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Transport effects on hydraulic loading rate and microbial removal performance in biosand filters

Julie Napotnik and Kristen Jellison

ABSTRACT

Biosand filters (BSFs) are increasingly designed using smaller and/or lighter casing material in an effort to reduce logistical requirements and implementation costs. The increased portability of a smaller, lighter design presents a potential negative consequence: the ability to move the installed/operational filter by the homeowner and potentially disturb the system. This study investigated the effects of moving and agitation on filter performance, using mature BSFs which had been in use for over nine months prior to the move. Data were analyzed for four replicate filters of three different filter types: the traditional concrete BSF and two plastic bucket (5-gal and 2-gal, respectively; 5-gal bucket = 18.9-L bucket, 2-gal bucket = 7.6-L bucket) BSFs. Filters were moved approximately 1 km and monitored for hydraulic loading rates (HLRs) and *Escherichia coli* removal for 8 weeks following the move. Moving the filters resulted in reduced HLRs, likely due to sand compaction, but *E. coli* removal remained high (log10 removal $\geq$2.8 for all sizes) and increased significantly as compared to data collected prior to the move. The resulting operational implications of moving BSFs are discussed.

Key words | biosand, *E. coli*, filtration, HLR, treatment, water

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INTRODUCTION

The biosand filter (BSF) is a household water treatment device that has been deployed in over 70 countries since the early 1990s (Manz *et al.* 1993), providing improved drinking water for rural populations without access to public treatment systems. Many BSF projects target communities in remote, rural areas with limited or no improved roadways. In light of the logistical and economic challenges associated with transporting the traditional concrete casing and filter media (rock and sand) to these remote communities, some implementing organizations use plastic casing materials. In some cases, the dimensions of the casing are also reduced, subsequently reducing the requisite volumes of filter media that need to be transported.

The increased portability of a smaller, lighter BSF design presents a potential negative consequence: the ability to move the installed/operational filter by the homeowner and potentially disturb the system. Typically, implementing organizations recommend that installed filters should not be moved and that the sand and rock should be removed and replaced after relocation to minimize negative impacts on filter performance (CAWST 2012). With traditional concrete filters, relocation is typically not an issue since installed filters, with rock, sand, and water, weigh close to 100 kg. However, it is reasonable to anticipate that users may move installed filters over shorter distances (e.g., within a household or from one house to another), especially for either the smaller bucket-sized or plastic-cased filters. Transport of a full-sized, plastic-cased BSF (polyvinyl chloride (PVC) pipe casing with 12 L reservoir volume) over an approximate distance of 60 m (across the street) was observed during a field study in Nicaragua (Figure 1). Three additional PVC filters from this same field study were observed to be moved over larger distances ranging from 0.2 to 1.2 km. The increased potential for filter transport following installation, and the subsequent effects on performance, are potential concerns associated with either changing the filter casing material and/or reducing the overall filter size. Until now, however, there was no supporting evidence of the effect of filter transport on performance.

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Figure 1 | Installed BSF (full size with PVC casing) being transported across the street from one household to another in Nicaragua (photo credits: J. Napotnik).

This study investigated the effects of moving and agitation on filter performance. Following a nine-month contaminant removal study on 12 full-scale BSFs (four each of three different types: traditional concrete, 5-gal plastic bucket, and 2-gal plastic bucket; 5-gal bucket = 18.9-L bucket, 2-gal bucket = 7.6-L bucket), the filters were moved approximately 1 km to a new laboratory location. Although the moving distance was short, the size and weight of the filters required the use of handcarts and a moving truck. All efforts were made to minimize tilting and disruption of the filters, but some jostling could not be avoided. For 8 weeks following the move, the filters were monitored for hydraulic loading rates (HLRs) and *Escherichia coli* removal.

