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Investigation of Maintenance Impacts on Flow Rates in Ceramic Disc Water Filters

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ABSTRACT. While many low-tech drinking water treatment technologies have been developed in an effort to improve delivery of safe drinking water to low income populations in the developing world, a continuing challenge for ceramic water filters (CWFs) is the deterioration over time of flow rate throughput. While the initial flow rate may be acceptable, significant declines in the flow throughput take place in the absence of a maintenance regime. In response, attaining more acceptable long-term performance is critical, to ensure adequacy of volumes to low income populations and imperative that improved guidance for the end-user as to the frequency and impact of cleaning regimes which is currently deficient in the literature be made available. This study describes research into the flow throughput trends of ceramic water filters and concludes that brushing the external surface of a CWF every 2 ~ 3 days maintains acceptable flow rates (> 1 L/h) for extended periods of time (average over 2.5 years of acceptable performance). An average lifetime throughput volume of 7308 L was observed; corresponding to a per area lifetime throughput volume of 9.7 L/cm^2 (for a 20 cm dual disc apparatus with surface area = 648 cm^2).

Keywords: ceramic water filter, cleaning regime, drinking water, maintenance options

1. Introduction

Access to sufficient quantities of safe drinking water is considered a basic human right, although approximately 748 million people lack access to safe drinking water (WHO and UNICEF, 2014). While this number has been slowly decreasing since the implementation of the United Nations sustainable development goals, one-third of the world's population is still at risk of dehydration and/or waterborne disease. According to bacterial fecal indicators, more than 1.1 billion people consume water with at least moderate risk of disease (WHO, 2014). Bacterial, viral, and protozoan species are the primary sources of diarrheal illness (Gall et al., 2015).

Among the world's populations where poverty is most severe, diarrheal diseases are the second leading cause of death (WHO, 2017). Diarrheal diseases were the cause of an estimated 1.39 million deaths in 2016 (WHO, 2017), and are among the leading causes of death among children under five years of age (UNICEF, 2012; WHO, 2016).

In response to these risks, there is increasing reliance upon demonstrated as able to deliver 'safe' water (defined herein as water which meets drinking water quality standards for microbial and chemical constituents). Analysis of household water treatment (HWT) interventions for low income populations have indicated that CWFs are superior to biosand filters, chlorine and safe water storage, and coagulant chlorine HWT technologies (Hunter, 2009). Part of the reason for the widespread CWF adoption is that CWFs are low cost and are easily manufactured with minimal capital investment. The combination of these factors has enabled utilization of CWFs in many developing regions (van Halem et al., 2009; Murphy et al., 2010a, b; Ren and Smith et al., 2013; Mellor et al., 2014; Farrow et al., 2018).

CWFs are available in an array of sizes and shapes but all rely upon the basic approach where a sacrificial material such as rice husk, sawdust, or coffee grounds, is mixed with clay. The clay/sacrificial material mix is then kiln-fired to achieve a product with a controlled porosity. The shapes commonly utilized include the clay pot (Murphy et al., 2010a), candle-shaped (Franz, 2005) and cylindrical or bottle-shaped (Brown et al., 2019). In some instances, additives have also been utilized (e.g., silver nitrate, silver nanoparticles), and the recipes (percentages and specifications on burn-out material: clay ratio) used vary between manufacturers. However, the premise for all CWFs is similar; during the firing process, the sacrificial material is burned off, leaving a series of small pores through which the water passes, hence the name 'filter'. The processes

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of filtration and biofilm development have been evidenced to attain bacterial removal levels > 99.9% (3 Log Removal, or LRV) (Brown et al., 2019).

It is noted that tests herein described were carried out utilizing disc-shaped filters (20 cm in diameter and 3.5 cm in thickness), sealed around the circumference of the disc. The disc shape is much easier to be consistent in the maintenance regime, in comparison with the clay pot, candle-shaped filter, and/or the cylindrical/bottle-shaped filter.

In addition to the need of safe water for human consumption, there is also the need to provide sufficient volumes for the consumer. For many households utilizing CWFs as Point-of-Entry/Point-of-Use (POE/POU) treatment, required flow throughput rate is typically between one and three L/hour.

While the preceding is the objective, one of the challenges that all CWFs face is that turbidity in the raw water, plus small particles (construction residue) from dislodged clay pieces from the filters themselves, migrate to partially block some of the pores through the CWF. The outcome is that the throughput volumes for CWFs decline over time.

