Determining the operational limits of the biosand filter

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ABSTRACT

Worldwide, access to clean drinking water is not available for more than 800 million people. The biosand filter (BSF), an intermittently operated slow sand filter, was developed to address this problem. The BSF is used in homes to improve water quality. Three main objectives were examined in this research: (1) investigate initial startup and recovery performance after cleaning BSF, (2) examine the number of people the BSF may effectively serve, and (3) determine effects of an extended pause period on BSF performance. Laboratory experiments examined the BSF’s ability to reduce fecal coliforms (FC) and turbidity for the various objectives. Results indicate that during the startup period, 27 days were needed to achieve 1 log reduction, while only 17 days were needed after cleaning the BSF to achieve 1 log reduction. A maximum of six people can be effectively served by a single BSF based upon the results of the experiment. A 7-day extended pause period determined that the bacterial layer will begin to go dormant or die off when the filter is not used for an extended period.

Key words | biosand, developing world, operational limits, point of use, reduction, water treatment

INTRODUCTION

Waterborne diseases kill 3.5 million people each year (Prüss-Üstün et al. 2008), with more than 1.6 million of the diarrheal deaths occurring in children under the age of 5 years (WHO 2006). To help solve this problem, the United Nations developed the Millennium Development Goals (MDGs). The MDGs consist of eight goals and 21 targets to be accomplished by 2015. Goal 7, Target C, seeks to halve the population without access to clean water and sanitation (UN 2010). Providing access to clean water with central distribution systems and water treatment systems like those in the developed world is a good option. However, in many cases this is too costly for users living in the developing world. Along with expense, centralized plants would not be ideal as many of the communities lacking access to improved water sources are in remote locations. As a result, point of use (POU) treatment technologies have been developed worldwide. POU treatment technologies treat contaminated water in the home on a smaller scale. Recent studies have shown wells, springs, and boreholes may show little to no contamination, but when the user returns home the water in the storage container shows contamination due to dirty containers (Sobsey et al. 2005; Lantagne et al. 2006; Pickering et al. 2010), thus emphasizing the growing need for not only improved access to clean water, but also the need for POU technologies.

While many POU’s exist and are used worldwide, one was identified as the most effective due to popularity and sustainability (Sobsey et al. 2008). This POU technology is known as the biosand filter (BSF). Developed in the 1990s by Dr David Manz, the BSF is similar to the traditional slow sand filter (SSF) that has been in use since the 1800s (Huisman & Wood 1974). A scaled-down version of the SSF, the BSF differs because of intermittent operation due to an elevated effluent standpipe (Figure 1). Over time, a biological film known as a ‘schmutzdeke’ forms at the watersand interface and increases reduction of viruses, protozoa, and hemeliths, while decreasing flow. Manufacturers of the BSF suggest it be used in combination with disinfection
(i.e. household bleach). When the user determines the flow is no longer sufficient, the user can clean the filter by filling the BSF with water to just below the diffuser plate, and stirring the water, suspending deposited and trapped solids, which can then be removed. The cleaning process minimizes sand removal and is repeated until the desired flow rate is achieved.

Today more than 200,000 BSFs have been distributed by non-profit organizations worldwide (CAWST 2010). Laboratory studies have shown 93–99.99% reduction of fecal coliforms (FC) and *Escherichia coli* (Stauber et al. 2006; Baumgartner et al. 2007; Elliott et al. 2008), 100% reduction of *Giardia* cysts, 99.98% reduction of *Cryptosporidium* oocysts (Palmateer et al. 1999), and virus reduction of 0–99.9% (Elliott et al. 2008). The variation in reduction rates is highest in the field where reduction of FC or *E. coli* range from 60 to 99.9% (Duke et al. 2006; Earwaker 2006; Vanderzwaag et al. 2009). The discrepancy and variation in BSF performance shows that there are still questions that need to be answered.

