

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

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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

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2 developing countries: Experimental investigation and modeling

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5 **Abstract:**

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

23 On average, the experimental filters removed 1.40 log fecal coliform CFU (SD 0.40 log,
24 N=249), 0.54 log MS2 PFU (SD 0.42 log, N=245) and 89.0 percent turbidity (SD 6.9 percent,
25 N=263). Effluent turbidity averaged 1.24 NTU (SD 0.53 NTU, N=263) and always remained

26 below 3 NTU. Under the best performing design configuration and operating mode (fine sand,
27 10 cm head, long operation, initial HLR of 0.01 to 0.03 m/hr), mean 1.82 log removal of bacteria
28 (98.5%) and mean 0.94 log removal of MS2 viruses (88.5%) was achieved.

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

42

43 **1.0 Introduction**

44 Access to improved drinking water is unavailable to an estimated 884 million people in the
45 world, most of who live in rural, dispersed, and often remote communities in developing
46 countries (WHO/UNICEF, 2010). Diarrhea and other water-borne diseases from exposure to
47 microbial pathogens in unsafe water constitute a major threat to health in these settings. The
48 World Health Organization recommends point-of-use household water treatment (POU) as an

49 intervention to address the need, drawing on appropriate low-cost technologies (Sobsey, 2002;
50 WHO, 2007).

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

63 In limited controlled laboratory testing of the original Davnor BioSand Water Filter™ (D-
64 BSF), the following improvements in the microbial quality of water have been reported: bacterial
65 removal for fecal coliform or E. coli ranging from 63 % up to 99% ($2 \log_{10}$) with averages of
66 94% and 96% (Buzunis, 1995; Stauber et al., 2006); viral removal ranging from 0 to 0.75
67 \log_{10} measured using MS2 and PRD-1 bacteriophage surrogates, and 1.14 \log_{10} of echovirus 12
68 (Elliot et al., 2008); protozoan removals of greater than 5 \log_{10} for Giardia lamblia cysts (6-16
69 μm diameter) and 99.98 % for Cryptosporidium oocysts (4-7 μm diameter) (Palmateer et al.,
70 1999).

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

82 Field designs and local construction methods in developing countries often result in BSFs
83 that differ from the original D-BSF design specifications. A single layer of local river sand of
84 variable size (characterized by effective size, d_{10} , and uniformity coefficient, UC) is often used
85 as the filtration media instead of the D-BSF's two different size layers of crushed sand (Manz,
86 2004). ISSF containers used in field projects are generally made of concrete, and can vary in
87 their maximum hydraulic head, sand column depth, and headspace volume to a greater or lesser
88 degree from the original plastic D-BSF container specifications.

89 Variations and less than ideal performance in field testing have been reported for BSFs,
90 ranging from negative up to 100 percent bacterial removal (Duke et al., 2006; Earwaker, 2006;
91 Fewster et al. 2004; Kaiser et al. 2002; Stauber et al., 2006; Wiesent-Brandsma et al. 2004) and
92 39 to 91 percent for turbidity reductions (Duke et al., 2006; Earwaker, 2006; Jenkins et al., 2009;
93 Stauber et al., 2006; Wiesent-Brandsma et al. 2004). Difficult logistics in developing countries

94 necessitate collecting BSF effluent and influent grab samples for field evaluations
95 simultaneously during a single house visit, limiting comparability and usefulness of field-
96 reported removal efficiencies. Influent water quality in settings where BSFs are typically
97 installed can vary from batch to batch as households switch sources and source water quality
98 varies naturally from day to day. A switch, for example, from a turbid surface source to a less
99 turbid rain feed can lead to erroneously low or even negative removal measurements based on
100 simultaneous influent-effluent (flush-pore) water sampling (Earwaker, 2006).

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

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

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

123

124 **2.0 Materials and Methods**

125 *2.1 Filter Design*

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

136 *2.2 Factorial Experimental Design*

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

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

149 BSF households typically operate their filter under a range of modes, treating from one to
150 three 20 L batches per day, resulting in wide variation in batch residence time (RT). In this
151 research, a short and a long batch RT operation were examined. The short RT operating mode
152 represents the shortest possible batch residence time (experimental average 5.1 hours; variable
153 with filter configuration) and is approximately equal to the start-to-start time of two successive
154 20 L batches fed to the filter with little or no pause between feeds. The long RT operating mode
155 represents the longest possible residence time (experimental average 15.6 hours; less than
156 theoretical 24 hours due to varying daily feed times) that would result from one 20 L batch per
157 day operation.

