Impact of surface maintenance on BioSand filter performance and flow

Sarah Singer, Brain Skinner and Raymond E. Cantwell

ABSTRACT

The BioSand filter (BSF) is a household scaled, intermittently operated, slow sand filter. The BSF requires maintenance to remove trapped sediments. This study evaluated the effects of maintenance on the filter's flow rate and performance. Four concrete BSFs received three styles of maintenance: surface agitation (SA), stirring method (SM), and sand removal (SR). Effluent water was collected from the filter between 0–2 L effluent (0–2 L effluent) and between 15–20 L effluent (15 L+ effluent). After maintenance, effluent at 15 L+ (no pause time) showed a significant decrease in thermotolerant coliform removal rates by 0.66–0.91 log (SA), 0.57–0.67 log (SM) and 0.32–0.83 log (RM) (<0.001). Effluent water at 0–2 L (with pause time) did not significantly decrease in thermotolerant coliform removal rates (>0.17) for any maintenance method. The recovery duration after maintenance for all methods at 0–2 L effluent had a median recovery of <1.2 days. The effluent at 15 L+ had a longer recovery period (at least 3.9, 3.0 and 12.75 days for the SA, SM, and SR method, respectively). The flow rate recovery for SA (76%) and SM (82%) was lower compared to SR (138%).

Key words | BioSand filter (BSF), household drinking water treatment, maintenance, point-of-use (POU), recovery, slow sand filtration (SSF)

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INTRODUCTION

Over 663 million people, 80% of whom live in rural areas, lack access to improved drinking water (WHO/UNICEF 2015). Point-of-use (POU) water treatment options are identified as appropriate solutions for the provision of safe drinking water in settings where households do not have access to piped water systems (Elliott *et al.* 2008; Clasen 2009). One such POU intervention, the BioSand filter (BSF), is a household-scale, intermittently operated slow sand filter. The BSF is a modification of a traditional slow sand filter, with the intent to be utilized in a household setting. As of 2014, over 650,000 household BSFs have been installed worldwide (Ngai *et al.* 2014).

To use the BSF, the user removes the filter's lid and pours influent water into the filter's reservoir. The water flows through the diffuser plate/box, which reduces the force of the water to protect the biological layer on the sand's surface (see Elliott *et al.* 2008; Wu *et al.* 2013 for BSF diagrams). The water in the reservoir (the charge water) displaces the pause water, which is the water located within the pores of the sand, which is approximately 12 L of water for version eight (Wu *et al.* 2013). As the filter flows in a near plug flow manner (Elliott *et al.* 2008; Mahaffy *et al.* 2015), the first ~12 L of effluent is water from the previous pour (water stored within the pore volume of the fine and coarse sand). After the initial 12 L of effluent is released, the water is a mix of previous and new water (water above the sand layer including the pause and charge water).

There are four main mechanisms of pathogen and particle removal within both BSFs and slow sand filters. These are: (i) mechanical straining; (ii) sedimentation; (iii) adsorption; and (iv) biological processes (Huisman &

doi: 10.2166/wh.2017.129

Wood 1974; Ellis & Wood 1985; Fox *et al.* 1994). Biological pathogen removal includes three different mechanisms: (i) predation at the top of the filter in the aerobic microbial community, commonly called the schmutzdecke; (ii) predation due to biological activity below the schmutzdecke; and (iii) die-off in the sand column, attributable to the limited availability of oxygen or nutrients.

Slow sand filters (Huisman & Wood 1974) and BSFs (Young-Rojanschi & Madramootoo 2014) tend to perform better when operated continuously. When BSFs are operated intermittently (as they often are in field conditions), microbial removal typically increases with a pause period. The pause period is the length of time the water remains inside the filter before undergoing displacement as effluent. Elliott *et al.* (2008) reported increased removal of *Escherichia coli* in filters that received 20 L of water per day, compared to filters that received half the pause period and were charged with 40 L of water per day (97.5 vs. 95.6% removal, respectively). There is some evidence that longer pause periods result in increased filter performance, but only up to a particular duration. The fecal coliform removal rate was greater for a 16-hour pause period, compared with a 5-hour one (Jenkins *et al.* 2011), and *E. coli* removal was greater in an 18-hour pause period, compared with a 6-hour one (Chan *et al.* 2015). However, Baumgartner *et al.* (2007) found a 12-hour pause period had higher total coliform removal rates (for water collected at a 10 and 20 L effluent collection point), compared with a 36-hour pause period. Young-Rojanschi & Madramootoo (2015) reported no change in filter performance with a pause period of 72 hours, as compared with one lasting 24 hours.

