lifetime in terms of water production and treatment efficacy. Some of the original aspects of this research include:

- Characterization of CPF flow rate behavior and its relationship with quantity and quality of treated water through a long-term study conducted under controlled and constant conditions.
- Identification of turbidity as the principal indicator of CPF lifetime in terms of water production capacity.
- Quantification of the impact of turbidity on average flow rate of the CPF.
- Identification of a method that predicts the average flow rate given the initial flow rate and the turbidity of the influent water, and establishes the turbidity limit for a target average flow rate.
- Characterization of the suspended particles rejected and released by the CPF.
- Characterization of CPF effectiveness and lifetime under real use conditions though a field monitoring program conducted continuously during 24 months.
- Assessment of CPF acceptance in coastal Guatemala.

3.2. RECCOMENDATION FOR FUTURE RESEARCH

The research conducted in this dissertation has yielded significant results and conclusions that can serve as the basis for further research. The following recommendations for future research are suggested:

- A relationship between average flow rates, and the ratio between initial flow rates and turbidity was found during a 23-day experiment at constant head. However, long-term investigations should be conducted to assess how this relationship changes over time.

- The characterization of the suspended particles rejected and released by the CPFs was performed. An investigation of the suspended particles retained in the ceramic matrix may be useful to understand clogging mechanisms, and the effects of pretreatments on CPF lifetime.
- Most of the examined CPFs had a carbon core composed of remnants of the pore former after the firing process. A long-term study on the effects of the carbon content on CPF water production and efficacy may add to the understanding of the parameters that impact CPF lifetime.
- This study showed that both flow rate and bacterial removal efficacy decline over time. An assessment of the effects of the rehabilitation by heat processing performed on used CPFs may be useful to future investigation of the CPF lifetime.
- The field investigation showed that most of the respondents reported that the use of the CPF had positive consequences on the health condition of family members. Future studies should provide more detailed information regarding health conditions of target and control groups.

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VITA

Carlo Salvinelli obtained his B.S. in Industrial Engineering in February 2007 from the University of Brescia, Italy. During his senior year he was selected for the Erasmus grant program and studied at the Technical University of Madrid where he developed his thesis entitled "Quality certifications for the exportation of agricultural and food products in the European community: the case Nicaraocoop". He received his M.S. in Engineering Management in November 2012 from the University of Brescia, Italy, where he developed his master thesis entitled "Technical, economic and organizational project for the development of a fish processing cooperative enterprise: the case CENTROMAR".

Prior work experiences include approximately six years as project manager of international development projects with technological content, especially in Guatemala.

As a doctoral student Mr. Salvinelli acted for three years as a graduate teaching and research assistant at the Missouri University of Science and Technology. During this time he was instructor of records of the senior design course sequence called International Engineering and Design and leaded student field trips to Guatemala. His research was focused in the effectiveness and lifetime evaluation of ceramic pot water filters. In 2014 he was selected to take part in the Graduate Leadership Development Program, a one-year initiative by the University of Missouri System. He has been a member of the American Society of Civil Engineers since 2014.

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