A study conducted by Baumgartner et al. (2007) examined the robustness of the BSF under various operating conditions, specifically pause period and water dosing volume. The water dosing volumes in the experiment were determined based upon the minimum amount of water needed per capita per day for human survival. The pause periods were chosen based on frequent filtration (12 h) and infrequent filtration (36 h). Upon completion of the study, the author stated that more research was required to maximize filter performance without having to adhere to a complex schedule (Baumgartner et al. 2007). Future research could maximize filter performance by better understanding the BSF and reducing user error.

This study seeks to expand upon the optimization work done (Baumgartner et al. 2007) by completing three objectives. The objectives of the experiments in this study were to (1) determine the amount of time needed for a BSF to achieve adequate reduction during the installation period and after cleaning, (2) establish the maximum number of people an individual BSF can effectively serve, and (3) quantify the effects of an extended pause period on reduction.

**METHODS**

**BSF setup**

Three BSFs along with media (support gravel, gravel, filtering sand) were obtained from Hydraid (Grand Rapids, Michigan, USA) and installed in the order and manner explained in the manufacturer’s instructions (Triple Quest 2010) but using deionized water (DI). Filters are made of UV resistant plastic, so that algal growth is inhibited and bacterial growth is encouraged. Initial effluent flow rates were measured immediately after the influent chamber had been filled to the top (flow rates were measured as 0.9, 0.9, and 0.7 L/min for BSFs 1, 2, and 3, respectively).

**Tracer study**

After installation of media into the BSF, a tracer study was performed on each BSF to determine the pore volume and confirm that the filters were acting in plug flow mode. Tracer studies were performed by first removing the DI water above the sand and then dosing the filter with 200 mg/L NaCl in DI water. Conductivity of the filtered water was measured in µS/cm with a Hach 40d probe (Hach Company) to follow the input of the tracer. Tracer tests were performed in duplicate for each new filter. Flow
rate was held constant by filling the filter to the top (18 cm above standing water height) with the NaCl solution, then using a peristaltic pump to maintain the flow rate throughout the experiment by matching the pump flow rate to the effluent flow rate of the BSF.

Source water

Water was obtained weekly in 5 gallon (18.9 L) buckets from Canyon Lake #2 (Lubbock, TX), a recreational lake fed with wastewater treated by land application and habituated by seasonal geese. Water was stored covered at room temperature until needed for experiments. Preliminary tests on the water indicated that <5 CFU/100 mL of FC were present in the lake water when tested using Method 9222D in Standard Methods for the Examination of Water and Wastewater (APHA 1995). To increase the population of FC, two percent primary effluent (Lubbock Water Reclamation Plant, Lubbock, TX) was added daily to water before dosing of the BSFs.

Installation period

During the installation period, the filter is considered to be ‘unripened’, as the media (sand and gravel) contains little organic matter or bacteria. In order to document the initial effectiveness of the BSFs, the time needed to achieve 1 log reduction during the installation period was determined. A 1 log reduction was chosen as the endpoint as 1 log reduction was slightly below the bottom of documented average reduction efficiencies in previous studies (Stauber et al. 2006; Baumgartner et al. 2007; Elliott et al. 2008), thus indicating that reduction of waterborne illness would occur (Stauber et al. 2009, 2011). Once the 1 log reduction mark is reached, past health studies have indicated lower diarrheal disease due to the high bacterial reduction (Stauber et al. 2011). Each filter (three in total) received 20 L of spiked lake water daily until 1 log removal was achieved. Samples of filtered water were collected in autoclaved 1 L glass containers after 18 L has passed through each filter and from influent spiked lake water. Samples were taken every other day for the first week (WHO 2011a, b), then weekly, until the flow rate was determined to be insufficient (0.2 L/min), at which stage the length of filter run was greater than 2 h, and cleaning of the BSF was required.

Then, the BSFs were cleaned according to Hydraid instructions (Triple Quest 2010) by filling the filters with water up to the base of the diffuser plate, removing the diffuser plate, stirring, and then removing the suspended solids with a 150 mL beaker. The suggested cleaning method aims to disturb the sand as little as possible so that no media is lost in the process. The cleaning process was repeated until the maximum flow rate (0.8 L/min) was reached.

