Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: Experimental investigation and modeling

Marion W. Jenkins[a]*, Sangam K. Tiwari[b], and Jeannie Darby[a]

[a] Department of Civil & Environmental Engineering
University of California, Davis
One Shields Ave.
Davis, CA 95616
USA

[b] Trussell Technologies, Inc.
232 North Lake Avenue, Suite 300
Pasadena, CA 91101
USA

*Corresponding Author.
Tel: 1-530-754-6427; Fax: 1-530-752-7872
Email: mwjenkins@ucdavis.edu

Keywords:

point-of-use; drinking water treatment; fecal coliform bacteria; MS2 bacteriophage; biosand filter; linear mixed models; factorial design experiment; residence time; influent turbidity

Highlights:

- 2-factor 3-block experiment on sand size, head, and operation effects, interactions
- Removal of bacteria, virus and turbidity, and measurement of effluent turbidity
- 18 filters operated 10 weeks with conditions representative of developing country
- All outcomes improved by fine sand, long residence time (pause) operation
- Negative effect of influent turbidity on viral removal

Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: Experimental investigation and modeling

M.W. Jenkins, S. K. Tiwari, and J. Darby

Abstract:

A two-factor three-block experimental design was developed to permit rigorous evaluation and modeling of the main effects and interactions of sand size (d_{10} of 0.17 and 0.52 mm) and hydraulic head (10, 20, and 30 cm) on removal of fecal coliform (FC) bacteria, MS2 bacteriophage virus, and turbidity, under two batch operating modes ('long' and 'short') in intermittent slow sand filters (ISSF). Long operation involved an overnight pause time between feeding of two successive 20 L batches (16 hr average batch residence time (RT)). Short operation involved no pause between two 20 L batch feeds (5 hr average batch RT). Conditions tested were representative of those encountered in developing country field settings. Over a ten week period, the 18 experimental filters were fed river water augmented with wastewater (influent turbidity of 5.4 to 58.6 NTU) and maintained with the wet harrowing method. Linear mixed modeling allowed systematic estimates of the independent marginal effects of each independent variable on each performance outcome of interest while controlling for the effects of variations in a batch's actual residence time, days since maintenance, and influent turbidity. This is the first study in which simultaneous measurement of bacteria, viruses and turbidity removal at the batch level over an extended duration has been undertaken with a large number of replicate units to permit rigorous modeling of ISSF performance variability within and across a range of likely filter design configurations and operating conditions.

On average, the experimental filters removed 1.40 log fecal coliform CFU (SD 0.40 log, N=249), 0.54 log MS2 PFU (SD 0.42 log, N=245) and 89.0 percent turbidity (SD 6.9 percent, N=263). Effluent turbidity averaged 1.24 NTU (SD 0.53 NTU, N=263) and always remained below 3 NTU. Under the best performing design configuration and operating mode (fine sand, 10 cm head, long operation, initial HLR of 0.01 to 0.03 m/hr), mean 1.82 log removal of bacteria (98.5%) and mean 0.94 log removal of MS2 viruses (88.5%) was achieved.

Results point to new recommendations regarding filter design, manufacture, and operation for implementing ISSFs in local settings in developing countries. Sand size emerged as a critical design factor on performance. A single layer of river sand used in this investigation demonstrated removals comparable to those reported for 2 layers of crushed sand. Pause time and increased residence time each emerged as highly beneficial for improving removal performance on all four outcomes. A relatively large and significant negative effect of influent turbidity on MS2 viral removal in the ISSF was measured in parallel with a much smaller weaker positive effect of influent turbidity on FC bacterial removal. Disturbance of the schmutzdecke by wet harrowing showed no effect on virus removal and a modest reductive effect on the bacterial and turbidity removal as measured 7 days or more after the disturbance. For existing coarse sand ISSFs, this research indicates that a reduction in batch feed volume, effectively reducing the operating head and increasing the pore:batch volume ratio, could improve their removal performance by increasing batch residence time.

1.0 Introduction

Access to improved drinking water is unavailable to an estimated 884 million people in the world, most of who live in rural, dispersed, and often remote communities in developing countries (WHO/UNICEF, 2010). Diarrhea and other water-borne diseases from exposure to microbial pathogens in unsafe water constitute a major threat to health in these settings. The World Health Organization recommends point-of-use household water treatment (POU) as an intervention to address the need, drawing on appropriate low-cost technologies (Sobsey, 2002; WHO, 2007).

A recent assessment of POU options in developing countries identified intermittently operated slow sand filtration (ISSF), commonly referred to as the BioSand filter (BSF), among the most promising (Sobsey et al., 2008). The BSF was adapted for household use from traditional slow sand filtration (SSF) and is designed to treat 20 to 60 L/day in a batch-like gravity flow operating mode (Buzunis, 1995; Manz, 2004) under close to plug flow hydraulics (Elliott et al., 2008). ISSF containers have typically been designed to accept about 20 L at a time at a maximum head of 17 to 29 cm, which continuously declines until filtration is complete. Ideally, the batch remains within the filter until the next batch is added, however, this retention depends greatly on a filter design that ensures at least a 1:1 volume ratio of sand pore space to batch feed and efficient plug flow hydraulics. Assuming a batch mostly remains within the filter until the next feed, the time from the start of one 20 L batch feed to the start of the next batch feed is defined in this study as the batch residence time.

In limited controlled laboratory testing of the original Davnor BioSand Water Filter^{TM} (D-BSF), the following improvements in the microbial quality of water have been reported: bacterial removal for fecal coliform or E. coli ranging from 63 % up to 99% (2 $\log_{10}$) with averages of 94% and 96% (Buzunis, 1995; Stauber et al., 2006); viral removal ranging from of 0 to 0.75 $\log_{10}$ measured using MS2 and PRD-1 bacteriophage surrogates, and 1.14 $\log_{10}$ of echovirus 12 (Elliot et al., 2008); protozoan removals of greater than 5 $\log_{10}$ for Giardia lamblia cysts (6-16 µm diameter) and 99.98 % for Cryptosporidium oocysts (4-7 µm diameter) (Palmateer et al., 1999).

The BSF has several advantages as a POU technology in low income developing country rural settings where improved water supplies are often difficult and costly to develop, operate or maintain. Using a concrete or plastic container with a typical sand column of 45 to 50 cm, the simple yet robust design of BSF units allows construction with local materials and skills found anywhere in the world, making it affordable (US $20-30/unit), accessible and durable (Duke et al., 2006; Fewster et al., 2004). There are no recurring costs and operation and maintenance requirements can be performed by the household. Relative to other options, for example, solar and chemical disinfection, ceramic filtration, and flocculants, the BSF's high flow rate and ability to tolerate turbid surface water provide added advantages. An estimated 140,000 locally constructed BSF units were in operation in over 24 countries by 2007, largely through the efforts of decentralized small-scale development organizations (Clasen, 2009).

Field designs and local construction methods in developing countries often result in BSFs that differ from the original D-BSF design specifications. A single layer of local river sand of variable size (characterized by effective size, d_{10}, and uniformity coefficient, UC) is often used as the filtration media instead of the D-BSF's two different size layers of crushed sand (Manz, 2004). ISSF containers used in field projects are generally made of concrete, and can vary in their maximum hydraulic head, sand column depth, and headspace volume to a greater or lesser degree from the original plastic D-BSF container specifications.

Variations and less than ideal performance in field testing have been reported for BSFs, ranging from negative up to 100 percent bacterial removal (Duke et al., 2006; Earwaker, 2006; Fewster et al. 2004; Kaiser et al. 2002; Stauber et al., 2006; Wiesent-Brandsma et al. 2004) and 39 to 91 percent for turbidity reductions (Duke et al., 2006; Earwaker, 2006; Jenkins et al., 2009; Stauber et al., 2006; Wiesent-Brandsma et al. 2004). Difficult logistics in developing countries necessitate collecting BSF effluent and influent grab samples for field evaluations simultaneously during a single house visit, limiting comparability and usefulness of field-reported removal efficiencies. Influent water quality in settings where BSFs are typically installed can vary from batch to batch as households switch sources and source water quality varies naturally from day to day. A switch, for example, from a turbid surface source to a less turbid rain feed can lead to erroneously low or even negative removal measurements based on simultaneous influent-effluent (flush-pore) water sampling (Earwaker, 2006).