158 *2.3 Filter Operation*

159 Each filter was fed a standard batch of 20 L of the influent water mixture per day for 10
160 weeks, except during weekly testing. Testing involved feeding three 20 L test batches over two
161 days, as explained with this example. Batch I was started at the same time (e.g., 3 pm) in all six
162 filters within a block on test day 1. Infiltration of batch I in a block of filters finished at varying

163 times on day 1. The next day (test day 2), batch II was started in the same six filters at the same
164 time (e.g., noon). Batch II finished infiltrating in filter A of the block at 4 pm. Upon complete
165 infiltration of batch II in filter A (equal to complete exit of batch I from filter A), batch III was
166 started in filter A. Infiltration of batch III in filter A finished at 8 pm, equal to the time batch II
167 fully exited filter A and could be tested. Batch I is the long RT batch which experiences an
168 overnight pause time in the filter pore space. Batch II is the short RT batch which is flushed out
169 of the filter as soon as it has finished infiltrating. In the example, the long batch I and short batch
170 II RTs for filter A are 21 hours (difference of start times of batch II and I) and 4 hours
171 (difference in start times of batch III and II), respectively.

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

181 Official testing began in week 3, allowing an initial 2-week maturation period for the
182 biological zone to establish within the sand. The filters were maintained by the wet harrowing
183 method, a gentle rubbing of the top two centimeters of sand followed by decanting of the
184 resulting suspension of clogging material. After maintenance, the filter was allowed to mature
185 for one week before resumption of sampling measurements. Filters in the first block were

186 maintained when their flow rate became too slow to filter a 20 L batch in 24 hours, whereas,
187 filters in blocks 2 and 3 were cleaned when their flow rates reached 50 percent of their initial
188 value, resulting in more frequent filter maintenance.

189 *2.4 Influent Water*

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

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

208 *2.5 Sampling and Measurements*

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

215 Samples were analyzed for fecal coliform bacteria, MS2 coliphage virus, and turbidity.
216 Fecal coliform was enumerated using Standard Method 9222D with M-FC medium as specified
217 therein (21st edition, APHA, 2005). MS2 coliphage was enumerated as per Standard Method
218 9224D (APHA, 2005) with *E. coli* (ATCC 15597) as the host and no antibiotics. Turbidity was
219 measured using a turbidimeter (Model 2100AN, Hach Company, Loveland, CO). The hydraulic
220 loading rate (HLR) was determined from the time to collect one liter of filtered water at the
221 beginning of each batch feed.

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

226 *2.6 Analysis and Modeling*

227 The research experiment was designed to identify statistically significant independent
228 effects on ISSF batch removal performance caused by differences in effective sand size, nominal
229 head, and residence time operation as well as the interactions among them. The significance and
230 size of the main factor effects was estimated using linear mixed modeling (LMM), controlling
231 for repeated sampling of a filter unit, random block differences, and covariate effects on

232 performance variability (Faraway, 2006; Verbeke, 2000). Accounting for repeated filter
233 measurement in LMM analysis controls for possible correlation (statistical non-independence) of
234 measurements from a given filter unit. Setting block as a random effect controls for the
235 possibility of unobserved systematic differences in filter set-up and operating characteristics
236 between blocks, such as sand batch differences, seasonal variation of influent water
237 characteristics, and maintenance schedules (Verbeke, 2000). Covariates of interest included in
238 the analysis were: a) deviation of the measured residence time of a long or short RT sample
239 batch from the long or short RT operation group average, b) days since filter maintenance, and c)
240 influent turbidity, with the latter included only in fecal coliform and MS2 removal performance
241 models. Temperature was unnecessary to include as it remained uniform throughout the
242 controlled experiment. Test batch measurements within seven days of a maintenance event were
243 excluded from performance results and analyses. Results were analyzed using SPSS statistical
244 software (SPSS Inc., Chicago, Illinois).

