Effects of physical disturbances on media and performance of household-scale slow sand (BioSand) filters

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ABSTRACT

Point-of-use (POU) water treatment provides households in rural and remote communities with a means of obtaining greater control over their water quality and its effects on human health. One of the most prevalent POU interventions, the BioSand filter (BSF), is a household-scale, intermittently operated slow sand filter used by over 300,000 households. The sand and gravel media within BSFs can be housed in concrete (cBSF) or Hydraid plastic (pBSF) bodies, with the latter becoming increasingly popular due to their portability, durability, and anticipated scalability. This study evaluated whether pBSFs, which are lighter and thinner than their concrete counterparts, can maintain their integrity and performance after being subjected to disturbances that could occur in a typical household. Eight pBSFs and two cBSFs were run in parallel for 13 weeks, and three disturbances – one-time filter movement, one-time side impacts, and daily bucket impacts – were applied. Moving and side impacts affected pBSFs more dramatically than cBSFs, causing marked decreases in sand column height (6–29 mm decrease, $p < 0.001$) and decreases in maximum initial flow rate (18–84% decrease, $p < 0.001$). Brief spikes in pBSF effluent turbidity (0.98–15.2 NTU greater than mean effluent levels) also occurred immediately after disturbances.

Key words | BioSand filter, household drinking water treatment, point-of-use, slow sand filtration

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INTRODUCTION

Over 750 million people, 80% of whom live in rural areas, lack access to improved drinking water (WHO/UNICEF JMP 2013). In rural, remote, and otherwise marginalized communities, a lack of access to water infrastructure often means that household members have to travel greater distances to secure safe water; this detracts from time available for education and income-generating activities (Montgomery & Elimelech 2007; Bartram & Cairncross 2010).

Point-of-use (POU) water treatment gives users greater control over the quality of their drinking water and is particularly useful in rural settings where households do not have consistent access to treated piped water. One such POU intervention, the BioSand filter (BSF), is a household-scale, intermittently operated slow sand filter used in over 300,000 households. The BSF is composed of a concrete or plastic filter body housing a sand media bed that rests on a gravel underdrain. An elevated outlet pipe ensures that the static water level remains above the sand surface so that the media bed is always saturated and a biological layer forms on its surface.

Although removal rates tend to vary, ranging, for example, from 0 to 99.7% removal of *Escherichia coli* in tests reported by Stauber *et al.* (2006), there is evidence of significant positive impacts of BSF use on household health. In field studies in Cambodia (Stauber *et al.* 2012), Kenya (Tiwari *et al.* 2009), and the Dominican Republic (Stauber *et al.* 2009), households with BSFs had significantly

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lower coliform concentrations in drinking water and significantly lower diarrheal disease rates than control communities/households. It should be noted, however, that difficulties in conducting fully blinded studies on the health effects of POU technologies have raised questions about the influence of bias on the positive health impacts reported in most literature (Hunter 2009; Schmidt & Cairncross 2009).

BSFs are traditionally contained in concrete filter bodies (cBSFs) made with locally sourced aggregate, but plastic Hydraid filter bodies (pBSFs) are becoming increasingly popular as a light and durable alternative. Without the weight and strength afforded by concrete walls, the sand inside pBSFs may behave differently when subjected to disturbances that occur during regular use. This is particularly important as pBSFs are lighter and – as postulated by Stauber *et al.* (2012) – may be more frequently relocated or jostled. Preliminary evidence from a Samaritan's Purse/Agua Viva pilot project in El Salvador suggests that sand in pBSFs becomes more compact over time than it does in cBSFs (personal correspondence with Ken Morrills, 26 January 2013). A laboratory study at Lehigh University was disrupted after several concrete, plastic, and bucket-style BSFs were relocated and their flow rates dramatically decreased, presumably due to media compaction caused by the move (personal correspondence with Derek Baker, 20 May 2013).

Current recommendations emphasize the importance of keeping BSFs stationary and protecting them from jarring impacts. The Centre for Affordable Water and Sanitation Technology (CAWST 2012) recommends installing filters in a safe location where they cannot be disturbed. The Manz Guidance Manual (Manz 2009) states: 'a BSF should not be moved unless absolutely essential. It is practical to remove the media in the filter, as best possible, and then move the filter container itself. The media can then be reinstalled.' Triple Quest (2011) also cautions against relocating pBSFs, but provides the following guidelines: 'if it must be moved short distances, it may be lifted by its upper rim. Keep the filter upright and level and avoid jarring or dropping.'