Systematic scientific investigation of the effects of variations in BSF design, construction and operation on performance across multiple outcomes of concern, including bacterial, viral, and turbidity removal, is absent in the literature. Several recent evaluations have pointed to the absence of and the need for rigorous investigations to support optimization of ISSF design (Elliot et al., 2008; Kubare and Haarhoff, 2010). Operating conditions are another likely important influence on performance. Baumgartner et al. (2007) demonstrated that residence time and dosing volume significantly affected total coliform removal in the D-BSF. Elliott et al. (2008) observed that feed volumes greater than 50 percent of the filter pore volume for the D-BSF tended to show decreased incremental removal efficiencies for E. coli and bacteriophages.

Application of slow sand filters for household use has spread rapidly across the globe in recent years, creating a need for sound scientific understanding of mechanisms and factors controlling ISSF microbial removal. This includes understanding of how performance is affected by variations in design, construction materials, sand characteristics, and household operation and maintenance practices. Such knowledge would provide a rational basis to inform development of design standards, quality control measures, and guidelines for local construction and operation to maximize ISSF performance in a local setting.

In this paper we report on experimental research undertaken to systematically investigate and measure the effects of ISSF design and operating factors on its ability to simultaneously remove bacteria, viruses and turbidity. A factorial design experiment was developed to permit rigorous evaluation and modeling of the main effects and interactions of sand size and hydraulic head on ISSF removal of fecal coliform bacteria, MS2 bacteriophage virus, and turbidity, under two batch operating modes.

2.0 Materials and Methods

2.1Filter Design

A diagram of the experimental ISSF filter is shown in Fig 1. The container was constructed from 12-inch polyvinyl chloride (PVC) irrigation pipe (30.5 cm diameter). Each filter consisted of a 5 cm rock layer at the base, followed by 5 cm of gravel, and 60 cm of a single layer of one of the two experimental sands. A single sand layer is commonly used in developing countries to save on costs. Two and a half cm of water were maintained above the sand at all times, ensuring saturated conditions. This configuration was selected to contain approximately 20 L of water within the sand column pore space and in the headspace at 30 cm above the static water level. Fig 1 shows a simple constant head controller (CHC) feed bottle above the filter constructed from a five gallon carboy. The CHC was required for filter configurations with less than 30 cm head to passively feed a 20 L batch without exceeding the filter's design head.

2.2 Factorial Experimental Design

A two-factor three-block experimental design was selected (Montgomery, 2005). Each block consisted of the same six filter configurations of interest (Table 1). The fine sand size (d_{10} of 0.17 mm) was selected to represent the recommended lower range for typical slow sand filters

(Huisman and Wood, 1974). The coarse sand size (d_{10} of 0.52 mm) was selected to represent a worst-case scenario for ISSF in places that have only coarse sand readily available. Naturally occurring river sand was used, as it is the most commonly available and affordable sand in developing community settings. The coarse and fine experimental sands were derived from ASTM concrete and utility river sand, respectively (Granite Construction Company, Sacramento, CA). A minimum hydraulic head of 10 cm was selected so that, when coupled with the fine sand, it produced a hydraulic loading rate (HLR) sufficient for minimum household daily drinking water needs. The maximum head of 30 cm represents one commonly used BSF container design (www.biosandfilter.org).

BSF households typically operate their filter under a range of modes, treating from one to three 20 L batches per day, resulting in wide variation in batch residence time (RT). In this research, a short and a long batch RT operation were examined. The short RT operating mode represents the shortest possible batch residence time (experimental average 5.1 hours; variable with filter configuration) and is approximately equal to the start-to-start time of two successive 20 L batches fed to the filter with little or no pause between feeds. The long RT operating mode represents the longest possible residence time (experimental average 15.6 hours; less than theoretical 24 hours due to varying daily feed times) that would result from one 20 L batch per day operation.

2.3 Filter Operation

Each filter was fed a standard batch of 20 L of the influent water mixture per day for 10 weeks, except during weekly testing. Testing involved feeding three 20 L test batches over two days, as explained with this example. Batch I was started at the same time (e.g., 3 pm) in all six filters within a block on test day 1. Infiltration of batch I in a block of filters finished at varying times on day 1. The next day (test day 2), batch II was started in the same six filters at the same time (e.g., noon). Batch II finished infiltrating in filter A of the block at 4 pm. Upon complete infiltration of batch II in filter A (equal to complete exit of batch I from filter A), batch III was started in filter A. Infiltration of batch III in filter A finished at 8 pm, equal to the time batch II fully exited filter A and could be tested. Batch I is the long RT batch which experiences an overnight pause time in the filter pore space. Batch II is the short RT batch which is flushed out of the filter as soon as it has finished infiltrating. In the example, the long batch I and short batch II RTs for filter A are 21 hours (difference of start times of batch II and I) and 4 hours (difference in start times of batch III and II), respectively.

At a 30 cm nominal head above the static water level, the headspace of the experimental filter held approximately 20 L, thus a 20 L batch was poured directly onto the diffuser plate at the start of each batch feed for the 30 cm head filter configurations. For the 10 and 20 cm nominal head configurations, the CHC was filled with 20 L and inverted above the filter at the start of a batch with its narrow mouth opening set at the prescribed height above the static water level so as to maintain the supernatant head at the filter's nominal head until the CHC was empty. After controlled release of all 20 L of water from the CHC into the headspace at the nominal head, the head of the remaining portion of the batch declined steadily until filtration was complete.

Official testing began in week 3, allowing an initial 2-week maturation period for the biological zone to establish within the sand. The filters were maintained by the wet harrowing method, a gentle rubbing of the top two centimeters of sand followed by decanting of the resulting suspension of clogging material. After maintenance, the filter was allowed to mature for one week before resumption of sampling measurements. Filters in the first block were maintained when their flow rate became too slow to filter a 20 L batch in 24 hours, whereas, filters in blocks 2 and 3 were cleaned when their flow rates reached 50 percent of their initial value, resulting in more frequent filter maintenance.

2.4 Influent Water

The influent water quality was designed to roughly simulate a typical surface water source used in a developing country. Influent water fed to the filters throughout the study was 95 percent untreated Sacramento River water augmented with 5 percent raw wastewater from the University of California, Davis Wastewater Treatment Plant (UCD WWTP). The wastewater had an average BOD of 200 mg/L, fecal coliform concentration of 2 million CFU/100 mL, and ammonia-N of 10 mg/L. The mixture was spiked every day with MS2 coliphage (ATCC 15597-B1) due to a low background concentration. The MS2 coliphage was prepared using Standard Methods 9224 C (APHA, 2005). Raw river water was collected weekly throughout the study. Raw sewage was collected every other day, except for sampling days when fresh raw sewage was collected and used.

Maximum, minimum, and mean values of the influent water characteristics within each block and overall are shown in Table 2. Influent turbidities and MS2 coliphage concentrations were significantly higher in block 1 than in blocks 2 and 3. Sacramento River water at the West Sacramento intake was considerably more turbid during the spring run-off months from April to June, when block 1 was conducted, than in the dry season summer months of July to September, when blocks 2 and 3 were conducted. Unobserved seasonal variation in chemical, physical and microbiological characteristics of Sacramento River water between block 1 and blocks 2/3 are also possible.

2.5 Sampling and Measurements

Following the initial 2 week startup, experimental measurements were conducted weekly on each filter for a long and short residence time test batch as described above. Influent and effluent water samples for each long and short test batch were collected. Effluent samples were collected from the 20 L composite effluent volume upon exit of the test batch. Influent samples were collected from the 120 L influent batch prepared separately for each test batch feed for each block of 6 filter units.

Samples were analyzed for fecal coliform bacteria, MS2 coliphage virus, and turbidity. Fecal coliform was enumerated using Standard Method 9222D with M-FC medium as specified therein (21st edition, APHA, 2005). MS2 coliphage was enumerated as per Standard Method 9224D (APHA, 2005) with E. coli (ATCC 15597) as the host and no antibiotics. Turbidity was measured using a turbidimeter (Model 2100AN, Hach Company, Loveland, CO). The hydraulic loading rate (HLR) was determined from the time to collect one liter of filtered water at the beginning of each batch feed.