Other persistent deficiencies of CWFs which must be considered as precautionary issues for CWF performance include relatively poor performance for removal of bacteria in the field (in contrast to laboratory studies) when there is contact by the CWF user with the exit side of a CWF (e.g., as with the clay pot) (Farrow et al., 2018). Further, the impact of silver impregnation on CWF bacterial removal efficacy is inconsistent (Fewtrell, 2014). However, the focus herein in this research is on hydraulic performance.

A major challenge associated with decline in throughput flow rate is that the household members may become sufficiently inconvenienced that they stop using the CWF and/or look for a replacement filter if the throughput drops below 1 L/h. Consequently, in an effort to maintain the hydraulic throughput through the CWF, of interest are the specifics of mainte-nance of the CWF (type and frequency) that will enable contin-uing/longer term use of the CWF.

2. Review of Technical Literature

Previous evaluations of CWF throughput volume decline have been conducted (e.g., Salvinelli and Elmore, 2015). However, no active cleaning regime was employed by Salvinelli and Elmore and therefore rapid clogging was observed. Of interest is to characterize CWF throughput to improve the understanding as how to maintain CWF hydraulic performance. While much has been reported on pathogen removal by CWFs, a primary need for users of the technology is cost and replacement timeframe - if the quantity of water throughput is insufficient for the family, people will stop using the CWF.

Numerous studies have been conducted over the last 30 years on the effectiveness of CWFs (with regard to both microbial removal and flow through rate). However, there is significant variation both between studies, and within studies. These technologies are subject to many inconsistencies. There are a number of variables that influence performance including: filter shape, organic material utilized, recipe (percentage of sacrificial material), manufacturer, surface area, pore size, source water, and testing protocol.

The Ceramics Manufacturing Working Group (CMWG, 2011) published 'acceptable flow limits' of 1 ~ 3 L/h. The lower limit is based on sufficiency of consumer need, whereas the upper limit results from the ability of the CWF, at 3 L/h of throughput, to produce drinking water that is 'safe' for consumption. High flow rates are often due to mechanical failure (e.g., cracks in the CWF) or non-uniform pore size distributions (due to clumping of burn-out material pre-firing). Therefore, flow rates above 3 L/h are indicative of filters that may not be capable of providing safe drinking water. The CMWG stated the most reliable flow that provided an acceptable level of bacteria removal was between 1 and 2 L/h. It should be noted that the flow rate stipulation of 1 ~ 3 L/h (CMWG, 2011) is based on an undefined filter size.

To maintain flow rates of ceramic filters, the CMWG has suggested that a cleaning regime of lightly brushing the top surface of each filter would help to restore flow rates to a satisfactory (but undefined) level. Lantagne (2001) and van Halem et al. (2007) reported that a limited cleaning regime only temporarily restored flow rate, causing declining flow rates to be the primary limiting factor of ceramic water filters.

The focus herein is on the flow rate through the CWF. Of interest then, are the opportunities to maintain a sufficient throughput flow to encourage continued (reasonably long-term) use of this technology.

3. Methodology and Protocols

To provide quantification of the effectiveness of cleaning regimes, a series of experiments were conducted to characterize the impact of cleaning regime on flow throughput. Disc-shaped filters consisting of 20% rice husk: 80% clay were utilized. Rice husk was milled and sieved prior to disc formation. The clay and rice husk were thoroughly mixed by hand and then kiln fired at 1,060 ^{o}C for approximately 14 hours. The discs were then mounted, as depicted in Figure 1, for testing.

Four ceramic disc filters were tested simultaneously in a single tank (46 × 73 × 70 (L × W × H) cm) to allow replicability of performance in long-term flow trials. Bacterial removal efficacy was also monitored to determine if there were significant changes in bacterial removal over the trial period. All samples were analyzed following USEPA. (2006) Method 1603 (Method 1603: *Escherichia coli* (*E. coli*) in water by membrane filtration using modified membrane-thermotolerant *Escherichia coli* agar). Influent *E. coli* concentrations ranged from 2.3×10^4 to 2.5×10^5 CFU/100 mL (average 1.2×10^5 CFU/100 mL) during the six-week trial period.

Each filter was flushed with deionized water for 48 hours prior to initiation of the throughput testing program, to remove debris and air that would prevent water from permeating through the internal pore structure. A constant water level (40 cm above the CWF) was maintained in the testing tank to ensure a consistent pressure head utilizing a float-valve and external top-off reservoir. All trials were completed using a deionized water influent source with zero initial turbidity (prior to bacteria addition).