All laboratory studies to date have employed stationary BSFs, making it difficult to confirm or improve upon the above recommendations. The objectives of this paper are:

(1) to assess the extent to which three household disturbances affect sand column compaction and flow rate in pBSFs;
(2) to determine whether these disturbances introduce sand gaps and preferential flow paths that could reduce a BSF's filtration performance and pose risks to human health.

MATERIALS AND METHODS

Set-up

Eight Hydraid pBSFs and two concrete v10 cBSFs were tested for leaks and installed according to the most current operating manuals (Triple Quest 2011; CAWST 2012), with media depths and charge volumes as specified in Table 1. All 10 filters were run in parallel for 13 weeks and one-time move/kick disturbances were not applied until at least 50 days had passed. Filters were charged daily each Monday through Friday with one 'sand pore volume' of influent water (Table 1). The charge volumes were chosen so that the cBSFs and pBSFs could be operated similarly from a treatment perspective, as each charge volume was equal to one pore volume.

Table 1 | Summary of media and parameters used for Hydraid plastic and concrete BioSand filters

	Depth of underdrain gravel[a] (cm depth)	Depth of separation gravel[b] (cm)	Depth of sand[c] (cm)	Charge volume (L)	Sand pore volume (L)	Charge volume/sand pore volume (–)	Maximum initial (MI)-flow (mean baseline) (mL/min)	Max. driving head (cm)
pBSF	7	5.7	42	9.0	9.0	1	465	14.2
cBSF	5	5.0	46	7.2	7.2	1	290	10.5

[a]Diameter = 6.25–12.5 mm.
[b]Diameter = 3.13–6.25 mm.
[c]Effective diameter = 0.19 mm; uniformity coefficient = 1.63.

Influent water was prepared by filling a mixing tub with 148 L of municipal tap water from the city of Hamilton, which was left to stand overnight, for at least 18 hours and no more than 72 hours. Each morning, 5.3 L of the water was replaced with an equal volume of raw sewage from the Dundas Wastewater Treatment Plant (Hamilton, ON) to approximate the presence of nutrients and microorganisms in untreated water (WHO 2011). Influent water was thoroughly mixed immediately after adding the sewage and before each filter was charged.

Disturbances applied to filters

A summary of the disturbances applied to each filter is given in Table 2. Filters with bucket disturbances were charged each day by dropping the rim of the bucket on the side of the filter and then tipping the bucket to fill the reservoir – as may happen if a user is not strong or tall enough to easily hoist the full bucket above the filter. 'Kick' disturbances were applied to filters to simulate side impacts that may occur from, for example, a soccer ball or person bumping into the filter. This was standardized through the use of a 10 lb sledgehammer attached to a fixed post. The sledgehammer was pulled back 50 cm and then released, contacting the filter at a height of 29 cm on the opposite side of the filter from the riser pipe. The move disturbance was applied by walking filters gently across the floor for a distance of 2.4 m (8 ft). Both cBSFs were moved rather than kicked because the number of available concrete units was limited; given this constraint, together with past field experience, the assumption was made that the bucket bump and move were more likely to occur to concrete filters in the field. Having no kicked concrete filters limited the comparability of the test results between the two body types, but provided a sense of the consistency of responses between filters of the same type (concrete) to the same disturbance.

Table 2 | Summary of disturbances applied to each plastic and concrete BioSand filter

Filter	Type	Disturbance applied	Timing of disturbance (number of days after installation)
P1	Plastic	–	–[a]
P2	Plastic	K	51 days
P3	Plastic	–	–[a]
P4	Plastic	M	57 days
P5	Plastic	B, K	63 days[b]
P6	Plastic	B	–[a]
P7	Plastic	B, K	51 days
P8	Plastic	B, M	57 days
C1	Concrete	B, M	64 days[b]
C2	Concrete	M	55 days

[a]Arbitrary date of 52 days was used for no one-time disturbance filters in the analysis presented in Figure 1.
[b]Delayed applying disturbance until a long baseline had been collected for comparison as a control.
– = none; B = bucket; K = kick; M = move.

