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The operation, flow conditions and microbial reductions of an intermittently operated, household-scale slow sand filter

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Recent Progress in Slow Sand and Alternative Biofiltration Processes

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32   The operation, flow conditions and microbial reductions of an intermittently operated, household-scale slow sand filter

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Abstract Nearly one-fifth of the world's population lacks access to safe, reliable sources of drinking water. Point of use (POU) household water treatment technology allows people to improve the quality of their water by treating it in the home. A promising emerging POU technology is the biosand filter (BSF). The BSF is a household-scale, intermittently operated slow sand filter that maintains a wet media bed containing a schmutzdecke and allows periodic water dosing by the user. Step input chemical tracer tests indicated that the BSF operates at near-plug flow conditions. Six-to-eight week longitudinal challenge studies were conducted with daily charges of surface water spiked with *E. coli* strain B bacteria, coliphages MS2 and PRD-1 and human enteric virus echovirus type 12. The BSF ripened in a manner similar to conventional SSFs. Flow rate slowed and microbial reductions improved over time with ripening. *E. coli* reductions were ~90% following filter startup but improved to 95–99.5% over time. Microbial reductions were greater with greater residence time within the filter, especially for water retained in the filter bed overnight. *E. coli* and echovirus 12 reductions were greater than those of coliphages MS2 and PRD-1.

Introduction

More than one billion people in the developing world lack access to improved sources of drinking water (WHO, 2004). For those with access to safe water, subsequent contamination during transport or household storage can pose significant health risks. Three-to-five billion cases of diarrhea occur annually and lead to 1.8 million deaths (WHO, 2004) in addition to massive morbidity and economic consequences.

The preferred solution to the problem of unsafe water causing disease is to provide universal access to inexpensive, safe, reliable piped water supplies. However, in many nations that reality is many decades away because authorities can not create the infrastructure and deliver reliable service. In the meantime, families obtain their own drinking water wherever they can, often from contaminated, unsafe sources. Most consume this water
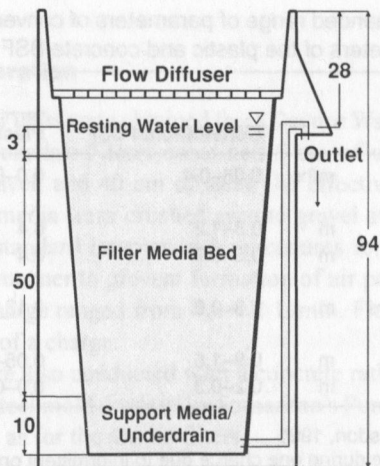
Figure 1.1 Cross-section of the concrete BSF. Lengths are in cm.

untreated because it is their only option. Some boil their water, but boiling requires large amounts of fuel, making it difficult, expensive, and a threat to the sustainability of natural resources.

Point of use (POU) drinking water treatment and safe storage technology allows people without access to safe water sources to improve the quality of their water by treating it in the home (Sobsey, 2002), thereby taking control of the safety of their drinking water. No one POU device is appropriate for all situations and many factors must be considered such as cost, simplicity of use, volume treated, local sustainability, cultural acceptability and treatment efficiency. One of the most promising emerging POU technologies is the biosand filter (BSF), a household-scale, intermittently operated slow sand filter (SSF).

The biosand filter consists of a concrete or plastic chamber filled with sand (Figure 1.1). An elevated discharge tube allows the filter to maintain a layer of water above the sand surface and prevents dewatering. Research has established that full-scale, conventional SSFs remove pathogens from water (Fox et al, 1994) but the effectiveness of this household-scale unit has until recently been uncertain because of different design and operational properties than conventional SSF.

The design and operational features of the BSF and the conventional SSF are compared in Table 1.1. The range of operational parameters listed for the BSF has evolved through rather limited experience in developing countries. The BSF is similar to conventional SSFs in that there is no pretreatment or backwashing and operation is simple, including gravity- rather than pressure filtration. As in conventional SSFs, the sand bed remains wetted throughout operation and a ripening process occurs, during which a schmutzdecke forms and performance improves.