Experiments were conducted over a 6-week period. Daily flow rates were monitored by collecting water which passed through each of CWF discs. The top surface of each filter was brushed at different intervals (generally every 2 ~ 3 days) to allow assessment of the impact of brushing on flow rate. A strict protocol for brushing was employed, using a soft brush four times across each disk surface in-situ, followed by another four times at 90º angles to the first brushing, in order to allow for comparison of test results. Directly following brushing, the throughput flow rate was obtained.

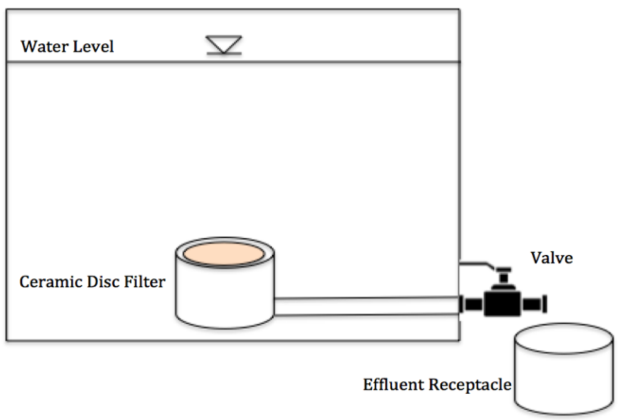

Figure 1. Ceramic disc filter apparatus.

4. Results and Discussion

Figures 2 through 5 depict the relationships between volumetric flow rate and cumulative throughput volume for four individual disks, each of 20 cm diameter. Initially, an increase of throughput was followed by a steep decline. Low flow rates were found after approximately 500 L of water throughout, similar to the results reported by Salvinelli and Ellmore (2015).

The trend lines used to characterize the flow throughputs, as depicted in Figures 2 through 5, were fit to the data to characterize flow rate decline. To avoid bias in determining the trend lines, if an individual data point was within 5 L of throughput volume to the next nearest data point, the point was not considered when fitting the trend line. This approach allowed more accurate characterization of the flow trends, by ignoring clustered data.

Maximum flow rates were observed after 200 ~ 400 L of throughput for all four CWFs. After observing maximum flows, the filters were monitored without an active cleaning regime for 700 ± 50 L (RH 1 and 2) or 1,150 ± 50 L (RH 3 and 4). As evidenced in Figures 2 through 5, there were significant decreases in flow rate prior to the active cleaning regime. Lantagne et al. (2010) attributes a portion of the initial steep decrease in flow rate to the migration of combustion residue trapped in the pores of the CWF, and this observation is confirmed herein.

The first cleaning event significantly increased flow rates in all four cases. Although flow rates did not recover to the maximum observed flow rate, 73 ~ 82% of the maximum flow was achieved after the first cleaning.

Comparison between the four CWFs (Table 1) indicates substantial variations in throughput volume between the four CWFs. It is noted that the four discs utilized in the research were manufactured in a similar manner to what would be utilized in practice (hand mixed, placed in a mold, and fired, to allow characterization of the type of variability that would realistically occur at a manufacturing facility in the developing world).

Maximum throughput volumes (prior to the flow rate dropping below specifications of 1 L/h or, equivalently, 0.0015 L/cm^2 h) varied between 2,157 and 19,399 L. This corresponds to a wide range of expected filter lifespans (0.74 ~ 6.64 years). Filter lifespan was determined by assuming an average household consumption rate of 8 L/day (2 L/person/day and 4 persons per household). Comparisons between RH-1/RH-2 and RH-3/RH-4 indicate that delaying the first cleaning event has a significant impact on the expected filter life. Performing the