METHODS

Experimental approach

Filter performance was monitored for an 8-week period following transport of the filters approximately 1 km to a new laboratory location. For all filters, the sand bed pore volume equaled the filter charge volume (and influent reservoir volume) and was 12 L for the concrete BSF, 3.6 L for the 5-gal bucket BSF, and 1.5 L for the 2-gal bucket BSF. Filters were flushed ten times after the move and prior to testing. Four *E. coli* challenge experiments were performed, and HLRs were monitored weekly to identify filters that required cleaning (HLRs were also recorded after each cleaning). Results of the *E. coli* challenge experiments and the HLRs were compared to previous results obtained in a nine-month study conducted on the same filters at the original laboratory location.

Bacterial growth and enumeration

Freeze-dried *E. coli* ATCC® 11775™ (Manassas, VA) were propagated for 24 hr at 35 °C in Luria–Bertani (LB) broth (BD Diagnostic Systems, Sparks, MD). The *E. coli* concentration of the inoculated broth was estimated via optical density at 600 nm obtained by a DR-4000 spectrophotometer

(Hach Company, Loveland, CO) and an experimentally determined standard curve. The broth volume was adjusted to obtain the target BSF influent spike concentration of 100 colony-forming units (CFU)/100 mL; inoculated broth concentrations were confirmed by direct plate counts on LB agar Lennox plates. Serial dilutions of BSF influent and multiple effluent volumes (diluted and undiluted) were analyzed by membrane filtration for *E. coli* via Standard Method 9222 (Rice *et al.* 2012) to quantify *E. coli* removal by the BSFs.

All samples (diluted or undiluted) were analyzed in triplicate. Following membrane filtration, membrane filters were placed in a culture dish that contained a sterile pad and 2 mL of m-ColiBlue 24® broth (Hach Company) and incubated at $35 \pm 0.5\,^{\circ}C$ for 24 hr. After the incubation period, membrane filters that yielded 10–100 colonies were considered acceptable and counted. Concentrations were calculated according to Standard Method 9222. If replicate filters of a given sample yielded acceptable colony counts, the resulting concentrations were averaged. For instances when all filters yielded zero colonies, the detection limit (1 CFU/total volume analyzed) was used as the effluent concentration for the subsequent calculation of removal efficiency (i.e., log reduction).

Hydraulic loading rate

Peak flow rates were measured at maximum hydraulic head (directly after adding a full reservoir volume to the filter) using a graduated cylinder and stop watch. The pressure head was the same for each filter of the same type, i.e., 18, 6, and 4 cm for the concrete, 5-gal bucket, and 2-gal bucket filters, respectively. Filters were filled with the same charge volume each time, i.e., 12, 3.6, and 1.5 L for the concrete, 5-gal bucket, and 2-gal bucket filters, respectively. From the peak flow rate, the peak HLR, which normalizes the flow rate to the surface area of the sand in each filter, was calculated (Equation (1)). The surface area of the top of the fine sand layer for the concrete, 5-gal, and 2-gal filters was 0.059, 0.059, and 0.039 m^2, respectively.

$$HLR = Q/A \quad (1)$$

where HLR = hydraulic loading rate ($m^3/(m^2*hr)$), Q = flow rate (m^3/hr), A = area (m^2).

The HLRs of BSFs decrease over time as particles become trapped within the pore spaces (Stauber *et al.* 2006; Elliott *et al.* 2008; Sisson *et al.* 2013). Users are instructed to clean the filter when the flow decreases to an unacceptable level or when the reservoir and top of the sand layer are noticeably dirty (CAWST 2012). To clean the filter, the top 1–2 cm of the sand bed is gently disturbed, releasing trapped particles and dislodging the top layer of the biofilm; the resultant dirty supernatant is decanted, clean water is added to the reservoir, and the process is repeated until the supernatant is clear. For this study, HLRs were monitored and cleaning was performed when HLRs were reduced to approximately half of the initial value.