Biological processes offer a substantial contribution to the overall performance of both slow sand and BioSand filtration. Previous field trials consisting of continuously operated slow sand filters report that a mature schmutzdecke alone can contribute up to a 3-log removal of *E. coli* (Bellamy *et al.* 1985; Barrett *et al.* 1991; Unger & Collins 2008). The contribution of the schmutzdecke is observed when a slow sand or BSF is first started. This period of time when a sand filter becomes biologically active is referred to as the ripening or acclimation period. During the ripening period, bacterial removal (e.g. *E. coli*, MS-2 phage) increases exponentially (Wang *et al.* 2014). In general, both implementers and researchers recommend an initial ripening period of 2–4 weeks (Elliott *et al.* 2011; Jenkins *et al.* 2011; CAWST 2012). The speed at which a slow sand and BSF ripens is influenced by the following factors: the microbial, nutrient and oxygen levels in the water; the volumes and frequency of charge water; and the ambient temperature (Huisman & Wood 1974; Bellamy *et al.* 1985; Ellis & Wood 1985; Fox *et al.* 1994; Unger & Collins 2008; Wang *et al.* 2014).

As microbes and solids accumulate in the schmutzdecke, the effluent flow rate of the BSF decreases. The removal of pathogens and turbidity typically increases as the flow rate decreases. A decrease in flow rate is only a concern to the user when the BSF is not producing sufficient water for the household. At this point, the BSF user should perform surface maintenance. There are three commonly used BSF maintenance methods: (i) surface agitation (also referred to as wet harrowing); (ii) the 5 cm stirring method (SM); and (iii) the 5 cm removal method.

While there are many published articles concerning the removal of bacteria and viruses in both laboratory and field conditions (Jenkins *et al.* 2011; CAWST 2012; Ngai *et al.* 2014), few researchers have considered the impact of surface maintenance on filter performance. In one study, after surface maintenance was performed, the removal of fecal coliforms returned to pre-maintenance levels within 2 days (Buzunis 1995). Duke & Mazumder (2009) performed a ‘swirl and dump’ method of maintenance on three different days during a 20-day filter testing period in a laboratory setting. After maintenance was performed, on average, flow rates recovered to 97% of the initial rate. Additionally, *E. coli* removal rates initially decreased with cleaning. Mature filters that had been in use for a year showed a decrease in *E. coli* removal rates by less than 5% from baseline after maintenance. Filters operating less than 3 months had variable *E. coli* removal rates post maintenance; these rates varied from 0 to more than 10%.

Duke & Mazumder’s (2009) findings of decreased effluent water quality after maintenance are supported by several other BSF researchers. Pincus (2003) and Earwaker (2006) state that performing filter maintenance reduces the removal rates. Pincus noted that during BSF testing, the schmutzdecke was believed to have been accidentally disturbed and as a result, *E. coli* removal rates dropped from 85 to 54%. For the next 11 days of testing, the filter performance was variable with a high of 57% in *E. coli* removal. Earwaker (2006) suggested that due to surface maintenance, bacteria removal experienced a 60–70% reduction in the pre-maintenance removal rate.

There are gaps in the literature on the specific and immediate impact of surface maintenance on BSF performance, the differences between maintenance methods and the duration of the re-ripening (recovery) period. Presently, there is also limited research on a BSF's performance in controlled field conditions. The objectives of this paper are: (i) to assess the extent to which three different maintenance methods affect effluent water quality and restore the filter's flow rate; and (ii) to quantify the duration of the recovery period after maintenance has been performed.

MATERIALS AND METHODS

Experimental set-up

Four concrete BSFs (version 8; version 8 BSFs were common during the timing of the study in 2009/2010. New version 10 BSFs have different dimensions including reservoir and pore volume) were installed according to current operation procedures (SPC 2008) and operated in parallel in a controlled laboratory for 26 weeks, starting on December 22, 2009. The research took place in Kamwenge, Uganda, a rural town with a population of approximately 5,000 and rainfall level of 44–214 mm per month. A local pond (2 km from the field laboratory) that was routinely used as a water source for community households was selected for supplying the influent/charge water. The filters were charged with 20 L of the pond water every day. However, for the first 4 weeks, each filter was charged with 40 L of water in an attempt to accelerate biological acclimation. The charge volume was intended to represent typical household usage. The filter media was purchased from a local rock quarry, sifted with a 1 mm mesh (which was common in 2009) and washed in a basin six times (typical procedure used by BSF implementers in Kamwenge, Uganda). The effective size and uniformity coefficients were 0.12 and 4.8 mm, respectively. The effective size fell below the recommended range of 0.15–0.20 mm (CAWST 2012) and the uniformity coefficient was greater than recommended (1.5–2.5) (CAWST 2012). Due to laboratory constraints in Uganda, the effective size and uniformity coefficient of the media were analyzed in Canada after the study was conducted.