The most important difference between BSF and SSF is the feed flow pattern. The filter is operated intermittently by introducing a single charge of water (perhaps only one per day) rather than continuously. The typical charge is 10-to-20 L after which the

Table 1.1 Recommended range of parameters of conventional SSFs and the range of parameters of the plastic and concrete BSFs.

		Conventional SSF[1]	Biosand Filter	
			Plastic	Concrete
Filtration Rate	m/hr	0.08–0.4	0.0–0.9*	0.0–1.2*
Depth of sand				
Initial	m	0.8–1.2	0.4	0.5
Minimum	m	0.5–0.7	0.4	0.5
Depth of supporting				
media & underdrains	m	0.3–0.6	0.13	0.1
Depth of Supernatant				
Water	m	0.9–1.5	0.05–0.17*	0.02–0.28*
Freeboard	m	0.2–0.3	0.0–0.04*	0.0–0.4*

[1]From Pyper and Logsdon, 1991
*Vary within this range during one charge due to intermittent operation.

water level above the filter media declines. The BSF operates, therefore, in the declining rate mode of filtration. The maximum application rate is about 1.1 m/h and at the maximum filtration rate, the filter area of a single BSF unit provides a product water flow rate of about 1.0 L/min. Operation is discontinued when water production (flow rate) is judged insufficient by the user. The filter is manually cleaned and immediately put back in use.

As shown in Figure 1.1, dewatering of the filter in between charges is avoided by a vertical discharge tube that rises from 2- to 5 cm above the height of the filter media. Another unique aspect of the BSF design is to promote uniform drip flow over the sand surface by use of a plastic or sheet metal diffuser above the filter media. This diffuser prevents the charge of water from disturbing the schmutzdecke.

With repeated daily filtration cycles, the schmutzdecke layer eventually develops to cover the media bed and severely limits the filtration rate. At this time, the user disturbs the top few cm of sand to open up pores that have been clogged or blocked by the schmutzdecke and accumulated suspended matter. Sand is not removed intentionally. The dirty supernatant water is then removed and the filter placed in service again.

A number of reports have presented practical aspects of the BSF such as field implementation, user satisfaction, and percentage removal of fecal coliforms or *E. coli* in the field (Murcott, 2002). Over 50,000 BSFs are in use worldwide. Users report satisfaction with the filter and improved health following its introduction into the home (Kaiser et al, 2002). Despite successful field implementation, there has been little systematic, process engineering research to substantiate the effectiveness of the BSF nor to optimize its design and operation. A M.S. thesis addresses bacterial reductions and performance characteristics (Buzunis, 1995) and one peer-reviewed publication reports removal of toxicants and parasites (Palmateer et al, 1999).

The objectives of this research on the BSF are: (1) to characterize its hydraulic operation and (2) to measure the reduction efficiency of enteric bacteria, bacteriophages and viruses under controlled laboratory conditions.

Methods

Filter and media preparation

Plastic, 60-L capacity, filter units were obtained from Davnor Water Treatment Technologies Ltd. (Calgary, Alberta, Canada). Filters contained 5 cm of underdrain gravel, 5 cm of medium-sized support gravel, and 40 cm of sand, the effective size (d10) of which was 0.19–0.22 mm. All filter media were crushed granite gravel available locally. The gravel was sieved according to standard international procedures for the BSF. The media were loaded into the filter in a manner to prevent formation of air pockets. The initial flow rate following the first 20-L charge ranged from 0.8–1.1 L/min. Flow rate was measured daily just after the introduction of a charge.

Some experiments were also conducted with a concrete rather than plastic BSF. These were constructed using a steel mold donated by Samaritan's Purse (Boone, NC). Media was added in the same fashion as for the plastic filters.

Design of microbial challenge studies

Four filtration experiments were conducted in which the daily charge was either 20- or 40 L. Results of four of these experiments are reported herein for which the filter feed conditions (type of filter, total length of filter operation, daily charge volume and feed water) are listed in Table 1.2.