On each test day and for each test batch and filter, several covariates of interest were measured and recorded. These included influent water and room temperature, date and time of start of each influent test batch feed and time of exit of test batch effluent, and date of each filter maintenance event.

2.6 Analysis and Modeling

The research experiment was designed to identify statistically significant independent effects on ISSF batch removal performance caused by differences in effective sand size, nominal head, and residence time operation as well as the interactions among them. The significance and size of the main factor effects was estimated using linear mixed modeling (LMM), controlling for repeated sampling of a filter unit, random block differences, and covariate effects on performance variability (Faraway, 2006; Verbeke, 2000). Accounting for repeated filter measurement in LMM analysis controls for possible correlation (statistical non-independence) of measurements from a given filter unit. Setting block as a random effect controls for the possibility of unobserved systematic differences in filter set-up and operating characteristics between blocks, such as sand batch differences, seasonal variation of influent water characteristics, and maintenance schedules (Verbeke, 2000). Covariates of interest included in the analysis were: a) deviation of the measured residence time of a long or short RT sample batch from the long or short RT operation group average, b) days since filter maintenance, and c) influent turbidity, with the latter included only in fecal coliform and MS2 removal performance models. Temperature was unnecessary to include as it remained uniform throughout the controlled experiment. Test batch measurements within seven days of a maintenance event were excluded from performance results and analyses. Results were analyzed using SPSS statistical software (SPSS Inc., Chicago, Illinois).

Four dependent variable outcomes were modeled: the measured $\log_{10}$ fecal coliform removal, $\log_{10}$ MS2 coliphage removal, percent turbidity reduction, and effluent turbidity in the measured long and short 20 L test batches, across the 18 experimental filter units. First, 2-factor LMM analysis was undertaken to examine the effects of grain size (2 levels) and nominal head (3 levels) separately for short and long RT batch operation. Then, batch operation mode (2 levels) was added as a third factor in a three-factor LMM model of all long and short batch measurements combined, comprising from 245 to 263 performance data points for each outcome of interest. Missing covariate values for batch residence time deviation and days since maintenance were replaced by group averages. Only statistically significant interaction terms, at the 0.10 level, were retained in the final model. The main factor and covariate effects and their marginal means from LMM modeling indicate level of significance of each factor or covariate on filter performance and the mean effect size of a change in a specified factor level, or a unit increase in a covariate, adjusted for repeated filter sampling and random block effects. Pairwise comparisons of mean performance effect size of each nominal head level were made using the Tukey method, which adjusts significance for multiple comparisons. Model appropriateness was assessed using the Levene-style test for equal variance of the residuals and graphical analysis of residuals. Normality was assessed using normal probability plots and the Shapiro-Wilks test. No violations of the LMM assumptions were found.

3.0 Results

3.1 Filter characteristics and experimental conditions

Average porosity of the sand column for the 18 filter units was 0.448 ± 0.022. The uniformity coefficient of the fine and coarse experimental sand was 2.4 and 2.1, respectively. The initial HLR of each unit varied from a low of 0.01 m/hr (fine sand, 10 cm head, Block 1) to a high of 0.41 m/hr (coarse sand, 30 cm head, Block 3) (Table 1). Average influent water and room temperature across all blocks was 24.2 and 24.3 deg C, respectively. Influent water pH ranged between 6.7 and 7. Influent water MS2 coliphage and turbidity characteristics during block 1 were significantly different from blocks 2 and 3 (Table 2). Influent turbidity varied from a low of 5.36 NTU to a high of 58.57 NTU.

Table 3 presents the range of covariate values within each block and overall during the experiment. On average, both the long and short batch residence times were longer in block 1 than in blocks 2 or 3. The two-tailed t-test for the long batch residence time difference is significant (at the 0.05 level) between blocks 1 and 2 (p=0.020), but not between blocks 1 and 3 (p=0.31) or blocks 2 and 3 (p=0.154). The short batch residence time difference between blocks 1 and 2 (p=0.003) and 1 and 3 (p=0.003) is also significant, but not between blocks 2 and 3 (p=0.72). A less frequent maintenance schedule applied during block 1 is the most apparent reason for the higher block 1 long and short batch residence times but could also be the result of influent water quality differences or small unobserved differences in the sand characteristics or packing of block 1 compared to blocks 2 and 3. Days since last maintenance is lowest for block 2 and highest for block 3, although this difference is not significant (p=0.075; 2-tailed t-test). Inclusion of model covariates for the deviation of a batch's actual residence time from the long or short group average (across all blocks), for days since maintenance, and for influent turbidity where relevant, allow explicit examination of the independent effects of these operational differences on filter performance, separated from the main factor effects. In particular, controlling for residence time variation of a particular batch of water separates configuration-related variations in residence time under a given operation mode, for example those attributable to sand size or nominal head configuration differences, from the main effect of the pause between batch feeds that arises under long RT operating mode.

3.2 Overall performance

Filter performance averaged across the six different configurations is shown in Table 4 for each block and combined across all blocks. On average, the experimental filters removed 1.40 log fecal coliform CFU (SD 0.40 log, N=249), 0.54 log MS2 PFU (SD 0.42 log, N=245) and 89.0 percent turbidity (SD 6.9 percent, N=263). Effluent turbidity averaged 1.24 NTU (SD 0.53 NTU, N=263) and always remained below 3 NTU. Filter performance on all four outcomes was better under long than under short operation.

Fecal coliform removal was higher and MS2 removal was lower in block 1 compared to blocks 2 and 3, under both long and short operation. Turbidity removal was higher in block 1 compared to blocks 2 and 3 under long operation. Fecal coliform removal ranged from a high of 3.19 log (99.94%) (fine, 10 cm, block 1, week 3, long) to a low of 0.50 log (68.4%)(coarse, 30 cm, block 3, week 3, short). MS2 removal ranged from a high 1.55 log (97.2%) (fine, 30 cm, block 3, week 8, long) to a low of -0.32 log (109% increase)(coarse, 20 cm, block 3, week 8.2, long). Highest and lowest turbidity removals were 98.9 percent (coarse, 10 cm, block 1, week 7, long) and 62.8 percent (fine, 20 cm, block 3, week 3, short), respectively.

3.3 Modeling results

LMM multivariate modeling results for the 2-factor long batch operation model, the 2-factor short batch operation model, and the combined 3-factor model are shown in Tables 5 and 6. They provide systematic estimates of the independent marginal effect of a change in the sand grain size, hydraulic head, and batch operation (combined 3-factor model) on each performance outcome of interest: bacteria removal, viral removal, turbidity removal and effluent turbidity based on our selected indicators organisms and measures, while controlling for the effects of variations in observed operating characteristics of interest, namely, a batch's actual residence time, days since maintenance, and influent turbidity.

Table 5 presents the significance levels of the factors and covariates of each model for each outcome. Table 6 lists the marginal effect size of each factor and covariate or interaction term for effects with a significance level of $p<0.10$ in the models shown in Table 5.

3.3.1 Significant factors and covariates affecting filter performance

Under long batch operation, all five conditions: sand size, head, residence time, maintenance, and influent turbidity significantly ($p<0.05$) and independently affected filter performance for one or more of the four outcomes of concern (see Table 5: 2-factor long batch model, shaded cells). Residence time (deviation) was the most consistently and highly significant variable, followed by sand size. In addition to their independent main effects, sand size and residence time produced a significant interaction effect on bacterial removal under long operation (p=0.004). Influent turbidity, included in models of bacterial and viral removal, produced highly significant effects on viral removal, and weak effects on bacterial removal. Head was highly significant for bacterial removal, weakly significant for effluent turbidity, and insignificant for viral and turbidity removal under long operation.

The significant factors and covariates of short batch performance differed from those for long batch performance (see Table 5: 2-factor short batch model, shaded cells). Residence time significantly affected bacterial removal and turbidity performance but not viral removal under short batch operation. Sand size was significant for short batch bacterial and viral removal but not for either of the two turbidity performance outcomes. Head effects on short batch operation were less significant for bacterial removal and more significant for viral and turbidity removal, compared to long batch operation. Maintenance effects were similarly important for both turbidity performance outcomes and bacterial removal under short and long operation. Lastly, influent turbidity was highly significant for viral removal and also significant for bacterial removal. No significant interactions were observed under short operation among the variables.