Pond water was collected either on or before the day that the filters were charged. The water was transported in 20 L containers and poured into a 250 L tank; it was then mixed at the laboratory site for homogeneity and stored in the tank until needed. Water was then discharged from the tank through a spigot into a 30 L bucket. The 30 L bucket was filled, then stirred. A 2.5 L jug was then used to evenly re-distribute the water from the 30 L bucket into four other 30 L buckets. This process was repeated until all four buckets contained 20 L of water of similar quality. Each bucket of water was then poured into the filter's reservoir.

Procedures for surface maintenance

For this research, three maintenance procedures were examined; each maintenance procedure is outlined below. Filter effluent served as the charge water during maintenance. After a maintenance procedure was performed, the filters were immediately charged with 20 L of influent water and water quality samples collected.

(i) Surface agitation method (SA): (1) Remove the lid and charge with 5 L of water; (2) remove the diffuser box; (3) agitate the entire surface area of the sand by rapidly tapping the top of the sand (no deeper than 1 cm) with fingertips; (4) scoop out the pause water on top of the sand with a 500 mL cup without making contact between the cup and the sand; (5) replace the diffuser box and charge the filter with 7.5 L of water; (6) repeat steps 2–5; (7) repeat steps 2–4; (8) level sand if necessary; (9) replace the diffuser box and lid.

(ii) 5 cm Stirring method (SM): (1) Remove the lid and charge with 5 L of water; (2) remove the diffuser box; (3) disturb sand using fingers to rake and stir the sand, no deeper than 5 cm into the sand; (4) scoop out the pause water with a 500 mL cup; (5) replace the diffuser box and charge the filter with 7.5 L of water; (6) repeat steps 2–4; (7) level sand if necessary; (8) replace the lid.

(iii) 5 cm Removal method (RM): (1) Remove the lid and diffuser box; (2) remove the pause water from the filter with a 500 mL cup; (3) remove the top 5 cm of sand and place that sand in a basin; (4) pour 5 L of water into the basin containing the sand, stir by hand 10 times, and dump out the supernatant water quickly; (5) repeat step 4 twice; (6) replace the diffuser box; (7) charge the filter with 2.5 L of water; (8) remove the diffuser box and place the newly washed sand in filter; (9) level the sand; (10) replace the diffuser box and lid.

The flow rate recovery (i.e. after maintenance) was defined by:

$$\text{Flow rate recovery (\%)} = \frac{\begin{array}{c}(\text{Previous maintenance recovery flowrate}*- \\ \text{Present maintenance recovery flowrate})\end{array}}{\text{Previous maintenance recovery flowrate}} \times 100$$

*During the first maintenance procedure, the installation flow rate was used.

Table 1 shows a summary of the surface maintenance schedule applied to each filter. Surface maintenance was performed when the flow rate dropped below 250 mL/min, which is considered low for the daily water needs of a six person family. Although each filter was designated to either be maintained by SA or SM methods, each filter was maintained by the 5 cm sand removal method once during the study period.

Table 1 | Summary of maintenance applied to laboratory filters

Filter	Surface maintenance applied	Timing of maintenance (number of weeks after study commencement)
SA-1	SA	5, 10, 13, 16[a], 19, 22, 24
SA-2	SA	5, 10, 13, 16[a], 19, 24
SM-1	SM	5, 10, 18[a], 24
SM-2	SM	5, 10, 18[a], 24

SA = surface agitation, SM = 5 cm stirring method.

[a] Week the filter was maintained by the 5 cm removal maintenance method.