Feed water comprised surface water from one of three local water supply reservoirs (Cane Creek Reservoir in Chapel Hill, N.C., University Lake in Chapel Hill, N.C., or Lake Michie in Durham, N.C.) to which was added up to 4% by volume of pasteurized primary effluent from a local wastewater treatment plant (OWASA, Chapel Hill, N.C.). The purposes of this amendment were to increase the supply of organic matter for development of a biofilm layer and to reproduce the presence of fecal contamination that may be more typical of the feed water in a developing country situation.

On each day of operation, the local surface water supply, which had been allowed to reach room temperature (20°C) was amended with pasteurized sewage and an aliquot of stock solutions of the challenge microorganisms as listed in Tables 1.2 and 1.3.

Table 1.2 Characteristics of longitudinal filter challenge experiments.

Experiment number	BSF type	Length (days)	Daily charge (liters)	Source water*	% sewage pasteurized
2	Plastic	44	40	CC, UL	0%
3	Plastic	54	40	CC	4%
4	Plastic	50	20	LM	1%
5	Concrete	43	20	CC, UL	1%

*CC = Cane Creek Reservoir (Orange County, NC, USA); UL = University Lake (Orange County, NC, USA); LM = Lake Michey (Durham, NC, USA)

Table 1.3 Target concentrations of microorganisms that were spiked into feed water.

Experiment Number	E. coli B cfu/mL	MS2 pfu/mL	PRD-1 pfu/mL	echovirus 12 pfu/mL
2	200	100	100	–
3	200	1000	1000	600
4	400	–	–	1200
5	800	100	–	1000

E. coli, MS2, PRD-1 and Echovirus type 12

A pure culture of *E. coli* strain B (ATCC No. 11303) was grown to log phase in shaker culture flasks of tryptic soy broth at 36°C, was cooled to approximately 4°C, and stored for up to 7 days at 4°C and maintained stable concentrations of viable *E. coli*. Cultures were prepared weekly as needed during the four dosing experiments. The culture was serially diluted into lake water immediately prior to seeding and this stock was dosed into feed water to achieve the desired *E. coli* concentration for each daily charge to the filter.

Pure stocks of bacteriophages MS2 and PRD-1 were grown up in the *E. coli* strain F-amp and *E. coli* strain CN13, respectively, by a modification of the double agar layer procedure EPA Method 1602 (EPA, 2001); these were stored at −80°C. Aliquots of each stock were thawed each week, serially diluted into phosphate buffered saline, and stored at 4°C for up to 7 days. Aliquots of this dilution were then dosed into feed water to achieve desired concentration for each daily charge.

A pure stock of echovirus 12 was propagated in monolayers of Frhk-4 cells with maintenance medium at 37°C. The stock was freeze-thawed and extracted. Extracted stock was stored at −80°C until needed. Aliquots of enumerated stocked were thawed weekly, serially diluted in phosphate buffered saline, stored at 4°C and added into feed water to achieve the desired echovirus 12 concentration for each daily charge.

On the day before each microbial assay, a control sample of the spiked charge was stored at room temperature to measure the die-off of microbes with time, independent of the activity of the filter.

Water analysis methods

The assay frequency was approximately once per week while the filters received a charge of feed water with the challenge microorganisms each day. Three types of samples were collected for assay: (1) samples of feed water from the previous and current charge; (2) grab samples of the filtered water taken throughout a daily filtration cycle; (3) a composite sample of the filtered water to represent the daily average concentration of microbes.

E. coli concentrations in water were quantified via membrane filtration on MI agar BBL™ (Becton-Dickinson, Franklin Lakes, New Jersey) using EPA Method 1604 (EPA, 2002). MS2 and PRD-1 concentrations were assayed using the single agar layer method (EPA Method 1602, EPA, 2001). Echovirus 12 samples were inoculated onto confluent monolayer of Frhk-4 grown in 60 mm plastic dishes (Manufacturer, City, State) using the

plaque forming assay. Turbidity and pH were measured using a turbidimeter (Model 2100N, Hach, Loveland, CO.) and pH meter (Model 215, Denver Instruments, Denver, CO).

Log_{10} removal of microorganisms was calculated by subtracting the log_{10} filtered water concentration from the feed water concentration. The log_{10} removals from each assay during a portion of a filter run were averaged and converted to percent removal which represents the geometric mean removal for each time period.