The above patterns of factor and covariate significance are confirmed in the 3-factor model which examined the full data set and included batch (long versus short RT operation) as a third factor (Table 5). Batch operation and actual residence time both had highly significant independent effects on all four filter performance outcomes, and interacted to produce significant additional interaction effects on bacterial removal (p<0.001). Head changes were significant or near significant for all four outcomes, independent of batch or residence time. Sand size was significant or near significant for bacterial and viral removal, but not for turbidity performance (neither removal nor effluent). Sand size and batch interacted to produce nearly significant additional effects on viral removal ($p<0.099$). Maintenance significantly affected both turbidity performance outcomes independent of other conditions, while influent turbidity had a significant independent effect on both viral and bacterial removal in the combined model.

The following sections review the magnitude of the significant factor and covariate direct and interaction effects on ISSF performance shown in Table 6.

3.3.2 Bacterial removal

Fine sand (d_{10} =0.17) increased bacterial removal (as measured by fecal coliform) by 0.16 log under short operation and 0.30 log under long operation, compared to coarse sand (d_{10} =0.52). Reducing head under long operation removed an additional 0.17 log at 20 cm and 0.29 log at 10 cm. Irrespective of operating mode, fine sand increased removal on average by 0.18 log independent of other conditions, while head reductions of 10 cm and 20 cm increased removal on average by 0.10 log and 0.16 log, respectively. Switching from short to long RT batch operation increased bacterial removal by 0.29 log on average, irrespective of configuration or operating conditions. Increasing residence time further increased bacterial removal by an estimated 0.050 and 0.063 log per hour, under long and short operation, respectively. The benefit from another hour of residence time occurred irrespective of sand size under short operation but was largely limited to the fine sand configuration under long operation. Each additional NTU of influent turbidity increased bacterial removal by approximately 0.0035 log, irrespective of batch, configuration, or other conditions. Days since maintenance was positively associated with bacterial removal however the effect was not significant ($p=0.18$).

3.3.3 Viral removal

Operation mode alone, and through interaction with sand size, had the greatest impact on viral removal. A change from short to long RT operation increased viral removal by 0.36 log on average, irrespective of filter configuration. When changing to long operation in a fine sand filter, an additional 0.31 log was removed over and above the average change. An even larger add-on increase in removal of 0.41 log occurred when changing to long operation in a coarse sand filter, indicating a notably larger *marginal* gain in viral removal for long over short operation in coarse sand filters. Beyond operation mode and sand size-operation mode interaction effects, each additional hour of residence time further increased removal, independent of other conditions, by an average 0.012 log, with this effect more pronounced under long operation (0.025 log per hour). Reducing head or sand size each produced limited viral removal improvements, compared to operation mode. Head reduction from 30 to 10 cm produced a significant increase of 0.082 log, on average, in viral removal, independent of other conditions, with this association stronger under short RT operation. Fine sand produced an average increase of 0.053 log in viral removal over coarse sand, independent of other conditions, also more pronounced and larger for short RT operation. Viral removal improvements from head and sand size reductions, while positive, are considerably smaller than those achieved for bacterial removal.

Influent turbidity had a consistently strong negative effect on viral removal: each additional NTU decreased viral removal by an average 0.017 log, independent of other conditions. Influent turbidity had a slightly greater negative effect on viral removal under short RT operation (-0.019 log per NTU). The negative impact of influent turbidity on viral removal (-0.017 log/NTU) is nearly 5 times the magnitude of the positive impact observed for bacterial removal (+0.0035 log/NTU).

3.3.4 Turbidity performance

Longer contact time, reflected in batch operation mode and residence time, produced the only consistent improvements in turbidity performance across the models, for both removal and effluent quality. Changing from short to long RT operation increased turbidity removal by 3.85 percentage points and decreased effluent turbidity by 0.40 NTU, independent of filter configuration or other conditions. Each additional hour of residence time increased removal by 0.46 percentage points and decreased effluent turbidity by 0.026 NTU. The use of fine sand, under long RT operation only, caused a small detrimental impact on turbidity performance compared to the use of coarse sand, decreasing removal by 1.67 percentage points and increasing effluent turbidity by 0.21 NTU, on average. Reducing head from 30 cm to 10 cm, under short operation, produced a marginally significant ($p=0.105$) improvement in removal of 4.26 percentage points but this did not translate into a significant improvement in effluent turbidity. Impacts of sand size and head on turbidity removal and effluent performance were no longer significant when controlling for batch and residence time deviations in the combined all-batch model. Each additional day since the last maintenance resulted in 0.11 percentage points more removal of influent turbidity and a 0.005 NTU reduction in effluent turbidity, on average.

4.0 Discussion

4.1 General Overview

Relative to earlier work, several new and important aspects of ISSF performance are addressed in this study that allow for a more thorough evaluation and understanding of performance and removal mechanisms. This is the first study in which simultaneous measurement of bacteria, viruses and turbidity removal at the batch level over an extended duration has been undertaken with a large number of replicate units to permit rigorous modeling of ISSF performance variability within and across a range of likely BSF filter design configurations and operating conditions. Published laboratory evaluations of the BSF to date have involved testing of 1 or 2 filter units for limited durations and have not reported on maintenance or its effects. This study included 18 filter units operated daily and maintained and sampled over ten weeks. Over the course of filter testing, significant seasonal variation in natural surface water turbidity was encountered and routine wet harrowing of the filters was required to maintain filter operation, conditions typically representative of real-life field-scale operation. Simultaneous measurement of turbidity removal in this study has revealed interactions between turbidity and microbiological removal in the ISSF which have not been reported and which have important implications for applications that treat surface waters with varying or high turbidity.

The experimental filter in this study differs in several ways from the D-BSF filter design used to date in published controlled laboratory studies of the BSF. The D-BSF design calls for a 40 cm column of crushed sand, comprised of an upper layer of effective size and uniformity coefficient of 0.15 mm and 1, respectively, and a lower sand layer with effective size and uniformity coefficient of 0.35 mm and 1, respectively (Manz, 2004). This sand specification is often costly to obtain or produce locally in developing communities. In this study, a 60 cm column composed of a single layer of river sand manually processed to meet specified sand size and uniformity characteristics was used to better reflect typical community sand sources and processing capability in developing countries. The slightly deeper sand column was chosen to maintain a minimum 1:1 ratio of filter pore space to 20 L batch charge volume, and also differs from the D-BSF's reported pore space to charge volume ratio of 0.9:1 (Stauber et al., 2006).

Across the 18 filter units and 10-week test duration, including both long and short operation but excluding the first 2 weeks of start-up and first seven days after maintenance, on average the ISSF was capable of removing 96% of bacteria (1.4 log fecal coliform), 71% of viruses (0.54 log MS2), 89% of turbidity and produced effluent always below 3 NTU turbidity in each 20 L sampled batch of treated water (Table 4). Results reported from testing of the D-BSF (Buzunis, 1995; Elliot et al., 2008; Stauber et al., 2006) in which no maintenance was performed, fall within the range of our testing results, for the most part. In contrast to Elliot et al (2008), however, we found viral shedding (negative viral removal) to be a real concern with ISSF performance. More importantly, the modeling analysis sheds light on those design and operating conditions that are most responsible for improved ISSF performance, including uncontrollable operating conditions, at both filter and batch scale, and provides insight into mechanisms of removal that have the greatest effects on ISSF performance for each of the four outcomes measured.

This study confirms that removal of bacteria and viruses in ISSFs is significantly lower than in SSFs. Even under the best performing design configuration and operating mode in this study (fine sand, 10 cm head, long operation, initial HLR of 0.01 to 0.03 m/hr) which achieved mean 1.82 log removal of fecal coliform bacteria (98.5%) and mean 0.94 log removal of MS2 viruses (88.5%), these rates are 0.5 log to 1.0 log lower than typically obtained by SSF (Hijnen et al., 2004). Viral shedding, which we found to be a problem with the ISSF, has also been observed in SSF challenge testing (Anderson et al., 2009). Anderson et al. report MS2 removal from 0.2 to 2.2 log for a range of typical SSF design and operating conditions. Recent work indicates iron amendments that enhance viral adsorption offer a potential solution for increasing viral removal in the BSF (Bradley et al., 2011).