RESULTS AND DISCUSSION

Prior to the move, the filters were filled three times per day for nine months, and the average post-cleaning HLRs dropped a total of 30.4, 22.8, and 18.0% over this time period for the concrete, 5-gal bucket, and 2-gal bucket filters, respectively (Figure 2; Table 1). These results show that the initial HLR of a newly installed filter is not regained even after cleaning; cleaning was performed 11, 10, and nine

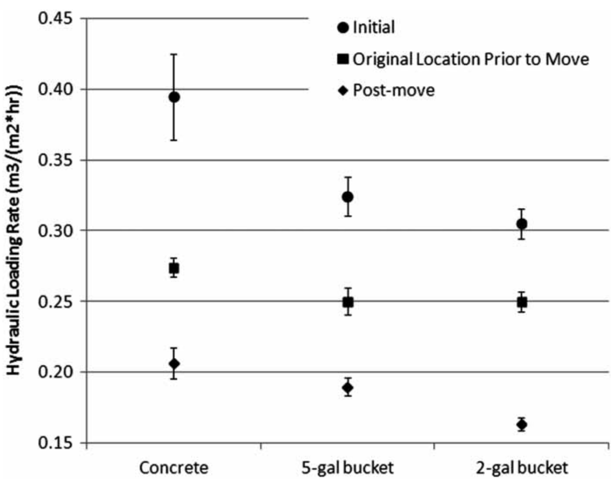

Figure 2 | HLRs for newly installed clean filters (initial, $n = 4$ for each filter type), cleaned filters after nine months of testing (original location prior to move, $n = 44$, 40, and 36 for the concrete, 5-gal bucket and 2-gal bucket filters, respectively), and cleaned filters after the move (post-move, $n = 21$, 24, and 19 for the concrete, 5-gal bucket and 2-gal bucket filters, respectively). Error bars indicate the standard error.

Table 1 | Percent reductions in HLRs observed from normal use over time and from filter transport effects

	Percent reduction		
Comparison of HLRs	**Concrete**	**5-gal**	**2-gal**
Initial vs. original location[a]	30.4	22.8	18.0
Original location[a] vs. post-move[b]	24.8	24.0	34.5
Initial vs. post-move[b]	47.7	41.4	46.3

[a]Average HLR of cleaned filters at the original location over nine months.
[b]Average HLR of cleaned filters at the move.

times on the concrete, 5-gal bucket, and 2-gal bucket filters, respectively. It is reasonable to attribute the majority of this reduction in HLRs to the entrapment of particles within the pore spaces of the sand bed (i.e., filter clogging).

When a filter is installed, sand is added to standing water within the filter casing to prevent air binding and short-circuiting. During the first few runs of the filter (following installation), the flow of the water will induce sorting and some compaction of the sand particles. A 6–8% reduction in porosity was calculated from measuring the change in the height of the sand layer following the first three charges to the filter post-installation. On average, the porosity of the sand bed during installation was approximately 45% and decreased to approximately 41% after three charge volumes. The particle settling and subsequent porosity reduction led to an observed reduction of the HLRs. Specifically, the filter HLRs reduced by 12–16% following the first three charge volumes (data not shown).

For 8 weeks following the move, HLRs were monitored multiple times per week and were observed to be substantially slower than they had been prior to the move. The post-move HLRs dictated cleaning filters almost every week; on average, cleaning was performed 6 out of the 8 weeks for the concrete and 2-gal bucket filters, and 7 out of the 8 weeks for the 5-gal bucket filters. As depicted in Figure 2, the HLRs measured directly after cleaning following the move were significantly slower than those from the original location (p-value <0.0001 for all three sizes comparing original location vs. post-move). Specifically, the move induced another 24–35% reduction in the HLRs (Table 1) corresponding to a total 41–48% reduction from the initial HLR observed at the original installation location. HLR reduction associated with filter transport is likely due to additional sand compaction and possibly some blocking of the outlet tube (some sand was visually observed in the outlet tubes during the deconstruction of the filters). Compaction of the sand bed will result in reduced porosity, reduced pore velocities, and increased frictional resistance which will reduce the HLR.