Water quality and characterization: influent and effluent

Water quality and filter operating data were collected weekly. When a filter was maintained, data collection occurred the day prior to maintenance, the day of maintenance, and collected daily for three consecutive days post-maintenance to monitor recovery. The following water samples were collected: pause water (idle water above the sand media), influent, effluent discharged within the first 2 L (henceforth referred to as 0–2 L), and effluent discharged between 15 and 20 L (henceforth referred to as 15 L+). The flow rate was measured immediately after the filter was charged with 20 L. Each sample was examined for temperature, pH (CyberScan pH11 portable meter), conductivity (CyberScan CON11 portable meter), turbidity (PalmScan TB4 Portable Turbidimeter), and thermotolerant coliforms (membrane filtration method), according to the manufacturer's instructions (Wagtech International, n.d.). Regarding the thermotolerant coliform testing, the filtration apparatus was sterilized with flaming methanol in between water samples, and typically each water sample had two different dilutions aiming to have a CFU count between 50 and 200 per petri dish. Typically, the dilutions were effective and the dilutions within the ideal count of CFUs per petri dish were used in removal rate calculations. In the rare case neither dilution was under 200 CFU per petri dish, the CFUs were still counted and averaged and dilutions adjusted the following day to accommodate. A duplicate sample was produced for each dilution. Incubation was for 18 hours at 44°C. Agar was prepared in the field with a lauryl sulphate broth. Removal rates were initially calculated arithmetically, and then processed into log base 10 removal rates and geometric means. Log transformations were calculated using the equation: log10 reduction = log 10 (influent) – log 10 (effluent).

Influent water samples were taken after mixing the influent and dividing it between the filters. Influent characterization parameters are shown in Table 2. Influent data was collected for each of the four laboratory filters, but an analysis of variance (ANOVA) test on the influent parameters found no statistically significant differences between the influent charged into the different filters ($p = 0.92$). This indicates the effectiveness of the mixing approach on the raw water. Therefore, this paper presents the influent data for all of the four filters grouped together.

Table 2 | Influent water characterization ($n = 52$)

	Temperature (°C)	pH	Conductivity (mS/cm)	Turbidity (NTU)	Thermotolerant coliform (cfu/100 mL)
Median	22.8	7.59	486	52.9	966
(first quartile, third quartile)	(22.0, 23.4)	(7.41, 7.73)	(418, 511)	(33.0, 83.2)	(554, 2989)

RESULTS AND DISCUSSION

Thermotolerant coliforms and turbidity removal

The average log removal rates and the median percent removal values of thermotolerant coliforms for each laboratory filter during regular (maintenance free) operation and after surface maintenance is shown in Table 3. The average thermotolerant coliforms removal was between 1.14 and 2.52 log removal (92.8–99.5%) during the regular operation period for each of the four filters. This is similar to the field trials, where literature reports bacterial removal rates of 0.70–1.52 log removal or 80–97% (Duke *et al.* 2006; Earwaker 2006; Stauber *et al.* 2006; Ngai *et al.* 2014). After maintenance, thermotolerant coliform removal values decreased in the 15 L+ between 0.32 and 0.91 log, depending on the applied maintenance procedure (see Table 3). This proved a statistically significant decrease in thermotolerant coliform removal values as compared with the removal values during regular operation for 15 L+ samples ($p < 0.001$, Wilcoxon rank-sum tests) during all maintenance methods. In contrast, when considering the 0–2 L samples, there was no significant difference found between the regular operation and recovery period for any of the

Table 3 | Thermotolerant coliform removal during 'regular' operation vs. maintenance recovery period

	Thermotolerant coliform removal (Log and %)							
	SA-1		SA-2		SM-1		SM-2	
Filter conditions	0–2 L	15 + L	0–2 L	15 + L	0–2 L	15 + L	0–2 L	15 + L
During 'regular' operation (excluding recovery) (n)	2.52 99.1% ($n = 4$)	1.62 96.4% ($n = 31$)	2.41 99.0% ($n = 4$)	1.43 95.4% ($n = 35$)	2.18 99.5% ($n = 3$)	1.31 94.2% ($n = 30$)	2 98.5% ($n = 3$)	1.14 92.8% ($n = 31$)
During the period of ripening after surface agitation (SA) (n)	1.72 98.3% ($n = 14$)	0.71 85.7% ($n = 11$)	1.69 98.0% ($n = 14$	0.77 83.6% ($n = 13$)				
'Regular' operation removal rate minus removal rate during surface agitation ripening period	0.80 0.8%	0.91 10.7%	0.72 0.9%	0.66 11.8%				
During the period of ripening after 5 cm strirring (SM) (n)					1.59 96.5% ($n = 11$)	0.67 80.2% ($n = 8$)	1.42 96.2% ($n = 11$)	0.57 79.0% ($n = 8$)
'Regular' operation removal rate minus removal rate during 5 cm stirring ripening period					0.62 3.0%	0.64 14.0%	0.58 2.2%	0.57 13.8%
During the period of ripening after 5 cm sand removal (RM) (n)	1.91 99.3% ($n = 3$)	0.71 77.6% ($n = 5$)	2.25 99.3% ($n = 3$)	1.11 92.1% ($n = 2$)	1.42 95.4% ($n = 3$)	0.59 71.0% ($n = 8$)	1.68 96.1% ($n = 3$)	0.81 83.6 ($n = 7$)
'Regular' operation removal rate minus removal rate during 5 cm sand removal ripening period	0.61 –0.2%	0.83 18.8%	0.16 –0.4%	0.32 3.3%	0.76 4.1%	0.72 23.2%	0.32 2.4%	0.33 9.2%