The residence time distribution (RTD) of water within the BSF was measured by a step input tracer test. The pores of a clean, unripened plastic BSF (BioSand Water Filter[TM], Davnor, Inc., Calgary, Alberta, Canada), were filled with deionized water (DI) at the start of the tracer test. The tracer test began by rapidly replacing the DI water above the filter with a 200 mg/L of NaCl. The head above the filter was maintained by two peristaltic pumps (Cole Parmer Cat. No. 7553-0 and 7545-0) introduced at a constant rate and conductivity of the filtered water was measured. The NaCl concentration was measured by conductivity (Fisherbrand Traceable[TM] Conductivity, Resistivity, and TDS Meter (Cat. No. 09-326-2). When conductivity in the filtered water reached the feed water value, the NaCl solution above the filter was removed and replaced by DI water. This provided another tracer test in which the subsequent decrease of conductivity in the filtered water was measured with time. The effect of head above the filter on RTD was determined by repeating the NaCl tracer tests at three head conditions: 5 cm (± 1 cm); 13 cm (± 1 cm); and head allowed to decrease with time from 17.3 to 2.0 cm.

Results and discussion

The results of the step input tracer test are presented in Figure 1.2. The rapid rise of conductivity to the feed value and the subsequent rapid decline of conductivity to the baseline value are indicative of plug flow. The head condition did not appear to affect the
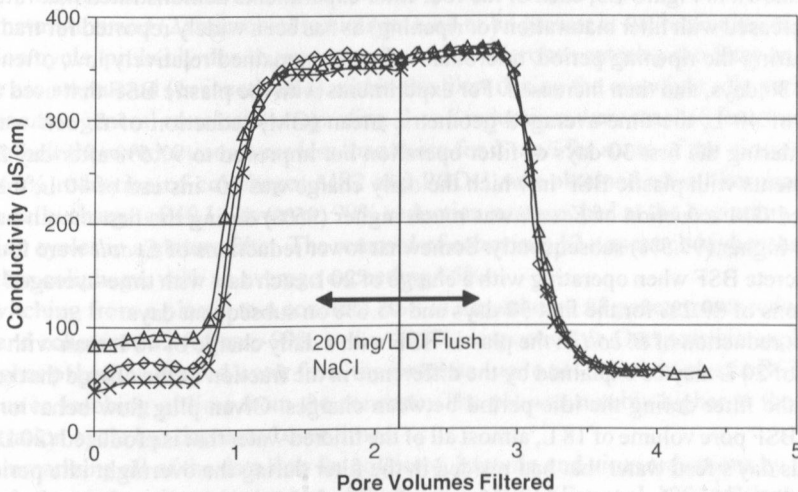

Figure 1.2 Results of three step-input tracer tests conducted wih the plastic BSF.
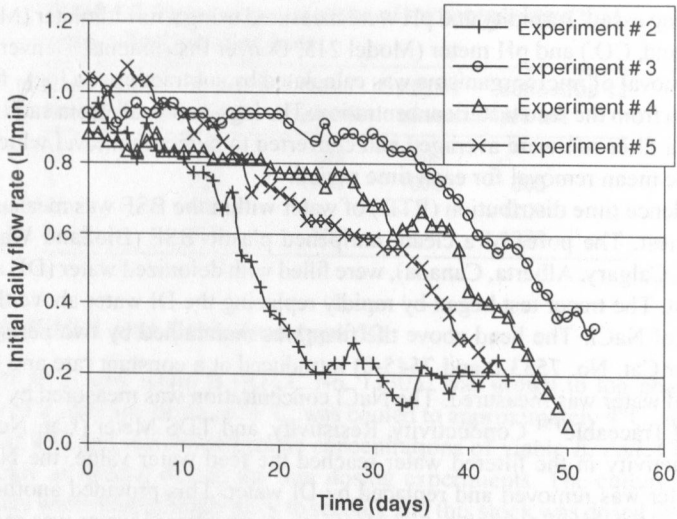
Figure 1.3 Daily flowrate after a 20 L charge for four filter experiments. Expts #2-4 conducted with plastic BSFs; Expt #5 with a concrete BSF.

result. The volume of water passed through the filter before conductivity rises to the feed value is also a measure of pore volume.