Time needed after cleaning

After BSFs have been cleaned, the biolayer is disturbed, and water quality is reduced (Triple Quest 2010). In order to determine the objective of time to recovery, the filters (two in total) were dosed with 20 L of lake water daily until consistent reduction (1 log) of FC was achieved, and the filters were considered to be ‘recovered’. The test was performed until bacterial reduction rates remained at a minimum of 1 log reduction consistently for 1 week.

Determination of maximum filtering volume

The maximum filtering volume was determined to evaluate the number of people that can be adequately served by one BSF. In order to determine the maximum number of people served, two BSFs received 20 L per day of spiked lake water until greater than 1 log reduction of FC was consistently observed. Upon consistent reduction, BSFs were challenged with 75 L per day of spiked lake water to determine the maximum number of people a BSF can effectively serve. A maximum volume of 75 L per day was determined based upon minimum ‘survival’ allocation of water (Reed 2005) of 7 L per capita per day (Lpcd) and the maximum number of people that can be effectively served (10 people) by one BSF per day, according to the website (Hydra). The filters were challenged until flow rates were reduced to <0.2 L/min, at which time each filter was cleaned and the experiment was repeated. Effluent samples were collected every other day after 18, 38, 58, and 75 L had been filtered through the BSF to determine its ability to filter the large volume of water.
Pause period limits

Pause period has been previously examined (Baumgartner et al. 2007) to determine the effects of a short pause period on reduction efficiency of the BSF. In order to quantify the effects of the pause period on the bacterial layer, an extended pause period needed to be examined. Manufacturers of the BSF suggest that, after a 48 h pause period, the nutrients and pathogens will be consumed by the microorganisms in the BSF and they will eventually die off (CAWST 2010; Triple Quest 2010). In order to achieve this objective, the BSFs were challenged with 20 L of spiked lake water. After filtering had ceased, the filters (two in total) were not dosed for 7 days, and this dosing pattern continued for 1 month. Samples were collected at the 18 L filtering point and examined for pH, dissolved oxygen (DO), turbidity and FC. The 18 L sample point was selected as the pore volume of the BSF media was previously reported at approximately 18.3 L (Elliott et al. 2008), and was verified for each of the current filters as was the plug flow pattern formerly reported and confirmed later in the current study. Thus, since the water moves together through the filter as a single unit, the sample point is representative of the first water volume entering and exiting the filter that has not been in the filter during the pause period.

Sampling and analysis

All samples of untreated spiked lake water were collected in autoclaved, 500 mL flasks from each 5 gallon (18.9 L) bucket and refrigerated at 4 °C until treated samples of BSF effluent were gathered (<8 h). Filtered water samples were obtained directly from the effluent spout of the BSF in flasks sterilized by autoclave, and refrigerated at 4 °C until analysis (<4 h). Samples were analyzed at the Environmental Sciences Laboratory (Texas Tech University, Lubbock, TX) for DO, pH, turbidity, and FC. Measurement of DO and pH were obtained using a Hach 40d meter (Hach Company) according to the manual provided. A Hach 2100 Turbidimeter was used to measure turbidity in triplicate. Instruments were calibrated weekly to ensure accuracy of measurements. All measurements were made in accordance with Standard Methods (APHA 1995). The enumeration of FC were completed in accordance with the Membrane Filtration Method 9222D as described in Standard Methods (APHA 1995). Samples were filtered through sterile 0.45 μm gridded filters (Millipore Company), then aseptically transferred to premade mFC agar plates (Difco). Following incubation at 44.5 °C for 24 ± 2 h, blue colonies were enumerated as FC. Serial dilutions were prepared for both lake water samples (1:10 and 1:100) and treated water samples (1:10 and 1:1). Average FC counts were calculated using method 9222D as described in Standard Methods (APHA 1995).

Statistical analysis

The arithmetic mean and standard deviations were calculated for all water quality data. The formula (influent − effluent)/influent ×100 was used to calculate removal efficiency for DO, and turbidity. FC log reduction, as well as percent reduction were calculated for bacterial samples. To determine statistical significance, the Shapiro-Wilk test was used to ensure data sets were normally distributed. When comparing influent and effluent samples, as well as samples gathered at different volumes, the Student’s T-test (two-tailed) was used to determine if reduction was significant.