Both average log removal and median percent removal are displayed to outline regular filter performance, filter ripening performance, and the difference between regular filter performance and filter ripening.

maintenance methods ($p > 0.17$), as determined by Wilcoxon rank-sum tests.

The median turbidity removal percentages during regular operation, during filter ripening, and the difference between these two phases are shown in Table 4. The turbidity removal rates fluctuated less than the thermotolerant coliform removal rates during the recovery period for all maintenance procedures (Table 4). When considering the 15 L+ samples, there was a 0.9–4.6% decrease in the median percent turbidity removal rate for all three maintenance procedures, which occurred as a result of the maintenance performed. The difference between the turbidity removal rates during regular operation compared with the rates during the recovery periods proved statistically significant ($p < 0.01$, Wilcoxon rank-sum tests) for all three maintenance methods (15 L+). This contrasts with the 0–2 L samples for which there appears to be an increase of up to 3% in the median percentage turbidity removal, which is associated with surface maintenance; however, none of the changes in the median turbidity removal for the 0–2 L samples were statistically significant ($p > 0.05$) as determined by Wilcoxon rank-sum tests.

From the literature, a reduction in each filter's performance as a result of surface maintenance was expected (Buzunis 1995; Pincus 2003; Duke & Mazumder 2009), although no study specifically considered the impact of pause time. The more substantial impact of surface maintenance on thermotolerant coliform removal (in the 15 L+ samples) as compared with the impact on turbidity removal is consistent with the role of the mature schmutzdecke for microbial removal since the schmutzdecke is vulnerable to damage by the disruptive nature of maintenance (Bellamy *et al.* 1985; Barrett *et al.* 1991; Unger & Collins 2008; Wang *et al.* 2014).

The findings that the surface maintenance did not have a statistically significant impact on the median removal of thermotolerant coliforms or turbidity in the 0–2 L samples is an important and unanticipated result. This suggests that independent of which surface maintenance method is used, the quality of water that has paused within filter (in this case for 18–24 hours) does not decrease as substantially after surface maintenance as compared with similar water that does not experience a pause period. Since the filter users in a rural household setting typically consume previously filtered water during the initial recovery period, this finding reinforces the benefit of biosand filters that have a pore volume equal to or greater than the charge volume. Version 10 of the BSF has a pore volume equal to the charge volume whereas version 8 of the concrete BSF,

Table 4 | Turbidity removal rates during 'regular' operation vs. maintenance recovery period

	Turbidity removal (%)							
	SA-1		**SA-2**		**SM-1**		**SM-2**	
Median values	**0–2 L**	**15 + L**	**0–2 L**	**15 + L**	**0–2 L**	**15 + L**	**0–2 L**	**15 + L**
During 'regular' operation (excluding recovery) (*n*)	95.6 ($n = 4$)	95.6 ($n = 32$)	96.8 ($n = 4$)	94.8 ($n = 36$)	96.9 ($n = 3$)	93.9 ($n = 31$)	98.0 ($n = 3$)	93.1 ($n = 32$)
During the period of recovery after surface agitation (SA) (*n*)	98.7 ($n = 13$)	94.7 ($n = 11$)	97.7 ($n = 14$)	93.0 ($n = 12$)				
'Regular' operation removal rate minus removal rate during SA recovery period	–3.0	0.9	–0.9	1.8				
During the period of recovery after 5 cm SM (*n*)					97.2 ($n = 11$)	89.3 ($n = 8$)	96.2 ($n = 11$)	88.6 ($n = 8$)
'Regular' operation removal rate minus removal rate during SM recovery period					–0.3	4.6	1.8	4.5
During the period of recovery after 5 cm sand removal (RM) (*n*)	97.7 ($n = 3$)	91.8 ($n = 5$)	96.7 ($n = 3$)	91.3 ($n = 2$)	96.6 ($n = 3$)	92.1 ($n = 8$)	96.0 ($n = 3$)	90.6 ($n = 7$)
'Regular' operation removal rate minus removal rate during RM recovery period	–2.1	3.8	0.2	3.6	0.3	1.8	2.0	2.5

the Hydraid® plastic BSF and other smaller BSFs (Tiwari *et al.* 2009; Jenkins *et al.* 2011) have a larger charge volume compared to their pore volume.