Water quality and characterization: influent and effluent

After the filters had acclimated for approximately 3 weeks, temperature, pH, and total dissolved solids (TDS) were regularly monitored to characterize influent and effluent water, with the same parameters being measured in each effluent sample the day after they were measured in the influent. Turbidity was measured every 1–4 days (Hach 2100Q Portable Turbidometer) as a proxy for filter performance. In the last week of the study, *E. coli* removal was also measured by membrane filtration (Hach USEPA method 8074 with m-Endo media, performed in triplicate).

Influent water samples were taken after mixing the influent. Effluent samples were taken as soon as the effluent had stopped (or nearly stopped) dripping from the filter. Influent water characterization parameters are shown in Table 3.

Table 3 | Influent water characterization

	Temp (°C)	pH	Turbidity (NTU)	TDS (mg/L)	COD (mg/L)
Median	20.8	7.2	3.1	181.6	17.0
(First quartile, third quartile)	(19.8, 21.5)	(7.1, 7.3)	(2.3, 3.7)	(180.3, 182.8)	(14.5, 19.9)
N	32	33	30	32	14

Sand column height, flow rate, tracer tests, and depth profiling

The depth of the standing head was measured every 2–4 days by averaging the distance from the static water level to the media surface at the front, middle, and back of the filter. For the first week of filter operation, the standing head was measured daily and the sand level was adjusted by adding more sand if necessary to maintain a 5 cm head. After the first week, the filters were allowed to naturally settle without the sand levels being adjusted. Changes in sand column height were calculated relative to the baseline (mean) standing head over the first 2 weeks of regular operation (after the initial week of adjustments).

Maximum initial flow (MI-flow) measurements were taken by charging the filter with its regular daily charge (9.0 or 7.2 L) and measuring the volume of effluent produced during the first minute of flow. MI-flow measurements were taken every 2–4 days. Changes in flow rate were calculated relative to each filter's baseline (mean) MI-flow rate from the first 2.5 weeks of filter operation after the flow rates reached equilibrium. MI-flow was not expected to be the same for the cBSFs and pBSFs given that each had a different surface area and driving head. Differences between pre- and post-disturbance sand levels and MI-flow rates were evaluated with the Wilcoxon rank-sum test (H_0 = no difference between pre- and post-levels). The same analyses were performed for differences between changes in disturbed filters compared to changes in control filters P1 and P3 (Table 4).

Tracer tests were performed before and after disturbances to evaluate whether the disturbances introduced preferential flow paths caused by the media shifting on impact. On day 1 of these hydraulic tracer tests, the regular daily charge volume was prepared with the addition of 40 mg/L Acid Yellow 17 and the filter was charged as usual. During the following 4–5 days, regular (no dye added) charges were applied to the filter and the effluent was sampled in 200–500 mL fractions. Absorbance at 400 nm was used to determine the concentration of Acid Yellow 17 in each sample, and the effluent concentration profile was plotted. Four-day batch tests were conducted with sand from the top of the BSFs to confirm that biodegradation and adsorption did not significantly affect dye concentrations over the length of the tracer tests.

At the end of the 13-week experiment, tall narrow windows were cut into the back of four filters (P1, P3, P5, and P8) and the heights of the sand–gravel interface and of the sand column were measured. Two cores (diameter 8.9 mm) were taken from each of the following depths: 0, 5, 20, and 38 cm. Volatile solids were measured for each core by ignition at 550 °C following EPA standard method 1684.

In the last few days of operation before these destructive tests, filters were cleaned to determine whether removing organic matter from the surface would lead to a recovery of flow rates. This was done by gently agitating the top of the sand surface and then decanting the cloudy water, as technicians would do in the field to reduce the biological layer if flow rates become low.

RESULTS AND DISCUSSION

Physical effects of disturbances

There were no visible effects of disturbances on the physical appearance of the filter bodies; no cracks or distortions appeared in the bodies and the circumference of the pBSF bodies did not change after moving or kicking.