RESULTS

Tracer study

Figure 2 presents the results of the tracer tests on the three BSFs. The pore volume of each plastic Hydraid BSF was determined to be 18.5 L (±0.2 L), which is consistent with pore volumes determined in previous studies (Elliott et al. 2008). The pore volume is the amount of water needed to fill the volume in the pore space of the media (sand and gravel). As observed in Figure 2, the sharp incline to the maximum conductivity occurs over one pore volume. The sharp rise provides indication of approximate plug flow in the BSF.

Data from tracer tests were then analyzed to confirm that the filters were acting in plug flow as reported in a previous study (Elliott et al. 2008). The Morrill dispersion index (MDI) was calculated according to the method provided by
Tchobanoglous et al. (2003). The MDIs for the BSF tracer tests were 1.68, 1.94, and 1.78. According to the US EPA (1986), the MDI for an ideal plug flow reactor is 1.0, while a complete-mix reactor MDI is 22. Plug flow is considered to be approximate if the MDI value is less than 2.0 (US EPA 1986).

Installation period and recovery from cleaning

Initial flow rates at startup averaged 0.78 L/min on day 1 of the experiment and remained fairly constant during the installation period, narrowly declining to 0.68 L/min on day 29 when the experiment reached its endpoint. Average influent and effluent pH, DO, and turbidity are listed in Table 1 for all experiments along with the WHO guideline for each parameter where available (WHO 2011a, b). Log reduction of FC reached the preselected endpoint (1 log reduction) on day 23 for one of the filters while the two other filters in the study did not establish 1 log reduction until day 29. Average reduction prior to achieving 1 log reduction was 0.73 log reduction (77.8 ± 33%).

Average pH, DO, and turbidity of spiked lake water and BSF effluent are presented in Table 1. Initial reduction efficiencies of FC after cleaning were 0.41 log reduction (61%) and remained below 1 log reduction until day 17 in all BSFs. During the 17 day recovery period from cleaning, the filters had an average reduction of 0.84 log (77 ± 20%). Figure 3 shows a comparison of average log reductions

Table 1 | Average water quality parameters for all experiments

<table>
<thead>
<tr>
<th>Water quality parameter</th>
<th>pH</th>
<th>DO (mg/L)</th>
<th>Turbidity (NTU)</th>
<th>FC log reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>WHO guidelines*</td>
<td>No guideline</td>
<td>No guideline</td>
<td>&lt;5 NTU accepted</td>
<td>0 CFU/100 mL</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>&lt;1 NTU preferred</td>
<td></td>
</tr>
<tr>
<td>Installation period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influent</td>
<td>8.09 ± 0.14</td>
<td>7.3 ± 0.81</td>
<td>4.51 ± 0.84</td>
<td>–</td>
</tr>
<tr>
<td>Effluent</td>
<td>7.41 ± 1.25</td>
<td>6.67 ± 0.89</td>
<td>1.43 ± 1.32</td>
<td>0.88 ± 0.28</td>
</tr>
<tr>
<td>Recovery after cleaning</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influent</td>
<td>8.28 ± 0.15</td>
<td>5.52 ± 2.42</td>
<td>6.89 ± 3.37</td>
<td>–</td>
</tr>
<tr>
<td>Effluent</td>
<td>7.86 ± 0.07</td>
<td>2.77 ± 0.52</td>
<td>0.73 ± 0.23</td>
<td>0.92 ± 0.59</td>
</tr>
<tr>
<td>Maximum volume</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Lake water</td>
<td>8.38 ± 0.12</td>
<td>5.65 ± 0.92</td>
<td>8.22 ± 4.42</td>
<td>–</td>
</tr>
<tr>
<td>18 L</td>
<td>7.97 ± 0.14</td>
<td>3.18 ± 1.19</td>
<td>0.88 ± 0.18</td>
<td>1.72 ± 0.39</td>
</tr>
<tr>
<td>38 L</td>
<td>–</td>
<td>–</td>
<td>0.87 ± 0.17</td>
<td>1.46 ± 0.26</td>
</tr>
<tr>
<td>58 L</td>
<td>–</td>
<td>–</td>
<td>1.09 ± 0.24</td>
<td>1.187 ± 0.49</td>
</tr>
<tr>
<td>78 L</td>
<td>–</td>
<td>–</td>
<td>1.13 ± 0.27</td>
<td>1.22 ± 0.41</td>
</tr>
<tr>
<td>1 week pause period</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Influent</td>
<td>8.12 ± 0.10</td>
<td>6.13 ± 0.62</td>
<td>11.11 ± 2.67</td>
<td>–</td>
</tr>
<tr>
<td>Effluent</td>
<td>7.88 ± 0.04</td>
<td>5.14 ± 0.60</td>
<td>1.02 ± 0.43</td>
<td>1.23 ± 0.62</td>
</tr>
</tbody>
</table>