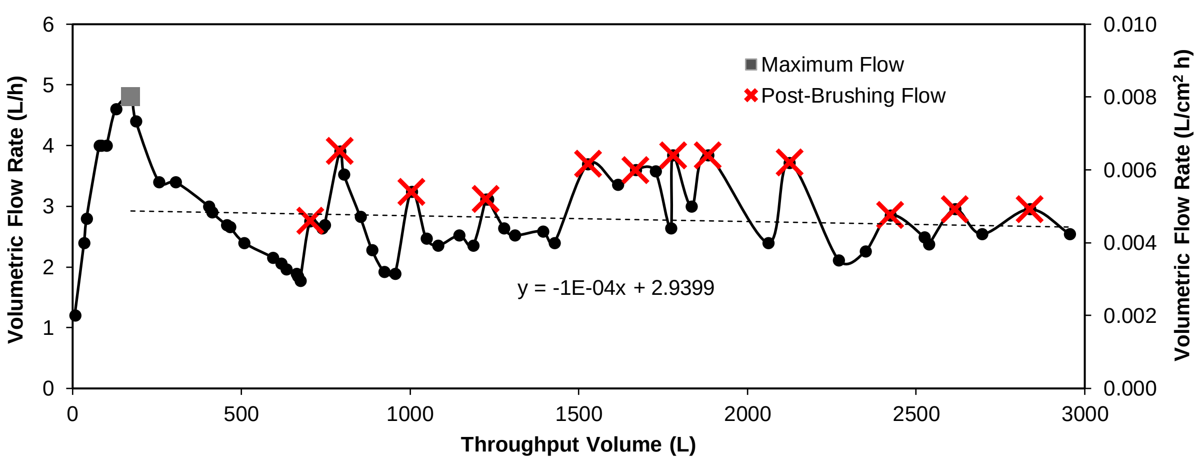

Figure 2. Volumetric flow rate (L/h & L/cm^2 h) vs. throughput volume (L): RH-1. Double-disc apparatus extrapolation.

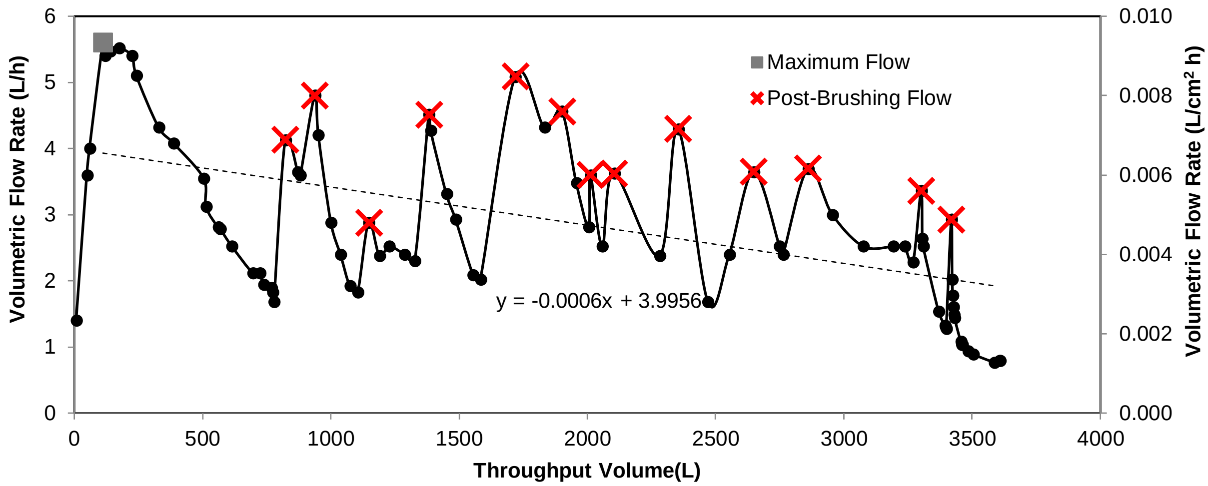

Figure 3. Volumetric flow rate (L/h & L/cm^2 h) vs. throughput volume (L): RH-2. Double-disc apparatus extrapolation.