4.2 Contact time

Contact time appears to be one of the most critical factors for adequate removal of bacteria, turbidity and, particularly, viruses, in the ISSF. Both Table 4 and the LMM modeling results highlight and quantify the independent and significant effects of long RT compared to short RT operation for all outcomes studied, irrespective of design configuration or other condition. On average, long RT operation can be expected to increase removal of bacteria by 0.29 log, viruses by 0.67 to 0.77 log (depending on sand size), turbidity by 3.85 percentage points, and reduce effluent turbidity by 0.40 NTU, relative to short RT operation. Additional benefits, beyond the gain from long RT operation to all four outcomes, accrue for each additional hour of contact time within the sand column beyond the operating average (15.6 hours for long, 5.1 hours for short) within the range studied (up to 27 hours).

If we consider the BSF as a plug flow batch reactor, having a pause time between feeds (long RT operation) appears important. The biological and physio-chemical processes within the sand column need sufficient time to clear pore spaces and biofilm adsorption sites loaded with contaminants, before the next batch is added. Indeed, for ISSF viral removal the most important controllable parameter of those tested appears to be batch contact time within the sand column reactor which is consistent with adsorption and attachment being the dominant mechanisms for successful viral removal in SSF (Anderson et al., 2009). The role of contact time in viral removal was also found by Elliot et al. (2011).

4.3 Importance of design factors and design and operation interactions

The main mechanisms that are responsible for removal of bacteria, viruses and turbidity in SSF, namely mechanical straining, adsorption, attachment, and biological activity including predation, are also expected to operate in ISSF. In theory, smaller sand size slows down the rate of infiltration, reduces the size of pore space passages, and supports a larger biofilm surface area. Thus a smaller media would be expected to improve ISSF removal performance by increasing settling and straining, increasing contact (residence) time, and providing more attachment sites. Reduced ISSF nominal head, resulting in a lower hydraulic loading rate, reduces a batch's maximum and average infiltration rate which allows for greater head space settling, increases contact time, and reduces biofilm shear forces at the beginning of batch infiltration. This research helps quantify the extent to which these different potential benefits from reduced sand size and head, within feasible operating ranges for the ISSF, translate into significant improvements in removal performance. These potential improvements may merit changes in BSF design alone, or in conjunction with operating changes.

The modeling analysis indicates that using fine rather than coarse sand size (d_{10} 0.17 mm vs. d_{10} 0.52 mm) yields a significant and meaningful increase in ISSF removal of bacteria (0.16 – 0.30 log), independent of the residence time effect from the sand size change, with less consistent effects observed for viruses (0 to 0.10 log). The combination of fine sand with long RT operation can be expected to produce a mean increase in removal of 0.63 log bacteria and 0.41log viruses over mean levels achieved with the combination of coarse sand with short RT operation, irrespective of head or other conditions. Changing to a lower head, without changing the batch volume (i.e., keeping the pore:batch ratio constant at 1:1 in this case), provides relatively small mean improvements in treated water quality for bacteria and viruses. This suggests that the enhanced supernatant settling and reduced velocity shear effects of a lower head achieve relatively little on their own (i.e., independent of the increased residence time effects of reduced head which were controlled for separately in the LLM modeling). No benefit of sand size or head reduction on turbidity performance, separate from the increased residence time benefits, was observed.

4.4 Important and opposing effects of influent turbidity on viral and bacterial removal

This study uncovered an important and relatively large and significant negative effect of influent turbidity on viral removal in the ISSF, estimated as an average reduction in removal of 0.017 to 0.019 log for each additional NTU of influent turbidity. To our knowledge, this is the first time the relationship between influent turbidity and viral removal, whether for SSF or ISSF, has been systematically identified and measured. At the same time, we found an opposite positive effect, albeit much smaller, of influent turbidity on ISSF bacterial removal in which 1 NTU of influent turbidity enhanced bacterial removal by an estimated 0.0035 log, on average. These opposing effects are plausible if influent turbidity particles competed effectively with the MS2 coliphage for adsorption sites whereas those same particles provided additional sites for bacteria removal. Although surface charges were not measured in this research and virus adsorption in soil is a very complicated phenomenon, it is likely that MS2 coliphage had a strong net-negative charge at the near-neutral pH of the influent water, causing repulsion by the negatively charged sand (Schijven and Hassanizadeh, 2000). Moreover, the bacteria were more likely to be particle associated due to their origin in the combined river water/wastewater influent whereas the MS2 coliphage were cultured in the laboratory and thus not indigenous.

The observed negative effect of turbidity on viral removal is a concern for ISSF performance in developing countries where this technology is needed the most because many

BSF-target households tend to be more rural and depend on surface water sources that may experience high levels of seasonal or year round turbidity.

4.5 Limited effects of maintenance on performance

This is the first time maintenance effects on ISSF performance have been evaluated systematically. The maintenance technique used in the experiments was wet harrowing which disturbs no more than the top 2 cm of the sand column. Consistent with SSF performance measured by Hijnen et al. (2004), we found no effect from disturbance of the schmutzdecke by wet harrowing on virus removal and a modest reductive effect on bacterial and turbidity removal seven days or more after a maintenance event. Lack of a maintenance effect on viral removal is consistent with adsorption and attachment within the whole sand column being the main removal mechanism for viruses and contact time the most important parameter affecting viral performance. Viruses are too small to be caught by the schmutzdecke sand surface mat so its disturbance by wet harrowing would be expected to have little or no impact on the retention of viruses. However, its disturbance would be expected to impact retention of larger sized bacteria and turbidity particles at the sand surface. Indeed, despite restricting performance results and removal values in the analysis to 7 or more days since a maintenance event, and replacement of missing values for days-since-maintenance with its average value, we found a small negative effect of filter maintenance on bacteria and turbidity performance.

4.6 Other sources of variability in ISSF performance

Examination of the experimental data in Table 4 indicates significant variability in performance between blocks. Some of the block-level variation can be explained by observed differences in influent turbidity and maintenance practices as discussed above, however, there may be other important unobserved influent water quality physical and chemical characteristics, separately or in conjunction with turbidity, such as hardness, alkalinity or pH, that may account for block performance differences. Small unobserved differences in the characteristics of unprocessed river sand and the manual sand processing and packing of filters between block 1 and blocks 2 and 3, as suggested by the lower block 1 initial HLR values for fine sand may also have contributed to block-level variations in overall performance. These additional parameters that may affect filter performance variability should be fully considered and processes developed to address them within BSF implementation and construction projects, especially those involving on-going large-scale filter production and distribution activities.

4.7 Implications for developing country design, local manufacturing, and operation

Results of this research point to a number of recommendations for implementing BSFs in local settings in developing countries. A single layer of manually processed natural river sand, used in this experiment, appears to produce comparable levels of removal performance as the more expensive 2-layers of crushed manufactured sand recommended by the D-BSF design. If treated BSF water is to be consumed, fine sand (d_{10} in the 0.15 mm range) should be used instead of coarse sand (d_{10} in the 0.35-0.50 mm) to maximize bacterial and viral removal. Sand size has emerged as the most important design factor on performance in this study. Controlling sand size to achieve close to SSF fine sand characteristics (0.15 mm d_{10} and under 3 UC) and maintaining quality control of filter packing during installation to achieve the low hydraulic loading rates required for sufficient residence time may be the most important aspects of filter design and production for maximizing performance on all four outcomes of concern.

Pause time and increased residence time have emerged as highly beneficial for improving removal performance on all four outcomes. Pause time may be particularly important for avoiding viral shedding by allowing sufficient time for adsorbed and attached viral particles to decay or be consumed before addition of the next batch. Thus, for a batch of treated ISSF water for drinking purposes, the residence time should be maximized in daily use routines by allowing for a pause time between feeds used for drinking. This implies instructing users to use either the morning batch for drinking if the filter idle time is longest at night, or the evening batch if the idle time is longest during the day, in households which require more than one 20 L batch a day.