Figure 1 depicts the changes in sand column height and flow rate, relative to baseline values, for each filter before and after disturbances occurred. A comparison between each filter's pre- and post-disturbance values, as given by Wilcoxon rank-sum tests, is summarized in Table 4. All filters showed significant ($p < 0.001$) decreases in sand column height due to natural settling over the duration of the experiment; however, changes were much greater in the filters that had been kicked and moved than in the controls (Table 4 and Figure 1). There was no significant difference between changes in P6 (bucket, no one-time disturbance) and the controls P1 and P3 (Table 4). This suggests that when filters are not disturbed in any other way, users can expect some minor media settling that is not affected by whether the bucket contacts the filter wall during charging. All other filters, i.e., those that received a one-time kick or move disturbance, experienced a

Table 4 | Summary of standing head, MI-flow rate, turbidity, and *E. coli* removal for each filter

	No one-time disturbance			**Kicked**			**Moved**			
	P1	**P3**	**P6[a]**	**P2**	**P5[a]**	**P7[a]**	**P4**	**P8[a]**	**C1[a]**	**C2**
Standing head (mm)										
Median before disturbance (*n*)	51 (11)	51 (11)	50 (11)	50 (11)	53 (13)	50 (11)	51 (12)	51 (12)	51 (13)	53 (11)
Median after disturbance (*n*)	53[b] (9)	53[b] (9)	53[b] (9)	59[b] (10)	66[b] (7)	64[b] (9)	80[b] (8)	76[b] (8)	60[b] (7)	59[b] (10)
Change in disturbed filters minus change in control filters (P1 and P3)	n/a	n/a	<1	6[b]	13[b]	11[b]	27[b]	23[b]	7[b]	6[b]
MI-flow rate (mL/min)										
Median before disturbance (*n*)	468 (9)	495 (10)	413 (10)	489 (9)	460 (11)	444 (10)	505 (11)	438 (10)	324 (12)	268 (10)
Median after disturbance (*n*)	475 (9)	493 (10)	415 (10)	400[b] (11)	299[b] (8)	70[b] (11)	288[b] (10)	266[b] (10)	300 (7)	265 (9)
Change in disturbed filters minus change in control filters (P1 and P3)	n/a	n/a	−4.5	86.5[b]	158.5[b]	371.5[b]	214.5[b]	169.5[b]	21.5	0.5
Effluent turbidity (NTU)										
Median before disturbance (*n*)	0.25 (9)	0.31 (8)	0.29 (10)	0.25 (9)	0.31 (12)	0.27 (9)	0.26 (11)	0.23 (11)	0.37 (13)	0.42 (10)
Median after disturbance (*n*)	0.22 (14)	0.19[b] (13)	0.23 (14)	0.26 (14)	0.35 (10)	0.18[b] (13)	0.18[b] (13)	0.18[b] (13)	0.27[b] (10)	0.24[b] (12)
Change in disturbed filters minus change in control filters (P1 and P3)	n/a	n/a	−0.02	−0.09[b]	−0.12[b]	0.01	<0.01	−0.03	0.03	0.10[b]
E. coli										
% removal (range) in final week of study (*n*)	76–84% (3)	68–91% (3)	76–87% (3)	78–93% (3)	69–82% (3)	82–88% (3)	88–92% (3)	82–88% (3)	86–91% (3)	72–90% (3)

[a]Refers to filters that received a daily bucket disturbance.
[b]Indicates a statistically significant difference at $\alpha = 0.01$ based on the Wilcoxon rank-sum test.