The media pore volume was determined empirically during the loading of three plastic filters and was found to be 18.3 ($\pm$0.1) L and 13.3 ($\pm$0.1) L for concrete BSFs. From the total volume of crushed granite gravel media in the filter, the porosity is 47%; this is somewhat high for filter media but not atypical of angular sands.

As shown in Figure 1.3, each of the four filter experiments demonstrated that filter flow rate decreased with filter maturation (or ripening) as has been widely reported for traditional SSF. During the ripening period, microbial reduction remained relatively low, often for as long as 30 days, and then increased. For experiments with the plastic BSF that used a daily charge of 40 L, the time-averaged geometric mean (GM) reduction of *E. coli* was only 73.6% during the first 30 days of filter operation but improved to 97.5% after day 31. For experiments with plastic BSF in which the daily charge was 20- instead of 40 L, the time-averaged GM reduction of *E. coli* was much higher (95%) during the first month but only slightly higher (99.5%) subsequently. Somewhat lower reductions of *E. coli* were found for the concrete BSF when operating with a charge of 20 L each day, with time-averaged *E. coli* reductions of 89.2% for the first 30 days and 95.6% on subsequent days.

Less reduction of *E. coli* in the plastic BSF with a daily charge of 40 L than with a daily charge of 20 L may be explained by the difference in the fraction of the charge that remains within the filter during the idle period between charges. Given plug flow behavior and a plastic BSF pore volume of 18 L, almost all of the filtered water that is produced (20 L) is the previous day's feed water that had resided in the filter during the overnight idle period. By contrast, the filtered water produced from a charge of 40 L is only about 50% composed of water (18 L) from the idle period. Therefore, a composite measurement of *E. coli* reduction
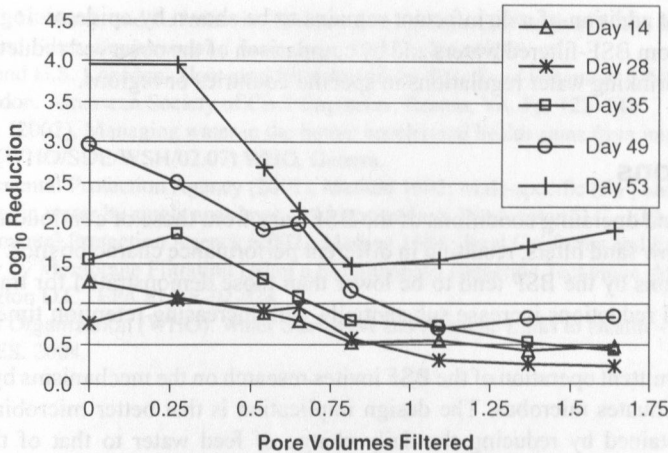
Figure 1.4 Run #3 *E. coli* reductions with pore volume. Results from Days 7 and 21 excluded for clarity (overlay Days 14 and 28).

from a 40 L charge could be less than from a 20 L charge because a smaller fraction of the filtered water had resided in the filter for the idle period. The reduction in *E. coli* is greater in water that remains overnight in an idle filter overnight than in water that passes through the filter bed without overnight idle, as indicated by the results described below.

The importance of idle time on *E. coli* reduction was explored further by measurements of *E. coli* concentrations in grab samples of filtered water taken at increments of time that correspond to cumulative pore volumes displaced during the days operation. The results for a series of 40 L charges (Experiment #3) are shown in Figure 1.4. These data indicate that: (1) microbial reductions improve with repeated daily charges of feed water due to filter maturation and (2) microbial reductions tend to be greater at the beginning each daily filtration cycle, probably due to processes by which microbes entering the filter on the day before are attenuated (or inactivated) within the filter during the overnight idle period.