245 Four dependent variable outcomes were modeled: the measured \log_{10} fecal coliform
246 removal, \log_{10} MS2 coliphage removal, percent turbidity reduction, and effluent turbidity in the
247 measured long and short 20 L test batches, across the 18 experimental filter units. First, 2-factor
248 LMM analysis was undertaken to examine the effects of grain size (2 levels) and nominal head
249 (3 levels) separately for short and long RT batch operation. Then, batch operation mode (2
250 levels) was added as a third factor in a three-factor LMM model of all long and short batch
251 measurements combined, comprising from 245 to 263 performance data points for each outcome
252 of interest. Missing covariate values for batch residence time deviation and days since
253 maintenance were replaced by group averages. Only statistically significant interaction terms, at
254 the 0.10 level, were retained in the final model. The main factor and covariate effects and their

255 marginal means from LMM modeling indicate level of significance of each factor or covariate on
256 filter performance and the mean effect size of a change in a specified factor level, or a unit
257 increase in a covariate, adjusted for repeated filter sampling and random block effects. Pairwise
258 comparisons of mean performance effect size of each nominal head level were made using the
259 Tukey method, which adjusts significance for multiple comparisons. Model appropriateness was
260 assessed using the Levene-style test for equal variance of the residuals and graphical analysis of
261 residuals. Normality was assessed using normal probability plots and the Shapiro-Wilks test.
262 No violations of the LMM assumptions were found.

263

264 **3.0 Results**

265 *3.1 Filter characteristics and experimental conditions*

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

274 Table 3 presents the range of covariate values within each block and overall during the
275 experiment. On average, both the long and short batch residence times were longer in block 1
276 than in blocks 2 or 3. The two-tailed t-test for the long batch residence time difference is
277 significant (at the 0.05 level) between blocks 1 and 2 ($p=0.020$), but not between blocks 1 and 3

278 (p=0.31) or blocks 2 and 3 (p=0.154). The short batch residence time difference between blocks
279 1 and 2 (p=0.003) and 1 and 3 (p=0.003) is also significant, but not between blocks 2 and 3
280 (p=0.72). A less frequent maintenance schedule applied during block 1 is the most apparent
281 reason for the higher block 1 long and short batch residence times but could also be the result of
282 influent water quality differences or small unobserved differences in the sand characteristics or
283 packing of block 1 compared to blocks 2 and 3. Days since last maintenance is lowest for block
284 2 and highest for block 3, although this difference is not significant (p=0.075; 2-tailed t-test).
285 Inclusion of model covariates for the deviation of a batch's actual residence time from the long
286 or short group average (across all blocks), for days since maintenance, and for influent turbidity
287 where relevant, allow explicit examination of the independent effects of these operational
288 differences on filter performance, separated from the main factor effects. In particular,
289 controlling for residence time variation of a particular batch of water separates configuration-
290 related variations in residence time under a given operation mode, for example those attributable
291 to sand size or nominal head configuration differences, from the main effect of the pause
292 between batch feeds that arises under long RT operating mode.

293 *3.2 Overall performance*

294 Filter performance averaged across the six different configurations is shown in Table 4 for
295 each block and combined across all blocks. On average, the experimental filters removed 1.40
296 log fecal coliform CFU (SD 0.40 log, N=249), 0.54 log MS2 PFU (SD 0.42 log, N=245) and
297 89.0 percent turbidity (SD 6.9 percent, N=263). Effluent turbidity averaged 1.24 NTU (SD 0.53
298 NTU, N=263) and always remained below 3 NTU. Filter performance on all four outcomes was
299 better under long than under short operation.

300 Fecal coliform removal was higher and MS2 removal was lower in block 1 compared to
301 blocks 2 and 3, under both long and short operation. Turbidity removal was higher in block 1
302 compared to blocks 2 and 3 under long operation. Fecal coliform removal ranged from a high of
303 3.19 log (99.94%) (fine, 10 cm, block 1, week 3, long) to a low of 0.50 log (68.4%)(coarse, 30
304 cm, block 3, week 3, short). MS2 removal ranged from a high 1.55 log (97.2%) (fine, 30 cm,
305 block 3, week 8, long) to a low of -0.32 log (109% increase)(coarse, 20 cm, block 3, week 8.2,
306 long). Highest and lowest turbidity removals were 98.9 percent (coarse, 10 cm, block 1, week 7,
307 long) and 62.8 percent (fine, 20 cm, block 3, week 3, short), respectively.