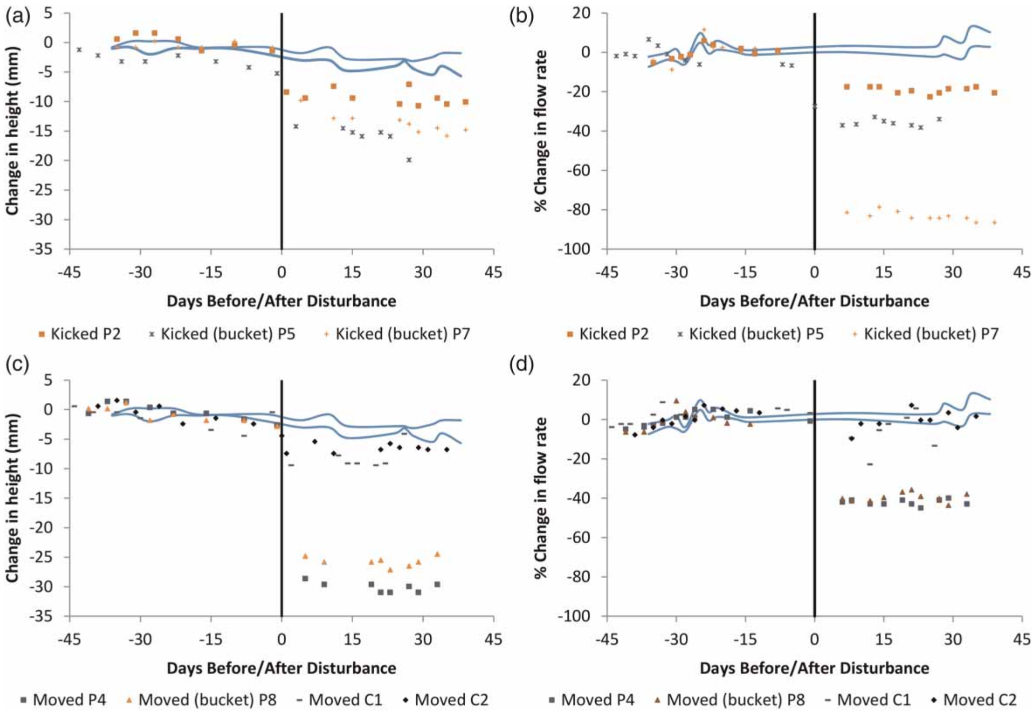

Figure 1 | Change in sand column height (left) and percent change in flow rate (right) for kicked (top, (a) and (b)) and moved (bottom, (c) and (d)) BSFs. Lines represent the maximum and minimum values for the filters that did not receive a one-time kick or move disturbance (P1, P3, and P6); an arbitrary date in the middle of the test period was chosen as day 0 for these three filters.

significantly greater decrease in standing head compared to the controls P1 and P3 (Table 4).

The kicked pBSFs (P2, P5, and P7) lost 9–14 mm of sand column height between pre- and post-disturbance. Moved pBSFs P4 ('no bucket') and P8 ('bucket') showed even greater drops of approximately 29 and 25 mm of sand, respectively. By comparison, cBSFs C1 and C2 only lost 9 and 6 mm in sand column depth, respectively, after being moved the same distance across the floor. In these filters, the concrete walls and/or square design afforded the sand some protection.

Only the pBSF filters that were given a one-time disturbance experienced a significantly greater decrease in MI-flow rate when compared to the control filters (Table 4). For the kicked and moved filters, greater changes in sand column height generally contributed to proportionally greater decreases in flow rate (Figure 1). Decreases in MI-flow (mL/min) from before to after disturbances were significant ($p < 0.001$) for all the three kicked pBSFs (89, 161, and 374 mL/min decreases, respectively, for P2, P5, and P7). MI-flow did not significantly change for moved cBSFs C1 or C2, both of which seemed to recover somewhat from an initial dip in MI-flow that occurred shortly after being moved. Moved pBSFs P4 and P8, on the other hand, experienced decreases in MI-flow of 218 and 172 mL/min, respectively, from pre- to post-disturbance levels.

Of all the kicked and moved filters, P7 (bucket + kicked) showed the most substantial drop in MI-flow rate (decrease of 374 mL/min or 84%) despite being subjected to the same standardized kick as P2 and P5 (Figure 1(b) and Table 3). It took approximately 2.5 hours to filter 75% of each daily charge for P7, whereas the other filters could process the same volume of water in only 30–50 minutes. A user repeatedly charging P7 as soon as the head declined would thus require over 15 hours to filter 40 L, the minimum WHO recommended volume for two household members. For filter P5 (also kicked), this same volume could be filtered in less than 5 hours despite the filter having decreased flow compared to the controls.