Given overall poor viral removal, a follow-up disinfection step is recommended. This may be especially necessary when deploying the BSF as a household technology to treat higher turbidity waters in settings where viral pathogens are a significant cause of water-borne illness. Simple options are likely to be highly efficacious in destroying residual bacteria and viruses in ISSF effluent.

Modifications to current BSF filter containers to treat a 20 L batch under the low hydraulic loading rates associated with reduced heads tested in this study could involve costly and complex design changes. Table 1 illustrates how the same reduction in head produces a greater absolute reduction in initial hydraulic loading rate in the coarse sand experimental filters compared to the fine sand experimental filters. One very simple way to improve removal performance for existing coarse sand BioSand filters would be to reduce the batch feed volume from the container design volume, effectively reducing the operating head, increasing the pore:batch volume ratio, and in turn increasing residence time and reducing the likelihood of breakthrough. While benefits would likely accrue for fine sand as well, given the smaller magnitude decrease in initial HLR from a lower head, the marginal gain in performance would likely be smaller.

5.0 Conclusions

- Across the 18 filter units and 10-week test duration, including both long and short residence time operation, the ISSF was capable of removing 96% of bacteria (1.4 log fecal coliform), 71% of viruses (0.54 log MS2 bacteriophage), 89% of turbidity and produced effluent below 3 NTU turbidity in each 20 L sampled batch of treated water.
- A single layer of manually processed natural river sand achieved performance comparable to that obtained with more expensive 2-layers of crushed manufactured sand recommended in current BSF field design.
- Sand size emerged as the most important design factor in this study. Controlling sand size in filter production and maintaining quality control of filter packing during installation to achieve the low hydraulic loading rates required for sufficient residence time is recommended to enhance performance on all four outcomes.
- A reduction in sand size increased removal of indicator bacteria on average by 0.16 – 0.30 log, independent of the residence time effect of the sand size change, with a less consistent viral indicator removal improvement of 0 to 0.10 log.
- On average, long residence time operation in which a pause occurs between batch feeds can be expected to increase removal of bacteria by 0.29 log, viruses by 0.67 to 0.77 log, turbidity by 3.85 percentage points, and reduce effluent turbidity by 0.40 NTU, compared to short residence time operation in which no pause occurs. Pause time may be particularly important for avoiding viral shedding by allowing sufficient time for adsorbed and attached viral particles to decay or be consumed before addition of the next batch.
- The best design and operation combines fine sand with long residence time operation, delivering marginal increases in mean removal of 0.63 log bacteria and 0.72 log viruses

compared to that achieved with coarse sand and short residence time operation, irrespective of head or other conditions.

- Additional benefits, beyond the mean gain from long relative to short residence time (pause vs. flush) operation, accrue to all four outcomes for each additional hour of contact time in the sand column beyond the operating average, within the range studied (up to 27 hours).
- Each NTU increase of influent turbidity reduced MS2 viral removal in the ISSF by 0.017 to 0.019 log per NTU. Turbidity's negative effect on viral removal is a concern for ISSF performance in developing countries and may necessitate a follow-on disinfection step in settings with high levels of seasonal or year round turbidity.
- Disturbance of the schmutzdecke by wet harrowing had no measurable effect on virus removal and only a modest reductive effect on bacterial and turbidity removal, based on measurements taken 7 days or more after the disturbance. However, maintenance reduces residence time which can be expected to reduce performance on all outcomes.

6.0 Acknowledgements

Funding for this research was provided by USAID through the Global Livestock Collaborative Research Program at UC Davis with additional support provided by a National Science Foundation grant and the Gerald T. Orlob Professorship at UC Davis. Granite Construction of Sacramento, CA donated the river sand. Bill Fleenor and Bill Sluis provided invaluable guidance with filter construction and experimental set up and operation.

7.0 References

Anderson, W.B., DeLoyde, J.L., Van Dyke, M.I., Huck, P.M., 2009. Influence of design and operating conditions on the removal of MS2 bacteriophage by pilot-scale multistage slow sand filtration. Journal of Water Supply Research and Technology-Aqua 58, 450-462.

APHA, 2005. Standard Methods for the Examination of Water and Wastewater (21th ed.). American Public Health Association, Washington, DC.

Baumgartner, J., Murcott, S., Ezzati, M., 2007. Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems. Environmental Research Letters 2.

Bradley, I., Straub, A., Maraccini, P., Markazi, S., Nguyen, T.H., 2011. Iron oxide amended biosand filters for virus removal, Water Research 45, 4501-4510.

Buzunis, B., 1995. Intermittently operation slow sand filtration: A new water treatment process, Department of Civil Engineering. University of Calgary, Calgary, Alberta, Canada, p. 235.

Clasen, T., 2009. Scaling Up Household Water Treatment Among Low-Income Populations. WHO/HSE/WSH/09.02. World Health Organization, Geneva.

Duke, W., Nordin, N., Baker, D., Mazumder, A., 2006. The use and performance of BioSand filters in the Artibonite Valley of Haiti: a field study of 107 households. Rural and Remote Health 6.

Earwaker, P., 2006. Evaluation of household BioSand filters in Ethiopia. Cranfield University, Silsoe, Bedfordshire, UK.

Elliott, M.A., Stauber, C.E., Koksal, F., DiGiano, F.A., Sobsey, M.D., 2008. Reductions of E-coli, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter. Water Research 42, 2662-2670.

Elliott, M.A., DiGiano, F.A., Sobsey, M.D., 2011. Virus attenuation by microbial mechanisms during the idle time of a household slow sand filter. Water Research 45, 4092-4102.

Faraway, J.J., 2006. Extending the linear model with R: Generalized linear, mixed effects and nonparametric regression models. Chapman & Hall/CRC, Boca Raton, FL.

Fewster, E., Mol, A., Wiesent-Brandsma, C., 2004. The long term sustainability of household bio-sand filtration, People-Centered Approaches to Water and Environmental Sanitation: 30th WEDC International Conference, Vientiane, Lao, pp. 558-561.

Hijnen, W.A.M., Schijven, J.F., Bonne, P., Visser, A., Medema, G.J., 2004. Elimination of viruses, bacteria and protozoan oocysts by slow sand filtration. Water Science and Technology 50, 147-154.

Huisman, L., Wood, W.E., 1974. Slow sand filtration. World Health Organization, Geneva.

Jenkins, M.W., Tiwari, S., Darby, J., Nyakash, N., Saenyi, W., Langenbach, K., 2009. The BioSand Filter for Improved Drinking Water Quality in High Risk Communities in the Njoro Watershed, Kenya. Research Brief 09-06-SUMAWA. Global Livestock Collaborative Research Support Program, University of California, Davis.

Kaiser, N., Liang, K., Maertens, M., Snider, R., 2002. BioSand household water filter evaluation 2001: a comprehensive evaluation of the Samaritan's Purse BioSand Filter (BSF) projects in Kenya, Mozambique, Cambodia, Vietnam, Honduras, and Nicaragua. Samaritan's Purse Canada, Calgary, AB.

Kubare, M., Haarhoff, J., 2010. Rational design of domestic biosand filters. Journal of Water Supply Research and Technology-Aqua 59, 1-15.

Manz, D.H., 2004. New horizons for slow sand filtration, The Eleventh Canadian National Conference and Second Policy Forum on Drinking Water and the Biennial Conference of the Federal-Provincial-Territorial Committee on Drinking Water, Promoting Public Health Through Safe Drinking Water, April 3-6, Calgary, Alberta, Canada, pp. 682-692.

Montgomery, G.C., 2005. Design and Analysis of Experiments, 5th Edition. John Wiley & Sons, New York.

Palmateer, G., Manz, D., Jurkovic, A., McInnis, R., Unger, S., Kwan, K.K., Dutka, B.J., 1999. Toxicant and parasite challenge of Manz intermittent slow sand filter. Environmental Toxicology 14, 217-225.

Schijven, J.F., Hassanizadeh, S.M., 2000. Virus removal by soil passage at field scale and groundwater protection of sandy aquifers. Water Science & Technology 46, 123-129.

Sobsey, M.D., 2002. Managing water in the home: accelerated health gains from improved water supply. World Health Organization, Geneva.