308 *3.3 Modeling results*

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

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

320 3.3.1 Significant factors and covariates affecting filter performance

321 Under long batch operation, all five conditions: sand size, head, residence time,
322 maintenance, and influent turbidity significantly ($p < 0.05$) and independently affected filter

323 performance for one or more of the four outcomes of concern (see Table 5: 2-factor long batch
324 model, shaded cells). Residence time (deviation) was the most consistently and highly
325 significant variable, followed by sand size. In addition to their independent main effects, sand
326 size and residence time produced a significant interaction effect on bacterial removal under long
327 operation ($p=0.004$). Influent turbidity, included in models of bacterial and viral removal,
328 produced highly significant effects on viral removal, and weak effects on bacterial removal.
329 Head was highly significant for bacterial removal, weakly significant for effluent turbidity, and
330 insignificant for viral and turbidity removal under long operation.

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

341 The above patterns of factor and covariate significance are confirmed in the 3-factor model
342 which examined the full data set and included batch (long versus short RT operation) as a third
343 factor (Table 5). Batch operation and actual residence time both had highly significant
344 independent effects on all four filter performance outcomes, and interacted to produce significant
345 additional interaction effects on bacterial removal ($p<0.001$). Head changes were significant or

346 near significant for all four outcomes, independent of batch or residence time. Sand size was
347 significant or near significant for bacterial and viral removal, but not for turbidity performance
348 (neither removal nor effluent). Sand size and batch interacted to produce nearly significant
349 additional effects on viral removal ($p < 0.099$). Maintenance significantly affected both turbidity
350 performance outcomes independent of other conditions, while influent turbidity had a significant
351 independent effect on both viral and bacterial removal in the combined model.

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

354 3.3.2 Bacterial removal

355 Fine sand ($d_{10} = 0.17$) increased bacterial removal (as measured by fecal coliform) by 0.16
356 log under short operation and 0.30 log under long operation, compared to coarse sand (d_{10}
357 $= 0.52$). Reducing head under long operation removed an additional 0.17 log at 20 cm and 0.29
358 log at 10 cm. Irrespective of operating mode, fine sand increased removal on average by 0.18
359 log independent of other conditions, while head reductions of 10 cm and 20 cm increased
360 removal on average by 0.10 log and 0.16 log, respectively. Switching from short to long RT
361 batch operation increased bacterial removal by 0.29 log on average, irrespective of configuration
362 or operating conditions. Increasing residence time further increased bacterial removal by an
363 estimated 0.050 and 0.063 log per hour, under long and short operation, respectively. The
364 benefit from another hour of residence time occurred irrespective of sand size under short
365 operation but was largely limited to the fine sand configuration under long operation. Each
366 additional NTU of influent turbidity increased bacterial removal by approximately 0.0035 log,
367 irrespective of batch, configuration, or other conditions. Days since maintenance was positively
368 associated with bacterial removal however the effect was not significant ($p = 0.18$).

369 3.3.3 Viral removal

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

387 Influent turbidity had a consistently strong negative effect on viral removal: each additional
388 NTU decreased viral removal by an average 0.017 log, independent of other conditions. Influent
389 turbidity had a slightly greater negative effect on viral removal under short RT operation (-0.019
390 log per NTU). The negative impact of influent turbidity on viral removal (-0.017 log/NTU) is

391 nearly 5 times the magnitude of the positive impact observed for bacterial removal (+0.0035
392 log/NTU).