With one in three kicked filters developing a constrainingly low flow rate, it is reasonable to conclude that side impacts to pBSFs could contribute to frustration and disuse. If households stop using BSFs because of the increased time cost associated with these disturbances, they may be at higher risk of contracting water-borne diseases. For this reason, users should be strongly urged to install filters in a secure location where they will not be in danger of impacts from passers-by, domestic animals, or other disturbances.

Because the pBSFs were more dramatically affected, these findings suggest that filter body material and/or shape strongly affect how susceptible the filtration media may be to physical disturbances. New BSF designs are emerging that are more portable and utilize light materials, such as sheet metal (Smith 2013), and other smaller plastics (e.g., the plastic bucket design used by Collin (2009)). Further work is required to assess which factors most strongly influence the susceptibility of BSFs to sand compaction and associated flow declines so that new designs can take these into consideration.

Depth profiling

The four side-profiled filters had similar sand–gravel interfaces (data not shown) and there was no evidence that sand had fallen into the gravel layers of the disturbed filters even in cases where substantial decreases in sand column height (as much as 29 mm in P4) had been observed. This suggests that the decreases in sand column height resulted from sand compaction rather than sand falling into the supporting media below. In the field, implementers should pay careful attention to quality control for gravel sizing as larger gravel may not be as effective in preventing sand from falling into the supporting layer. The separation gravel used in this study was carefully sorted and pre-packaged specifically for BSFs (diameter < 6.25 mm) and appeared to perform well in this capacity.

The sand–gravel interface was approximately 2.5 cm lower at the back of filter P5 (kicked) than it was in the dismantled control filters (not shown). This could be a consequence of inconsistent installation of the sand or gravel in the filter or it may have resulted from gravel being forced up and displaced when the kick occurred. The latter is a reasonable conclusion given that P7 (also kicked, but not side-profiled) displayed signs of sand and gravel displacement. When P7 was dismantled, sand poured out of the bottom opening as the riser pipe was removed. This did not happen to the other filters, and likely means that in P7 a wedge of sand dropped to the bottom layer of the filter, displacing the gravel when the kick occurred and resulting in the much lower flow rates described above. In cBSFs, the riser pipe connects to the floor of the filter, but in pBSFs it enters on the side, a factor that may have contributed to this problem in P7. To avoid this issue, an elbow joint could be added in the pBSF riser pipe so that it connects right at the floor of the filter beneath both gravel layers. It should be noted, however, that this study was unable to evaluate whether side impacts would have the same effect if they were applied at different radial or vertical locations on the filter bodies; the same impact, delivered in a slightly different location, might not have had the same effect.

Volatile solids analysis revealed that only cores taken at the sand surface (depth of 0 cm) had, on average, higher volatile solids than uninstalled sand (data not shown). These results suggest that very little organic matter was accumulating below the sand surface, even at depths of only 5 cm; thus biomass accumulation lower in the filter bed likely does not explain the decrease observed in MI-flow. When filters were cleaned during the last week of operation there was no subsequent flow recovery as would be expected if a build-up in the biological layer was responsible for the low flow rates. This finding has important implications for filter monitoring and troubleshooting; technicians can be trained to recognize that low flow, when combined with decreased sand column height, may point to a physical disturbance.

Tracer tests

The filters in this study had similar concentration profiles to those observed by Elliott *et al*. (2008) in their tracer tests, but with longer tails following the negative input (data not shown). Elliott *et al*. (2008) used a clean, unripened filter and a smaller tracer molecule (NaCl) while the tests reported here used a comparatively larger tracer molecule and biologically active filters in which some retardation was expected.

While minor variations in curve shape were observed, there was no obvious change in tracer transport pathways caused by the moving or kicking disturbances, as the curves before and after disturbances were almost identical. This indicates that preferential flow paths likely did not develop in the filters as a result of sand shifting on impact; if such pathways had developed, the post-disturbance curves would have shown earlier breakthrough peaks. Thus these disturbances – while causing flow rates to decline – did not appear to affect the transport pathways taken by water that passed through the filters. This conclusion is further supported by the filter performance results.