For BSFs where the design does not have a pore volume equal to charge volume, implementers typically teach that the first water from the filter each day is the best quality water (due to the fact that is has paused in the filter overnight). The results of this study suggest this is particularly important during the recovery period.

Duration of recovery period

After surface maintenance, a filter was considered recovered when the thermotolerant coliform removal rate (influent minus effluent 15 L+) was at least 95% of the removal rate before maintenance was performed. The length of time between when maintenance was performed and when the filter was considered recovered was defined as the recovery period. With this definition, the mean and the upper bound of the 95% confidence interval for the recovery period was determined as shown in Table 5. The data from this study indicates that the sand removal method caused the longest recovery time for the effluent at 15 L +, but resulted in the quickest recovery time when examining the 0–2 L effluent (although not statistically significantly different, potentially due to the low sample size). The recovery periods were substantially shorter for the 0–2 L samples (i.e. at least a quarter of the duration for nearly every estimate in Table 5) as compared with the 15 L+ samples providing evidence that the pause period decreases the recovery period.

Figure 1 shows the average of the thermotolerant coliform log removal for each of the three maintenance procedures for both the 15 L+ and the 0–2 L effluent. The day of maintenance is day '0' and denoted with a dashed vertical line. In the graphs, there are fewer pre- and post-maintenance days for the 0–2 L effluent, as the 0–2 L effluent data requires successive days of testing, and that was not completed beyond the days depicted on the graph. The graphs show that for the 0–2 L effluent, removal rates are typically above 1.0 log including the day of maintenance. This finding contrasts the removal rates associated with the 15 L+ effluent, where large variations are observed on both the day of maintenance, and the subsequent recovery days. The average log removal of thermotolerant coliforms for the 15 L+ effluent water from day one through the tenth day post-maintenance were: 1.02, 0.84 and 0.82 for the SA, SM, and RM filters, respectively (or median thermotolerant coliform removal of 91.2, 87.3 and 79.1%, respectively). The average log removal of thermotolerant coliforms for the 0–2 L effluent from day one through the third day post-maintenance were: 1.57, 1.31 and 1.31, for the SA, SM, and RM filters, respectively (or median thermotolerant coliform removal of 99.1, 98.0 and 97.2%, respectively).

Flow rate and filter performance

The calculation for computing the flow rate recovery is outlined in the Material and methods: Procedures for surface maintenance section. The removal percentage of thermotolerant coliforms and turbidity linearly regressed (i.e. $y = mx + b$) against the flow rate for the four laboratory filters. The regression models consider the flow rate independent of whether the schmutzdecke layer was recently disrupted by surface maintenance. R^2 values were low (<0.1), which indicates that flow explains only a small fraction of the

Table 5 | Duration of thermotolerant coliform recovery period

	0–2 L			15 L +		
	Surface agitation method	**5 cm SM**	**Sand removal method**	**Surface agitation method**	**5 cm SM**	**Sand removal method**
Number of surface maintenance events	8	5	4	8	6	4
Mean duration (days) for 95% recovery	0.8	1.2	0.25	>3.9[a]	>3.0[a]	>12.75[a]
Upper 95% conf. interval for 95% recovery (days)	1.7	4.2	0.9	8.5	6	23

[a]As water quality testing was not conducted daily, the exact date of recovery duration is unknown for some of the 15 L+ water samples.