During the study period, the filters were subjected to four *E. coli* challenge experiments (four replicate filters yielded $n = 16$ per filter type). The results of these challenge experiments were compared to those performed in the previous nine months at the original location (test days 1–275) and showed a significant increase in log removal after the move (p-values of 0.0143, 0.0067, and 0.0392 for the concrete, 5-gal bucket, and 2-gal bucket filters, respectively). Figure 3 displays the range of removals for each filter size over five test periods, four from the original location and the fifth post-move. Note that actual log removal values may be higher than those shown in Figure 3 because there were instances when the detection limit (1 CFU/total volume analyzed) was used to calculate log removal because all effluent samples and dilutions yielded zero colonies.

Transport-induced compaction of the sand bed resulted in an 11, 31, and 32% reduction in porosity (estimated from the change in the height of the sand layer) for the concrete, 5-gal, and 2-gal filters, respectively. Assuming negligible loss of sand during cleaning and not accounting for any additional reduction of porosity due to entrainment of particulate contaminants, the resultant post-move porosities for the concrete, 5-gal, and 2-gal filters were 0.36, 0.28, and 0.28, respectively. These reduced porosities and lower post-move HLRs led to a reduction in pore velocities (m/hr) from 0.96, 0.81, and 0.73 before the move to 0.69, 0.75, and 0.63 after the move for the concrete, 5-gal, and 2-gal filters, respectively. Comparison of pore velocities to the settling velocity of *E. coli* (0.02–0.08 cm/hr, calculated per Stoke's law) suggests that sedimentation of *E. coli* during the filter run is not a primary mechanism of removal in the sand bed. It is more likely that compaction of the sand bed from the move, and resultant reduction in porosity, yielded an increase in the entrapment of *E. coli* cells via interception during filter operation. During the pause period, however, removal of *E. coli* by sedimentation is likely to occur.