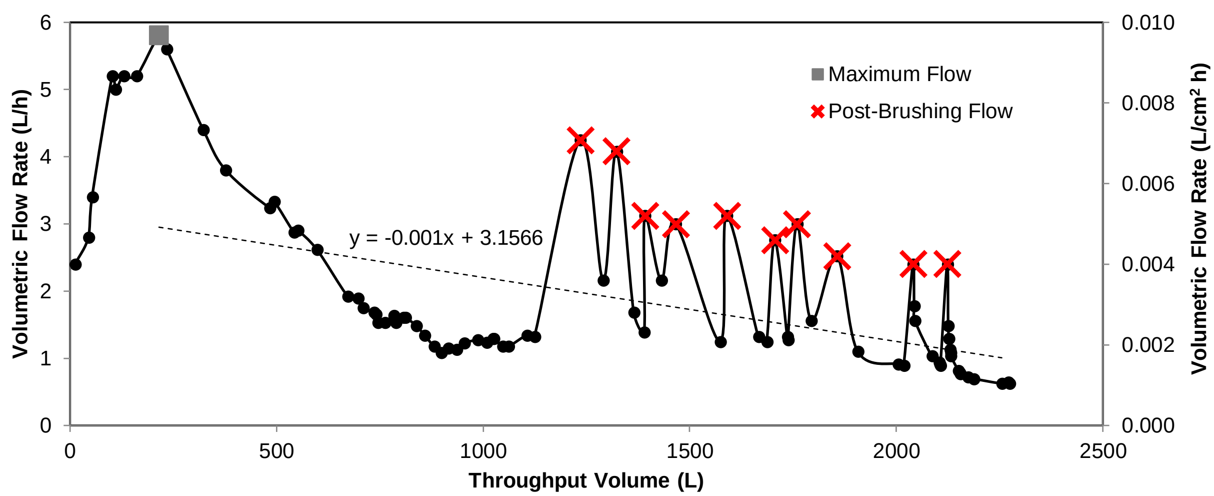

Figure 4. Volumetric flow rate (L/h & L/cm^2 h) vs. throughput volume (L): RH-3. Double-disc apparatus extrapolation.

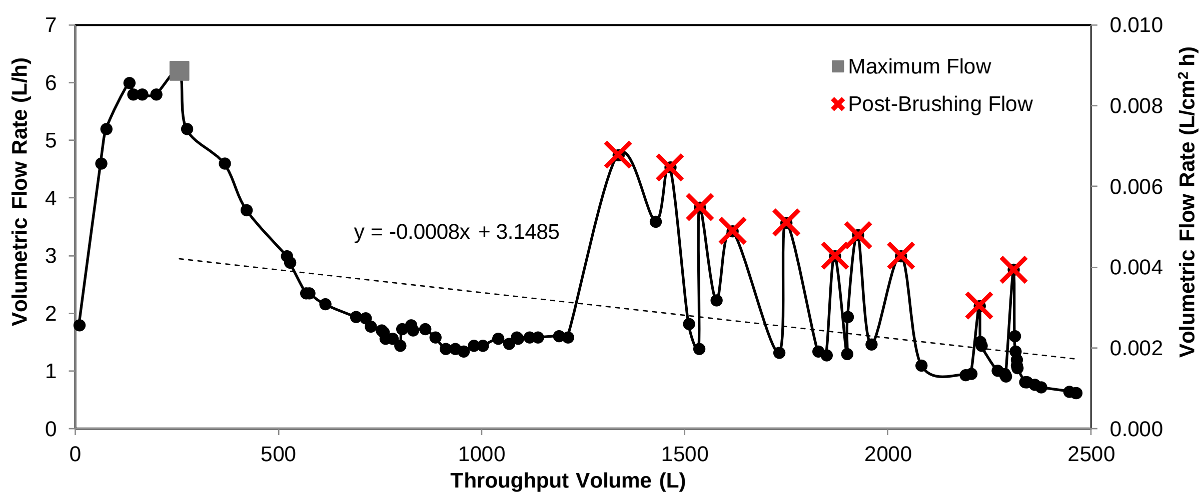

Figure 5. Volumetric flow rate (L/h & L/cm^2 h) vs. throughput volume (L): RH-4. Double-disc apparatus extrapolation.

Table 1. CWF Flow Summary Table

CWF Reference	Trend Line Equation	Throughput Volume Prior to First Cleaning (L)*	Lifetime Throughput Volume (L)*	Expected Filter Life (years)**
RH-1	y = -0.0001x + 2.9399	674	19399	6.64
RH-2	y = -0.0006x + 3.9956	778	4993	1.71
RH-3	y = -0.001x + 3.1566	1124	2157	0.74
RH-4	y = -0.0008x + 3.1485	1211	2686	0.92
Average		946	7308	2.5

* Corresponds to the throughput volume when flow rate drops below 1 L/h.
**Assuming a consumption rate of 2 L/person/day and a household of 4 people.

first cleaning event at 700 ± 50 L evidenced an average lifetime throughput volume of 12,200 L; however, performing the first cleaning event after 1,150 ± 50 L indicated a much lower average lifetime throughput volume of 2,400 L.