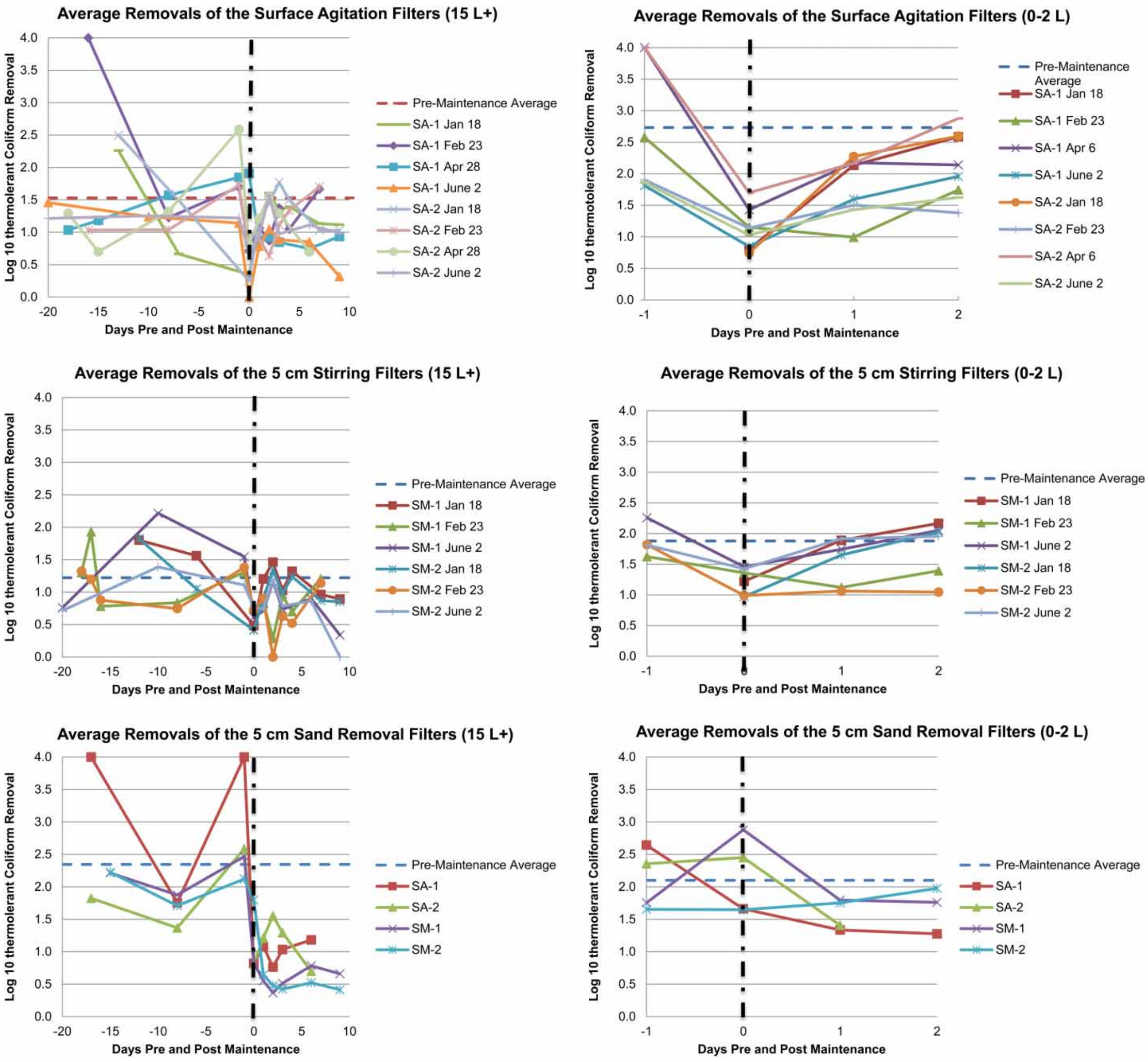

Figure 1 | Thermotolerant coliform removal surrounding maintenance day. The average pre-maintenance thermotolerant coliform removal for each filter is illustrated on each graph to show the contrast between 'regular' operation and the 'ripening' period post maintenance.

variability in the data. The results indicate that for every 100 mL/min increase in flow rate, the removal of thermotolerant coliforms decreases by 3.4 and 0.36% for the 15 L+ and 0–2 L samples, respectively. This suggests that for 0–2 L samples in which the test water paused in the BSF, the removal rates were approximately 10 times less susceptible to change due to flow rates. Napotnik & Jellison (2014) also correlated a reduced hydraulic loading rate to a significantly improved rate of *E. coli* removal. Turbidity removal rates for the 15 L+ were fairly robust against the changes in flow rates as an increase of 100 mL/min only decreased turbidity removal by 0.46%. No statistically significant relationship between the turbidity removal percentage and flow rate for the 0–2 L samples was found.