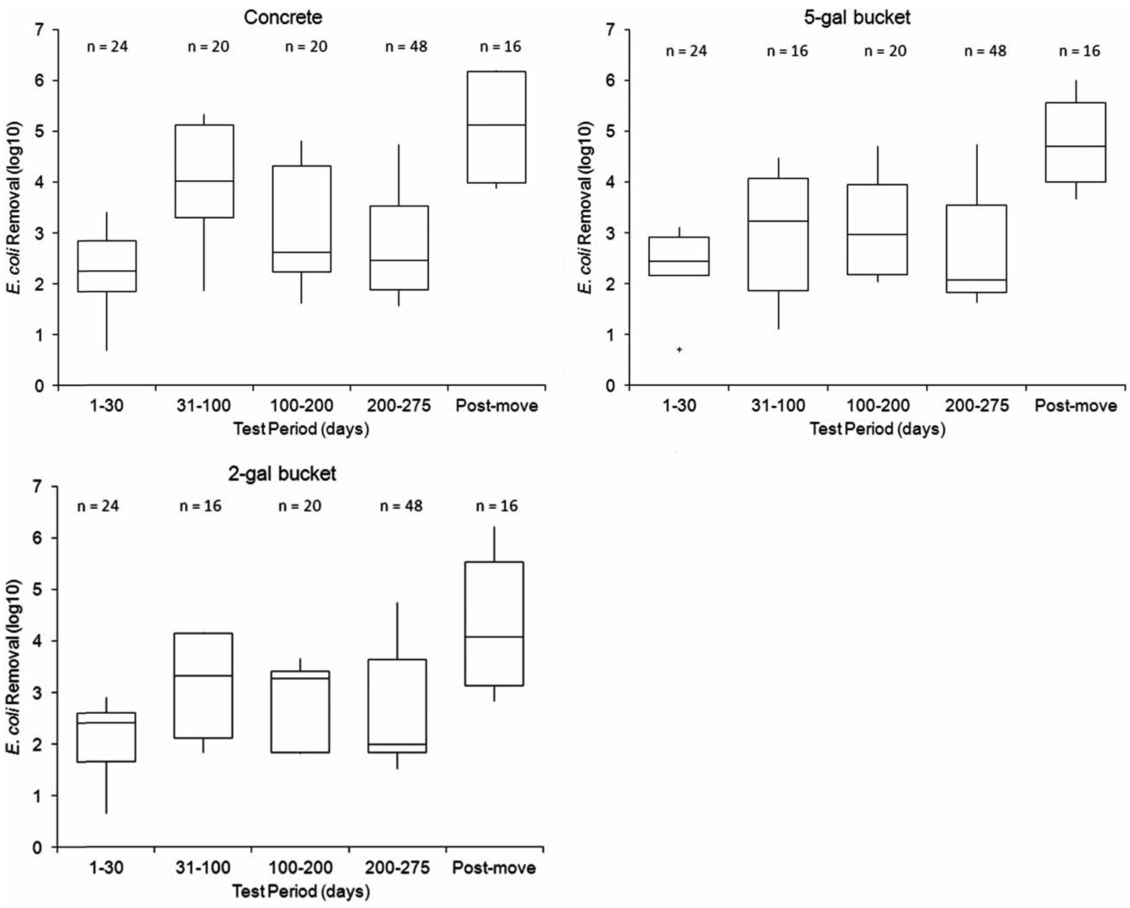

Figure 3 | Range of *E. coli* removals (log10) for filters before (test days 1–275) and after (post-move) transport to a new laboratory location. Boxes indicate the 25th, median, and 75th quartiles, respectively. Whiskers extend to furthest observations within 1.5 of the 25th and 75th quartiles, respectively, with any outliers, less than or greater than these values, identified by asterisks.

CONCLUSIONS

This study has shown that transporting filters over a moderate distance (1 km) resulted in reduced HLRs, likely due to sand compaction, but *E. coli* removal remained high and was significantly improved. While it is likely that filters will slow over time as particles become trapped within the pore spaces of the sand media, the rate and magnitude of HLR decline is difficult to predict as it will be determined, in part, by the turbidity and particle size distribution of the water charged to the filters. For this study, filters were charged three times per day following a 3-hr pause period with turbid waters ranging from 5 to 50 nephelometric turbidity units (NTU); long-term monitoring of replicate filters of various sizes showed that: (1) within the first year of use, the post-cleaning HLR can slow by 25% as compared to the initial HLR; and (2) an additional 25% reduction in HLR is a reasonable estimate if filters are transported after installation.

In conclusion, smaller filters may yield a greater potential for movement after installation by the end-user, but if adequate flushing of the filter is conducted post-move, this will not result in a risk to human health from a bacterial removal standpoint. In this study, filters were flushed with ten charge volumes following the move and then tested for bacterial removal capabilities. Following the move, filters exhibited greater bacterial removal capabilities and reduced HLRs associated with reduced porosity, increased frictional resistance, and slower pore velocities. Thus, the greater risk appears to be in the potential for filter abandonment if the HLR drops to a level deemed unacceptable by the end-user. Proper education on the use and maintenance of any sized BSF is critical to sustained use and water quality improvement. As the first charge volumes post-move were not tested, and since transport of the filter has the potential to release previously trapped particles, the importance of post-move flushing of the filter and potential impacts to HLRs associated with filter transport should be incorporated into educational materials to set reasonable expectations among users and discourage behaviors which may reduce the value of the filters in the eyes of the intended beneficiaries.

Additional work is needed to evaluate the effluent turbidity and *E. coli* concentrations in the first charge volumes that follow filter transport and to identify the number of fills required to adequately flush the filter before quality water is produced. Future work is also warranted to evaluate post-move filter performance over a range of operational pause periods and to investigate the impact of a move on the ability of the BSF to remove other types of microorganisms, including protozoan parasites and viruses.

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