These results are significantly different from those reported by Salvinelli and Elmore (2015) who found that suitable flow rates were maintained for 8,000 L of throughput volume with non-turbid influent sources. However, there are significant differences in procedure between the study reported herein, and those reported in Salvinelli and Elmore (2015). The primary difference is that all trials reported herein utilized an influent with high concentrations of *E. coli* (2.3×10^4 to 2.5×10^5 CFU /100 mL). This may be one of the reasons for the more rapid decrease in flow rate observed; as compared to Salvinelli and Elmore (2015) who utilized deionized water as their non-turbid influent source. Additionally, Salvinelli and Elmore (2015) did not report on the physical dimensions of the CWF investigated; surface area is one of the largest contributing factors to throughput volumes and thus greatly impacts filter lifespan.

The results depicted in Figures 2 through 5 clearly demonstrate that irreversible clogging occurs if the filters are not maintained regularly, which indicates the importance of the disseminating the findings being reported herein; for long-term success, adequate performance is of critical performance for the technology to be widely adopted in the developing world.

The brushing efforts outlined above were instituted with 'X' indicating the flow rate following the brushing. The results indicate that brushing has a significant impact on flow throughput, as expected. A similar conclusion was found by Lantagne (2001) and van Halem et al. (2007), with both studies indicating that brushing only offered a temporary restoration in flow. However, the conclusion reported by van Halem et al. (2007) (with the recommendation that cleaning regimes are not effecttive) is not consistent with the results herein. Although only a temporary restoration of flow is achieved, consistent brushing results such as described in the cleaning regime described herein resulted in consistently higher flow throughput rates (in comparison with no cleaning regime).

When implementing the cleaning regime discussed herein, average flow rate decline was determined to be - 0.00063 h^{-1}. Results prior to the implemented cleaning regime indicate a rate of decrease of - 0.0078 h^{-1}. The rate of 'flow throughput decrease' in absence of maintenance is approximately 12 times higher than an active cleaning regime. Therefore, a consistent cleaning regime is crucial to maintaining flow rates long-term. It is noted that turbidity significantly affects flow through rate and filter life, although the results depend on the degree of turbidity and this is beyond the scope of this paper.

To monitor the removal of bacteria, microbiological tests using the CWFs were conducted periodically. Filters were tested 7 ~ 9 times over the study; an average of once per week (and illustrated in Figure 6). Average LRVs for all filters ranged from 3.6 ~ 4.6. The CWFs assessed are protective, from a microbial risk perspective, according to the WHO Guidelines for Drinking-Water Quality, 2011. There was no significant change in microbial removal efficiency over the study period indicating that the cleaning regime had no significant impact on microbial removal.

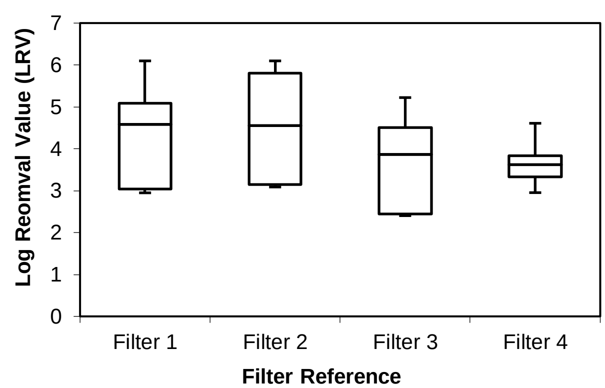

Figure 6. Log-removal value (LRV) of CWFs utilized during flow trials. Box represents 25th and 75th percentiles; lines extending vertically from the boxes (whiskers) represent maximum/minimum values.

5. Conclusions and Recommendations

Ceramic water filters have an important capability to contribute to the objective of providing safe drinking water for low income populations in developing countries. The findings indicate that periodic (every 2 ~ 3 days) brushing of the filter surface is critical, as an approach to maintain flow throughput rates above the acceptable limit. Delays in implementation of recommended maintenance regimes result in irreversible clogging and significantly reduces filter life span. An average expected filter life (prior to flow throughput rate dropping below the recommended 0.0015 L/cm^2 h was determined to be 2.5 years. However, if recommended maintenance is implemented more rapidly after attaining peak flow, the average life span increases to 4.2 years.

Subsequent evaluations of CWF performance should reference physical dimensions to allow comparisons on a L/cm^2 h basis, due to differences in CWF size, shape and design between studies. Guidelines regarding proper maintenance of ceramic water filters is deficient in the literature and should be more thoroughly developed.

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