393 3.3.4 Turbidity performance

394 Longer contact time, reflected in batch operation mode and residence time, produced the
395 only consistent improvements in turbidity performance across the models, for both removal and
396 effluent quality. Changing from short to long RT operation increased turbidity removal by 3.85
397 percentage points and decreased effluent turbidity by 0.40 NTU, independent of filter
398 configuration or other conditions. Each additional hour of residence time increased removal by
399 0.46 percentage points and decreased effluent turbidity by 0.026 NTU. The use of fine sand,
400 under long RT operation only, caused a small detrimental impact on turbidity performance
401 compared to the use of coarse sand, decreasing removal by 1.67 percentage points and increasing
402 effluent turbidity by 0.21 NTU, on average. Reducing head from 30 cm to 10 cm, under short
403 operation, produced a marginally significant ($p=0.105$) improvement in removal of 4.26
404 percentage points but this did not translate into a significant improvement in effluent turbidity.
405 Impacts of sand size and head on turbidity removal and effluent performance were no longer
406 significant when controlling for batch and residence time deviations in the combined all-batch
407 model. Each additional day since the last maintenance resulted in 0.11 percentage points more
408 removal of influent turbidity and a 0.005 NTU reduction in effluent turbidity, on average.

409 **4.0 Discussion**

410 *4.1 General Overview*

411 Relative to earlier work, several new and important aspects of ISSF performance are
412 addressed in this study that allow for a more thorough evaluation and understanding of
413 performance and removal mechanisms. This is the first study in which simultaneous

414 measurement of bacteria, viruses and turbidity removal at the batch level over an extended
415 duration has been undertaken with a large number of replicate units to permit rigorous modeling
416 of ISSF performance variability within and across a range of likely BSF filter design
417 configurations and operating conditions. Published laboratory evaluations of the BSF to date
418 have involved testing of 1 or 2 filter units for limited durations and have not reported on
419 maintenance or its effects. This study included 18 filter units operated daily and maintained and
420 sampled over ten weeks. Over the course of filter testing, significant seasonal variation in
421 natural surface water turbidity was encountered and routine wet harrowing of the filters was
422 required to maintain filter operation, conditions typically representative of real-life field-scale
423 operation. Simultaneous measurement of turbidity removal in this study has revealed
424 interactions between turbidity and microbiological removal in the ISSF which have not been
425 reported and which have important implications for applications that treat surface waters with
426 varying or high turbidity.

427 The experimental filter in this study differs in several ways from the D-BSF filter design
428 used to date in published controlled laboratory studies of the BSF. The D-BSF design calls for a
429 40 cm column of crushed sand, comprised of an upper layer of effective size and uniformity
430 coefficient of 0.15 mm and 1, respectively, and a lower sand layer with effective size and
431 uniformity coefficient of 0.35 mm and 1, respectively (Manz, 2004). This sand specification is
432 often costly to obtain or produce locally in developing communities. In this study, a 60 cm
433 column composed of a single layer of river sand manually processed to meet specified sand size
434 and uniformity characteristics was used to better reflect typical community sand sources and
435 processing capability in developing countries. The slightly deeper sand column was chosen to

436 maintain a minimum 1:1 ratio of filter pore space to 20 L batch charge volume, and also differs
437 from the D-BSF's reported pore space to charge volume ratio of 0.9:1 (Stauber et al., 2006).

438 Across the 18 filter units and 10-week test duration, including both long and short operation
439 but excluding the first 2 weeks of start-up and first seven days after maintenance, on average the
440 ISSF was capable of removing 96% of bacteria (1.4 log fecal coliform), 71% of viruses (0.54 log
441 MS2), 89% of turbidity and produced effluent always below 3 NTU turbidity in each 20 L
442 sampled batch of treated water (Table 4). Results reported from testing of the D-BSF (Buzunis,
443 1995; Elliot et al., 2008; Stauber et al., 2006) in which no maintenance was performed, fall
444 within the range of our testing results, for the most part. In contrast to Elliot et al (2008),
445 however, we found viral shedding (negative viral removal) to be a real concern with ISSF
446 performance. More importantly, the modeling analysis sheds light on those design and operating
447 conditions that are most responsible for improved ISSF performance, including uncontrollable
448 operating conditions, at both filter and batch scale, and provides insight into mechanisms of
449 removal that have the greatest effects on ISSF performance for each of the four outcomes
450 measured.