Values represent mean ± standard deviation.

*WHO (2011a, b).
during the initial startup and recovery after cleaning experiments. The experiments were performed back to back in the same BSFs, hence, the data represent how the biological layer forms during the startup period as reduction increases, and then is disturbed after the filter has been cleaned. The biological layer then appears to reestablish as indicated by the increase in reduction.

**Maximum filtering volume**

Initial flow rates in the first and second trials were 0.6 and 0.65 L/min, respectively. During the first trial, the filters no longer produced flow after 4 days, while the filters required cleaning after 7 days in trial 2. Turbidity removal of spiked lake water in BSF effluent samples at 18, 38, 58, and 78 L are presented in Table 1. Average influent turbidity and standard deviation was 9.6 ± 4.7 NTU over the course of the experiment. Overall, average effluent and standard deviations for turbidities were 0.9 ± 0.2, 0.9 ± 0.2, 1.1 ± 0.2, and 1.1 ± 0.3 NTU in the 18, 38, 58, and 78 L samples, respectively. Removal efficiency was greatest at the 58 L sample (89%), but not significantly greater (p > 0.05) than the removal efficiencies documented at 18 L (87%), 38 L (87%), or 78 L (88%). Other water quality parameters (pH and DO) were only taken from the influent water source, and not at the filtered volumes, and are therefore not included in the results.

A graph comparing average reduction of FC at various volumes filtered is presented in Figure 4. Average reduction of FC at 18 L was 2.032 log (98 ± 2%), while average reductions of FC at 38, 58, and 78 L, were 1.453 (96 ± 3%), 1.187 (89 ± 11%), and 1.189 log (89 ± 9%) reductions, respectively. Significantly greater reduction (p < 0.05) was observed in the 18 L sample when compared with the 38, 58, and 78 L samples. While the sample at 38 L showed significantly lower reduction in FC when compared to the 18 L sample, the reduction was significantly greater (p < 0.05) than that observed in the 58 and 78 L samples.

**Pause period limits**

Flow decreased during the course of the 28 day experiment, although water was only filtered once per week. Initial flow rates were 0.51 and 0.56 L/min, while flow rates at the end of the experiment were 0.31 and 0.25 L/min. Throughout the experiment, the pH was reduced on average (Table 1). Average pH of the spiked lake water was 8.11 ± 0.09, while average effluent pH was reduced to 7.88 ± 0.04. Reduction of DO was also observed during the course of the experiment; with average filtered effluent = 5.13 ± 0.60 mg/L while spiked lake water averaged 6.13 ± 0.62 mg/L. The mean lake water turbidity was 11.1 ± 2.7 NTU, while BSF effluent mean turbidity was 1.02 ± 0.4 NTU, representing about 91 ± 3% removal. Figure 5 shows a weekly comparison of percent reduction of FC after having a 1 week pause period. Average reduction over the course of the experiment was 1.23 log reduction (89 ± 11%).
DISCUSSION