The same general conclusions regarding *E. coli* reductions were reached for virus reductions, albeit these reductions were less than those for *E. coli* for some of the viruses tested. Only 69% reduction of coliphages MS2 and PRD-1 was obtained after filter maturation with a daily charge of 40 L; however, 90% reduction was reached at the beginning of daily filtration cycles in a mature filter. The removal of echovirus 12 was much higher than those for either coliphage, with an average exceeding 95%.

Switching from a plastic to a concrete BSF in Experiment #5 gave greater reduction of MS2 and echovirus 12 (often >99% and >99.9%, respectively). One possible explanation is a higher pH of the filtered water from the concrete (up to pH 9.3) than plastic BSF (pH < 8.2) due to leaching of lime from the concrete. The pH was notably higher at the start of the filtration cycle but decreased over time.

Summarizing all of the data thus far collected, bacteria and virus reductions by the BSF tend to be lower than those demonstrated for traditional SSF (Fox et al, 1994). Whether these microbial reductions are considered sufficient to provide microbiologically safe drinking

water without addition of a disinfectant remains to be shown by epidemiological study of heath risks from BSF-filtered waters and by comparison of the observed reductions to those required by drinking water regulations in specific countries or regions.

Conclusions

The design and operating conditions of the BSF vary from those of continuously operated, traditional slow sand filters, resulting in different performance characteristics. Bacteria and virus reductions by the BSF tend to be lower than those demonstrated for traditional SSF but microbial reductions increase substantially with increasing retention time in a mature filter.

The intermittent operation of the BSF invites research on the mechanisms by which filter idle time attenuates microbes. The design implication is that better microbial reductions would be obtained by reducing the daily charge of feed water to that of the filter bed pore volume and/or providing a longer interval between introduction of each charge. The effects of filter maturation and the volume, frequency and duration of each water charge on microbial reductions need systematic study. With more detailed engineering analysis, operational practices that yield optimum performance and are acceptable to the user can be put forward. Further research is also needed to explain differences in extent of removals for different microbes, particularly for viruses.

Finally, the research question of most practical importance is whether microbial reductions observed in this study are typical of BSFs in household use globally. The ultimate test is whether microbial reductions achieved by the BSF correlate with reductions in household waterborne illnesses, such as diarrhea.

Acknowledgments

References

Buzunis, B.J. (1995) Intermittently Operated Slow Sand Filtration: A New Water Treatment Process, Master's Thesis, University of Calgary, Department of Civil Engineering. Calgary, Alberta.

Fox, K.R., Graham, N.J.D., and Collins, M.R. (1994), Slow Sand Filtration Today: An Introductory Review. In Slow Sand Filtration. Edited by M.R. Collins and N.J.D Graham. American Water Works Association. Denver, CO. Pp. 1–8.

Kaiser, N., Liang, K, Maertens, M. and Snyder, R. Biosand Household Water Filter Evaluation 2001. (2002) Samaritan's Purse Canada. Calgary, AB.

Murcott, S. Nepal Water Project 2001–2002. (2002) Massachusetts Institute of Technology, Department of Civil Engineering. Cambridge, MA (2002).

Palmateer, G., D. Manz, and A. Jurkovic. Toxicant and Parasite Challenge of Manz Intermittent
Slow Sand Filter. *Environmental Toxicology*. **14**:217–255 (1999).

Pyper, G.R. and G.S. Logsdon. Slow sand filter design. In *Slow Sand Filtration*. Edited by
G. Logsdon. American Society of Civil Engineers. Reston, VA. Pp. 122–148.

Sobsey, M.D. (2002), Managing water in the home: accelerated health gains from improved water
supply, (WHO/SDE/WSH/02.07) WHO, Geneva.

U.S. Environmental Protection Agency (2001), Method 1602: Male-specific (F+) and somatic
coliphage in water by single agar layer (SAL) procedure, Washington D.C., EPA 821-R-01-029.

U.S. Environmental Protection Agency (2002), Method 1604: Total Coliforms and Escherichia coli
in Water by Membrane Filtration Using a Simultaneous Detection Technique (MI Medium),
Washington D.C., EPA 821-R-02-024.

World Health Organization (WHO). Water Sanitation and Hygiene Links to Health – FACTS AND
FIGURES. 2004.