Filter performance and influent/effluent water quality

In general, effluent had higher pH and lower turbidity, chemical oxygen demand (COD), and *E. coli* than the influent water parameters given in Table 3; this was in agreement with findings published by previous authors such as Chiew *et al.* (2009) and Stauber *et al.* (2006). TDS, temperature, and pH of effluent were generally not affected by the disturbances applied to the filters and did not substantially differ between filters. One exception was concrete filter C2, which had an effluent pH as high as 9.25 (just outside WHO guidelines) at the beginning of the study. This pH gradually declined, reaching a similar pH to the other filters after filtering approximately 360 L of water. A similar pH shift was also observed by Murphy *et al.* (2010b), who attributed this change to the leaching of calcium carbonate from the concrete filter body.

Mean influent and effluent turbidity levels were 3.38 and 0.28 NTU, respectively, which represents an average turbidity removal of 92%. Effluent turbidity was consistently below the WHO guideline value of 5 NTU and the recommended maximum level of 1 NTU, and removal rates ranged from 71 to 99% during normal operation (see median effluent turbidity values in Table 4). Previous laboratory studies found similar mean turbidity removal rates of 89% for experimental PVC BSFs (Jenkins *et al.* 2011) and 88–97% for pBSFs (Kennedy *et al.* 2012). Effluent turbidity was significantly ($p < 0.01$), but not substantially, lower (i.e., decreases of 0.01–0.15 NTU) after disturbances for six of the ten filters including control P3 (Table 4). This trend was not correlated to any particular disturbances, and none of the filters had significantly increased effluent turbidity post-disturbances. However, in the first charge immediately following a disturbance, each pBSF demonstrated a sudden and brief spike in effluent turbidity up to between 1.26 NTU (P4) and 15.4 NTU (P5) (data not shown; data from disturbance days were excluded from the pre-/post-disturbance analysis described in Table 4). This is likely a result of colloidal material and inorganic salts being mobilized in the plastic filters upon impact. Without knowing whether the colloids released could include pathogens, it is recommended that users do not consume water immediately after disturbances because these elevated turbidity levels may affect potability. The concrete filters had less dramatic spikes of up to 0.42 NTU (C1) and 0.51 NTU (C2) immediately after being moved – well within WHO guidelines – and so their thicker walls may have protected the media.

Filter performance was confirmed through enumeration of *E. coli* in the influent and effluent during the last week of filter operation. Mean influent and effluent *E. coli* concentrations were 1,793 and 262 CFU/100 mL, respectively. Removal rates ranged from 68 to 93% (Table 4), although there were insufficient data to test for the significance of differences between filters. It should be noted that biological treatment methods are highly heterogeneous and it can be difficult to separate the effect of treatment methods from the effects of differences between individual filters. This heterogeneity was controlled as much as possible by comparing each filter's turbidity removal, standing head, and flow rate to its own internal (pre-disturbance) control; however, the small number of filters used in this analysis and the lack of pre-disturbance *E. coli* removal data limit the degree to which the results may be interpreted.

CONCLUSIONS

Although the sample size in this study was limited, particularly for the concrete filter cases, this study provided important initial evidence to assess the effects of disturbances on the performance and behavior of BSFs.

Small daily (bucket) impacts did not affect sand compaction, flow, or filter performance. Larger one-time disturbances (moving and side impacts) caused significant decreases in sand column height of 6–9 mm for cBSFs and 9–29 mm for pBSFs. Control filters decreased by only 2 mm during the same period.

Sand compaction caused by these one-time disturbances led to significant decreases in flow rate for pBSFs. MI-flow rate decreased by 18–84% for disturbed pBSFs but did not significantly decrease for control pBSFs or moved cBSFs. Sand compaction appeared to be the primary reason for these decreases in flow; there was no evidence that it was caused by organic matter accumulation within or on the surface of the media.

There was no evidence of preferential flow paths introduced by the physical disturbances. Water quality was generally unaffected, aside from brief but substantial turbidity spikes that occurred immediately after disturbances in pBSFs. To avoid putting users' health at risk, water should not be consumed without additional treatment for the first 1–2 charges immediately after any disturbance or suspected disturbance.

The results presented here confirm the importance of installing filters in safe/secure locations where they are unlikely to be moved or bumped. Users should be urged not to relocate their BSFs. Technicians could be trained to recognize that an abrupt decrease in sand level, when accompanied by a decrease in flow rate, may point to a physical disturbance and thus will not be effectively addressed through filter cleaning.

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