Influent water quality

Over the course of the experiment, the influent water was prepared the same way for each of the subexperiments performed in this study. Though care was taken to ensure a consistent water source, variability was still observed. Turbidity and FC influent concentrations in this study ranged from 2.2 to 14.1 NTU and 28 to 2,600 CFU/100 mL, respectively. Increases in both turbidity and FC concentrations can be attributed to variations in animal populations during various seasons and runoff due to precipitation events as the study spanned from spring to fall, and various precipitation events caused spikes in turbidity and FC concentration. Variation in influent water quality can affect effluent water quality as well as the growth of the biological layer. Influent water quality in the developing world is also variable as previously documented in several studies (Earwaker 2006; Vanderwaag et al. 2009) where influent turbidity ranged from approximately 9 to greater than 100 NTU while influent E. coli ranged from approximately 0 to greater than 10,000 CFU/mL (Earwaker 2006). Therefore, the influent water quality in the present study was not determined to be a hindrance to the determination of the study objectives as it was consistent with what has been reported.

Recovery time

When comparing time to a minimum of 1 log removal of initial startup and recovery after cleaning, the time for an initial startup is 1–2 weeks longer than the recovery time for an established filter (17 days). During the recovery and startup times, the reduction rates of FC were highly variable, with relative standard deviations of 34 and 58% for the startup and recovery, respectfully. Additional studies not included in this paper suggest that as the biological layer matures over time, the recovery time is similar (17 days or more) even after multiple filtering cycles (Stauber et al. 2006; Elliott et al. 2008; Kennedy et al. 2012). The length of time to 1 log reduction is longer than the suggested 5–14 days in the Hydraid manual (Triple Quest 2010). After this time period, the manual suggests that ‘the biological layer has reached full maturity and effectiveness.’ The manual for the concrete version of the BSF published by the Center for Affordable Water and Sanitation Technology (CAWST) suggests that 30 days might elapse before the filter’s biological layer has fully formed. After reaching 1 log reduction, the BSFs in this study showed an average of 2.06 log reduction of FC, suggesting that the biofilm was still maturing or recovering after reaching 1 log reduction.

Growth of the biological layer is dependent upon many factors such as the source water quality, number of uses per day and amount of water filtered. While this study is not representative of all BSFs, as water quality, volume of water treated, and other factors vary from BSF to BSF, it suggests that biolayer will vary from location to location. Therefore, the importance of suggesting the use of the BSF along with some disinfection technology (solar water disinfection, household bleach, etc.) is further supported by the results of this study.

Maximum filtering volume

Turbidity reduction at each volume was consistent with previous studies, as well as reduction observed in this experiment. Reduction of turbidity is a function of filtration and not the pause period, as suggested by the comparison of the 18 and 38 L sample points. The results indicate reduction of FC was significantly reduced as the volume of water filtered in a day increased. This inverse relationship
is consistent with the literature (Elliott et al. 2006; Baumgartner et al. 2007), as reduction rates decreased in samples as the amount of water filtered by the BSF increased. Reduction rates at the 18 L sample point were comparable with previous studies, while log reduction of FC at greater than 18 L was significantly less than reported results (Stauber et al. 2006; Baumgartner et al. 2007; Elliott et al. 2008; Vanderzwaag et al. 2009; Kennedy et al. 2012). Since the pore volume of each filter was approximately 18.5 L, the higher reduction rate of FC in the 18 L sample was likely observed due to the water retained in the filter overnight pause period. During the pause period, FC are reduced though natural die-off, adsorption, as well as by the microorganisms present in the BSF consuming the pathogens and nutrients present in the influent water, thus explaining the increased reduction in the 18 L sample. Using this logic, one would have expected the water quality of the samples taken at 38, 58, and 75 L to have no significant difference in reduction as the main mechanisms responsible for reduction of FC at these volumes were mechanical trapping and adsorption. Differences in the reduction efficiency between the sample points might be attributed to average population of FC present in the influent water. All influent water was prepared in the same manner (2% primary effluent, <30 min before dosing), but influent water samples associated with the 18 and 38 L samples had higher average influent FC concentrations (2,200 CFU/100 mL) than those associated with the 58 and 75 L samples (1,500 CFU/100 mL). Previous studies have shown a correlation between influent bacterial concentration and log reduction (Vanderzwaag et al. 2009) in which higher concentrations showed higher log reduction rates.