Sobsey, M.D., Stauber, C.E., Casanova, L.M., Brown, J.M., Elliott, M.A., 2008. Point of use household drinking water filtration: A practical, effective solution for providing sustained access to safe drinking water in the developing world. Environmental Science & Technology 42, 4261-4267.

Stauber, C.E., Elliott, M.A., Koksal, F., Ortiz, G.M., DiGiano, F.A., Sobsey, M.D., 2006. Characterisation of the biosand filter for E. coli reductions from household drinking water under controlled laboratory and field use conditions. Water Science and Technology 54, 1-7.

Verbeke, G., 2000. Linear mixed model for longitudinal data. Springer, New York.

WHO, 2007. Combating waterborne disease at the household level. World Health Organization, Geneva.

WHO/Unicef, 2010. Progress on Sanitation and Drinking-water: 2010 Update. WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation, World Health Organization, Geneva.

Wiesent-Brandsma, C., Fewster, E., Mol, A., 2004. Medair Kenya BioSand filter project evaluation - interpretation of results. Medair, Ecublen

Figures

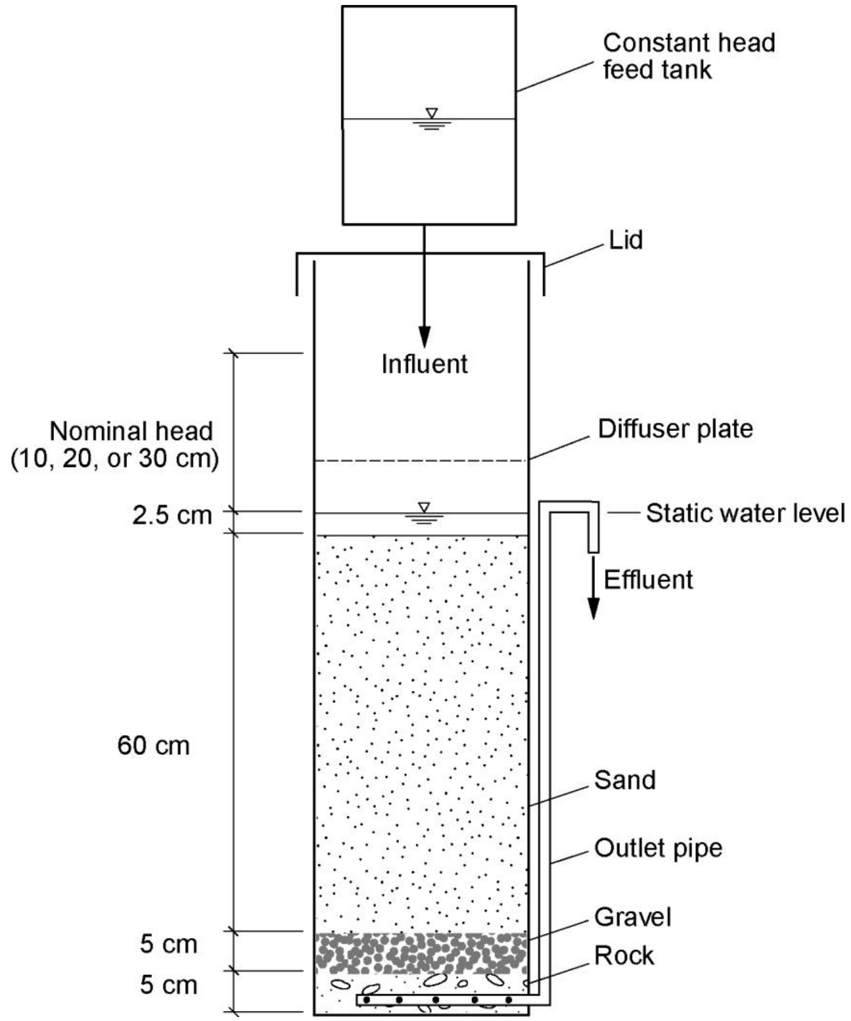

Figure 1. Experimental intermittent slow sand filter

Table 1. Experimental Design Filter Configurations

Block [a]	Unit	Factor 1 Effective Grain Size d_{10} mm / UC [b]	Factor 2 Nominal Head cm	Initial Hydraulic Loading Rate [c] m/hr
1	1	0.17 / 2.4	10	0.01
	2	0.52 / 2.1		0.11
	3	0.17 / 2.4	20	0.06
	4	0.52 / 2.1		0.31
	5	0.17 / 2.4	30	0.13
	6	0.52 / 2.1		0.4
2	7	0.17 / 2.4	10	0.03
	8	0.52 / 2.1		0.1
	9	0.17 / 2.4	20	0.07
	10	0.52 / 2.1		0.24
	11	0.17 / 2.4	30	0.1
	12	0.52 / 2.1		0.39
3	13	0.17 / 2.4	10	0.02
	14	0.52 / 2.1		0.08
	15	0.17 / 2.4	20	0.07
	16	0.52 / 2.1		0.25
	17	0.17 / 2.4	30	0.11
	18	0.52 / 2.1		0.41

a – Block 1 was conducted from April 4 to June 18, 2006 and blocks 2 and 3 were conducted simultaneously from July 7 to September 17, 2006.

b – d_{10} is the sand size diameter for which 10% of the sand mass is smaller and 90% is larger in size; UC is the uniformity coefficient of the sand measured as the ratio of the d_{60} to d_{10} grain size.

c – Determined from time to collect one liter of filtered water at the beginning of each batch feed.

Table 2. Filter Influent Water[a] Quality Characteristics

Block		**Water Quality Parameter**		
		Log Fecal coliform CFU/100 mL	Log MS2 coliphage PFU/100 mL	Turbidity NTU
1	Mean ± S.D. (N)[b]	5.18 ± 0.48 (96)	6.77 ± 1.21 (96)[c]	24.19 ± 12.4 (96)[c]
	Min – Max	4.40 – 5.99	4.94 – 8.05	12.93 – 58.57
2	Mean ± S.D. (N)	5.18 ± 0.48 (114)	4.96 ± 0.53 (114)	12.99 ± 7.9 (126)
	Min – Max	3.94 – 5.84	4.04 – 6.27	5.51 – 37.60
3	Mean ± S.D. (N)	5.16 ± 0.49 (120)	4.95 ± 0.51(120)	11.89 ± 5.4 (132)
	Min – Max	4.12 – 5.84	4.15 – 6.37	5.36 – 26.27
Combined				
	Mean ± S.D. (N)	5.17 ± 0.48 (330)	5.48 ± 1.14 (330)	15.62 ± 10.1(354)
	Min – Max	3.94 – 5.99	4.04 – 8.05	5.36 – 58.57

a – Includes filter measurements during initial and maintenance weeks.

b – N refers to the number of sample measurements.

c – Block 1 influent water quality is significantly different from quality of Block 2 and 3 influent, at $p < 0.001$, for MS2 coliphage concentration and turbidity.

.

Table 3. Filter Operating Characteristics

Block		**Operating Characteristic**		
		Days Since Last Filter Maintenance or Startup	Hours Residence Time – Long Batch	Hours Residence Time – Short Batch
1	Mean ± S.D. (N) [a]	24.1 ± 15.8 (61)	16.6 ± 4.0 (31)	7.9 ± 6.1 (30)
	Min – Max	8 – 58	12.33 – 23.75	2.17 – 21.75
2	Mean ± S.D. (N)	22.8 ± 14.5 (86)	14.6 ± 3.0 (40)	4.2 ± 1.4 (46)
	Min – Max	8 – 67	12.17 – 24.62	2.27 – 6.83
3	Mean ± S.D. (N)	26.9 ± 16.9 (98)	15.7 ± 4.1(46)	4.3 ± 1.4 (52)
	Min – Max	8 – 67	12.17 – 26.92	2.32 – 6.83
Combined				
	Mean ± S.D. (N)	24.8 ± 15.9 (245)	15.6 ± 3.8 (117)	5.1 ± 3.5 (128)
	Min – Max	8 – 67	12.17 – 26.92	2.17 – 21.75

a – N refers to the number of valid values measured during a block’s run.