Flow recovery from surface maintenance

The average flow rate recoveries are shown in Table 6. The surface agitation and SM demonstrated average flow recoveries of 76 and 82%, respectively. These results were

Table 6 | Summary of post-maintenance flow recoveries

Maintenance method	Average flow rate recovery (%)	Source
Surface agitation (SA)	76	Current study
5 cm SM	82	Current study
5 cm sand removal method (RM)	138[a]	Current study
Scraping	95	Buzunis (1995)
Surface agitation	71	Thye (2007)
15 mm sand removal and washing	75	Thye (2007)
Swirl and dump method (similar to surface agitation)	97	Duke & Mazumder (2009)

[a] 82% recovery as compared with the installation flow rate.

similar to the flow recoveries reported by Thye (2007). Such low flow recoveries suggest a continually declining flow rate. In this 6-month study, it was not clear what flow rate would be required for an equilibrium to be reached or when more aggressive maintenance would be required. As the surface agitation filters had a lower flow rate recovery compared with the 5 cm SM, maintenance was required two or three more times for the surface agitation filters over the same time period. Buzunis (1995) and Duke & Mazumder (2009) reported flow recoveries of 95 and 97%, respectively, which is more sustainable in terms of ensuring that the filter provides sufficient water quantity for the user. Both Buzunis (1995) and Duke & Mazumder (2009) employed a 'clean in place' method impacting only the top 5 cm of sand (similar to the SA or 5 cm SM). This indicates that such a method can achieve sustainable flow recoveries.

For the 5 cm sand removal method the four filters averaged a flow recovery rate of 138% (when compared to the previous maintenance recovery flow rate). This cleaning method was applied towards the end of the study, after the filters had been declining in their flow rates for several months. When the flow rate recovery for the 5 cm sand removal method was calculated in comparison to the initial flow rate, the recovery was 82%. This suggests that while the 5 cm removal substantially increased the flow rate, it did not result in producing a flow rate equal to the installation flow rate.

CONCLUSIONS

A pause period lasting 18–24 hours reduces the impact of surface maintenance on filter performance during the recovery period. Without a pause period (15 L+ effluent), thermotolerant coliform removal rates decreased after maintenance and decreases ranged from 0.66 to 0.91 log (SA), 0.57 to 0.67 log (SM) and 0.32 to 0.83 log (RM). These decreases are all statistically significant ($p < 0.001$). In contrast, with a pause period (0–2 L effluent), the impact of SA, SM, and RM on the median removal of thermotolerant coliforms was not statistically significant ($p > 0.17$).

The water that did not undergo a pause period displayed the most significant initial decrease in thermotolerant coliform removal rates. Following maintenance, the average log removal of thermotolerant coliform for the effluent at 15 L+ were 1.02, 0.84 and 0.82 for the SA, SM and RM filters, respectively. Conversely, the paused water (0–2 L effluent) had higher thermotolerant coliform removal rates with an average log removal greater than 1.3 following the first 3 days after maintenance for all three maintenance procedures.

The upper bound of the 95% confidence interval for the recovery period for SA, SM, and RM filters without a pause period (15 L+ effluent) was 8.5, 6 and 23 days, respectively. The recovery period was considerably faster for the water that was paused, with recovery days within a 95% confidence interval of 1.7, 4.2 and 0.9 days for the SA, SM and RM filters, respectively.

The results presented add to the evidence that intermittently operated BSFs, with an appropriately long pause period, provide increased microbial removal rates, particularly during the recovery period, as compared to no pause period. This research highlights the benefit of using BSF version 10, which has equal pore and charge volumes. The authors do not recommend using the 5 cm removal method because of the long recovery period (approximately 3× that of surface agitation and SM) and the magnitude of the initial drop in thermotolerant coliform removal rates after maintenance, unless more cleaning is required to aid flow recovery. The authors recommend using the surface agitation method for filter maintenance, as this method was associated with higher removal rates of thermotolerant coliforms and turbidity for both the paused (0–2 L effluent) and non-paused (15 L+ effluent) water. These recommendations are targeted for new BSF implementation programs. As addressing the relationship between maintenance methods and behavior change was outside the scope of this research, it is unknown how readily acceptable new maintenance procedures will be welcomed or viewed by those already using the BSF. The authors recommend future study to determine whether shorter pause periods (i.e. less than 18 hours) mitigate the impact of surface maintenance on filter performance during the recovery period.

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First received 26 April 2016; accepted in revised form 13 November 2016. Available online 1 February 2017