Also of note from this study was the shortened length of the filter runs compared to studies in which BSFs received 40 L or less (Stauber et al. 2006; Elliott et al. 2008; Ahammed & Davra 2011). The two filters used in the study were in operation 4 months prior to the 75 L challenge. Previous runs lasted on average 45 days, while the 75 L challenges lasted 4 days during the first run and 7 days during the second. The duration of the filtering run length was likely shortened due to increase in volume of water per day which in turn led to an increased mass of particles. The increased number of particles provided an increased amount of organic matter, which the bacteria in the BSF may use as substrate. During the pause period, the microorganisms use the deposited organic matter as a food source, but also enough oxygen must be available for the microbes to oxidize the organic matter. The BSF is designed so that the standing water depth is low enough to provide adequate oxygen diffusion to the microorganisms living in the upper portion of the sand, so while DO was not measured after the pause period, it is assumed that oxygen was not the limiting factor in the oxidation of the organic matter that likely led to the shorter filter runs. While bacteria consume the organic matter, the sudden change in filtering volume likely cause the bacterial populations to be upset (Huisman & Wood 1974), which emphasizes the importance of consistently dosing the BSF.

The results indicate that only the water from the first 18 L should be considered as the best quality for the user. Current state of practice suggests that the BSF can adequately serve the needs of eight to 10 people effectively. According to Reed (2005), minimum ‘survival’ water allocation per person per day is 7 L; therefore a volume of 56–70 L clean water would need to be produced per day to meet the needs of the current state of practice. The results of this study suggest that the BSF should only be used to serve the drinking water needs of approximately three people. If the users were to operate the filter twice a day with a long pause period (>12 h), the filter could serve six users. Additionally, the shortened length between cleanings when 75 L is consistently filtered further suggests that if BSFs are used for large volumes each day, disinfection must be used as well. Other studies confirm that the first pore volume is of the best quality (Elliott et al. 2006; Baumgartner et al. 2007), and that the BSF is not appropriate for filtering large volumes on its own.

Pause period limits

Reduction results from the 1 week pause period experiment indicate that after a week of no filtering the BSFs are capable of slightly better reduction than that of a BSF that had just been cleaned. The reduction observed during the experiment suggested that the bacteria have not completely died off, while also implying that the bacterial layer is not ripening or maturing as it would during a normal (multiple...
dosings per week) 4 week filter run. In week 4, it is noted that the FC reduction is high. The influent FC concentration was much greater at week 4 (1,595 CFU/100 mL) than the previous 3 weeks (average 490 CFU/100 mL) and it is likely the higher reduction is a function of the higher influent concentration. The results of the study emphasize the importance of using the BSF multiple times per week, as suggested by the current state of practice for the plastic and concrete BSFs. If an extended period without use is unavoidable, the BSF should be used with household bleach or some other form of disinfection to ensure the best water quality possible.

**CONCLUSIONS**

The BSF is used worldwide as a household water treatment technology. The BSF is effective at increasing water quality when used properly. Results from the current study suggest modifications should be made to BSF operation recommendations. During the startup and recovery period, the study determined that the bacterial layer could take up to 27 days to reach a 1 log reduction of FC, almost 2 weeks more than that suggested by current state of practice. During startup and recovery periods, a disinfectant such as household bleach should be used along with the BSF in order to ensure the best water quality. For the standard plastic BSF (Hydraid®, 18.5 L pore volume), the experiments indicated that individual dosings should not exceed the pore volume in order to maximize FC reduction. From this information it was determined that the BSF could serve the minimum water needs of six people. The experiments also confirmed that it is necessary that the BSF be used several times per week in order to maintain the best reduction. For best water quality, it is suggested that these limitations be reconsidered by future distributors of the BSF.

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