Table 4. Mean Performance[a] Across Blocks of All Filter Configurations Combined

	Long Batch Outcomes			
Block	FC Removal, Log10	MS2 Removal, Log10	Turbidity Removal, %	Effluent Turbidity, NTU
1 Mean ± S.D. (N) [a] Min – Max	1.65 ± 0.56 (32) 0.81 – 3.19	0.47 ± 0.24 (31) -0.04 – 1.08	95.4 ± 2.6 (32) 90.1 – 98.9	1.03 ± 0.48 (32) 0.50 – 2.03
2 Mean ± S.D. (N) Min – Max	1.45 ± 0.26 (41) 0.96 – 1.94	0.77 ± 0.35 (40) -0.21 – 1.30	90.8 ± 6.1 (44) 69.6 – 97.7	0.93 ± 0.41 (44) 0.26 – 1.94
3 Mean ± S.D. (N) Min – Max	1.46 ± 0.40 (46) 0.52 – 2.29	0.84 ± 0.39 (46) -0.32 – 1.55	89.4 ± 6.0 (50) 67.2 – 98.9	1.09 ± 0.40 (50) 0.45 – 1.88
Combined Blocks Long Batch Mean ± S.D. (N)	1.59 ± 0.42 (119)	0.72 ± 0.37 (117)	91.4 ± 5.9 (126)	1.02 ± 0.43 (126)
	Short Batch Outcomes			
Block	FC Removal, Log10	MS2 Removal, Log10	Turbidity Removal, %	Effluent Turbidity, NTU
1 Mean ± S.D. (N) [a] Min – Max	1.60 ± 0.41 (31) 0.85 – 2.53	0.15 ± 0.19 (30) -0.16 – 0.64	89.5 ± 6.2 (31) 77.1 – 96.9	1.45 ± 0.61 (31) 0.55 – 2.59
2 Mean ± S.D. (N) Min – Max	1.23 ± 0.24 (47) 0.72 – 1.85	0.42 ± 0.42 (46) -0.31 – 1.21	88.5 ± 5.4 (50) 75.1 – 96.6	1.30 ± 0.46 (50) 0.58 – 2.71
3 Mean ± S.D. (N) Min – Max	1.18 ± 0.31 (52) 0.50 – 1.78	0.46 ± 0.40 (52) -0.22 – 1.13	83.5 ± 7.4 (56) 62.8 – 93.8	1.56 ± 0.53 (56) 0.55 – 2.79
Combined Blocks Short Batch Mean ± S.D. (N)	1.30 ± 0.36 (130)	0.38 ± 0.39 (128)	86.7 ± 7.0 (137)	1.44 ± 0.53 (137)
	All Batches			
All Blocks Mean ± S.D. (N)	1.40 ± 0.40 (249)	0.54 ± 0.42 (245)	89.0 ± 6.9 (263)	1.24 ± 0.53 (263)

a – Based on measurements taken after 14 days of filter maturation and 7 days since filter maintenance.

Table 5. Significance of Fixed Factor and Covariate Effects on Filter Performance (dark shading, bold = $p < 0.05$; light shading = $0.05 < p < 0.10$)

Linear Mixed Model	Factor (F) or Covariate (C)	ISSF Performance Outcome			
		Log10 FC Removal p-value 1	Log10 MS2 Removal p-value 2	Turbidity % Removal p-value 3	Effluent Turbidity p-value 4
2-factor analysis [a] (Long Batch)	(F) Sand	**<0.001**	0.691	**0.020**	**0.019**
	(F) Head	**<0.001**	0.646	0.318	0.105
	(C) Residence Time (hrs) [e]	**<0.001**	**<0.001**	**<0.001**	0.167
	(C) Days Since Maint. [f]	0.188	n/i [d]	**0.037**	0.090
	(C) Influent Turbidity	0.396	**<0.001**	NA [c]	NA [c]
2-factor analysis (Short Batch)	(F) Sand	**0.011**	**0.010**	0.757	0.370
	(F) Head	0.108	0.065	0.085	0.184
	(C) Residence Time (hrs)	**<0.001**	0.565	**0.001**	**0.004**
	(C) Days Since Maint.	0.280	n/i [d]	**<0.001**	0.126
	(C) Influent Turbidity.	**0.014**	**<0.001**	NA [c]	NA [c]
3-factor analysis [b] (Combined Batches)	(F) Sand	**<0.001**	0.071	0.748	0.172
	(F) Head	**<0.001**	**0.048**	0.153	0.200
	(F) Batch	**<0.001**	**<0.001**	**<0.001**	**<0.001**
	(C) Residence Time (hrs)	**<0.001**	**0.009**	**<0.001**	**0.001**
	(C) Days Since Maint.	0.121	n/i [d]	**<0.001**	**0.014**
	(C) Influent Turbidity	**0.011**	**<0.001**	NA [c]	NA [c]

a – For Log FC removal 2-factor long batch analysis, sand and residence time interaction was significant (p=0.004).

b – In Log MS2 removal 3-factor analysis, sand and batch interaction was nearly significant (p<0.099) indicating that 0.17 mm sand provides relatively greater MS2 viral removal under short batch operation than it does under long batch operation. In Log FC removal 3-factor analysis, batch and residence time interaction was significant (p<0.001).

c – NA: not applicable to this performance outcome.

d – n/i: not included in final model due to lack of any bi-variate relationship.

e – Actual residence time adjustment in plus or minus hours, relative to the mean batch residence time for long or short batch.

f – Includes measurements for filters after 14 days since start-up or at least 7 days since maintenance.

Table 6. Effect on ISSF Performance of Significant Factor Level Differences and Covariates

Performance Outcome	Significant Factors & Covariates (p<0.10 from Table 5)	Factor Level Paired Comparison or Covariate Increment		Significant Performance Difference (for comparison or covariate p <0.10)		
		Better	Worse	2-factor analysis Short Batch 1	2-factor analysis Long Batch 2	3-factor analysis All Batches 3
Log FC Removal	(F) Sand	0.17 mm	0.52 mm	0.16	0.30	0.18
	(F) Head	10 cm	30 cm	NS	0.29	0.16
		20 cm	30 cm	NS	0.17	0.10
	(F) Batch	Long	Short	n/a	n/a	0.29
	(C) Residence time	1 additional hour		0.064	n/a	n/a
	(F*C) Sand & Res. Time interaction	1 additional hour – 0.17 mm sand		NS	0.053	NS
		1 additional hour – 0.52 mm sand		NS	NS	NS
	(F*C) Batch and Res. Time interaction	1 additional hour - Long batch		n/a	n/a	0.050
		1 additional hour - Short batch		n/a	n/a	0.063
	(C) Influent turbidity	1 additional NTU		0.0039	NS	0.0035
Log MS2 Removal	(F) Sand	0.17 mm	0.52 mm	0.10	NS	0.053[a]
	(F) Head	10 cm	30 cm	0.094[b]	NS	0.082
	(F) Batch	Long	Short	n/a	n/a	0.36
	(F*F) Sand and Batch interaction	0.15 mm and Long	0.15 mm and Short	n/a	n/a	0.31
		0.52 mm and Long	0.52 mm and Short	n/a	n/a	0.41
	(C) Residence time	1 additional hour		NS	0.025	0.012
	(C) Influent Turbidity	1 additional NTU		-0.019	-0.017	-0.017
Turbidity % Removal	(F) Sand	0.17 mm	0.52 mm	NS	-1.67	NS
	(F) Head	10 cm	30 cm	4.26[c]	NS	NS
	(F) Batch	Long	Short	n/a	n/a	3.85
	(C) Residence Time	1 additional hour		0.49	0.24	0.46
	(C) Days Since Maint.	1 additional day		0.15	0.049	0.11
Effluent Turbidity (NTU)	(F) Sand	0.17 mm	0.52 mm	NS	0.21	NS
	(F) Batch	Long	Short	n/a	n/a	-0.40
	(C) Residence Time	1 additional hour		-.034	NS	-0.026
	(C) Days Since Maint.	1 additional day		NS	-.0038[d]	-0.0048

a – Sand paired difference Bonfernoi significance = 0.071
b – Head paired difference Bonferoni significance = 0.080
c – Head paired difference Bonferoni significance =0.105
d – Days since maintenance marginal effect significance =0.090