451 This study confirms that removal of bacteria and viruses in ISSFs is significantly lower than
452 in SSFs. Even under the best performing design configuration and operating mode in this study
453 (fine sand, 10 cm head, long operation, initial HLR of 0.01 to 0.03 m/hr) which achieved mean
454 1.82 log removal of fecal coliform bacteria (98.5%) and mean 0.94 log removal of MS2 viruses
455 (88.5%), these rates are 0.5 log to 1.0 log lower than typically obtained by SSF (Hijnen et al.,
456 2004). Viral shedding, which we found to be a problem with the ISSF, has also been observed in
457 SSF challenge testing (Anderson et al., 2009). Anderson et al. report MS2 removal from 0.2 to
458 2.2 log for a range of typical SSF design and operating conditions. Recent work indicates iron

459 amendments that enhance viral adsorption offer a potential solution for increasing viral removal
460 in the BSF (Bradley et al., 2011).

461 *4.2 Contact time*

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

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

480 *4.3 Importance of design factors and design and operation interactions*

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

494 The modeling analysis indicates that using fine rather than coarse sand size (d_{10} 0.17 mm vs.
495 d_{10} 0.52 mm) yields a significant and meaningful increase in ISSF removal of bacteria (0.16 –
496 0.30 log), independent of the residence time effect from the sand size change, with less
497 consistent effects observed for viruses (0 to 0.10 log). The combination of fine sand with long
498 RT operation can be expected to produce a mean increase in removal of 0.63 log bacteria and
499 0.41log viruses over mean levels achieved with the combination of coarse sand with short RT
500 operation, irrespective of head or other conditions. Changing to a lower head, without changing
501 the batch volume (i.e., keeping the pore:batch ratio constant at 1:1 in this case), provides
502 relatively small mean improvements in treated water quality for bacteria and viruses. This
503 suggests that the enhanced supernatant settling and reduced velocity shear effects of a lower head

504 achieve relatively little on their own (i.e., independent of the increased residence time effects of
505 reduced head which were controlled for separately in the LLM modeling). No benefit of sand
506 size or head reduction on turbidity performance, separate from the increased residence time
507 benefits, was observed.

508 *4.4 Important and opposing effects of influent turbidity on viral and bacterial removal*

509 This study uncovered an important and relatively large and significant negative effect of
510 influent turbidity on viral removal in the ISSF, estimated as an average reduction in removal of
511 0.017 to 0.019 log for each additional NTU of influent turbidity. To our knowledge, this is the
512 first time the relationship between influent turbidity and viral removal, whether for SSF or ISSF,
513 has been systematically identified and measured. At the same time, we found an opposite
514 positive effect, albeit much smaller, of influent turbidity on ISSF bacterial removal in which 1
515 NTU of influent turbidity enhanced bacterial removal by an estimated 0.0035 log, on average.
516 These opposing effects are plausible if influent turbidity particles competed effectively with the
517 MS2 coliphage for adsorption sites whereas those same particles provided additional sites for
518 bacteria removal. Although surface charges were not measured in this research and virus
519 adsorption in soil is a very complicated phenomenon, it is likely that MS2 coliphage had a strong
520 net-negative charge at the near-neutral pH of the influent water, causing repulsion by the
521 negatively charged sand (Schijven and Hassanizadeh, 2000). Moreover, the bacteria were more
522 likely to be particle associated due to their origin in the combined river water/wastewater influent
523 whereas the MS2 coliphage were cultured in the laboratory and thus not indigenous.

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

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

528 *4.5 Limited effects of maintenance on performance*

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

544 *4.6 Other sources of variability in ISSF performance*

545 Examination of the experimental data in Table 4 indicates significant variability in
546 performance between blocks. Some of the block-level variation can be explained by observed
547 differences in influent turbidity and maintenance practices as discussed above, however, there
548 may be other important unobserved influent water quality physical and chemical characteristics,

549 separately or in conjunction with turbidity, such as hardness, alkalinity or pH, that may account
550 for block performance differences. Small unobserved differences in the characteristics of
551 unprocessed river sand and the manual sand processing and packing of filters between block 1
552 and blocks 2 and 3, as suggested by the lower block 1 initial HLR values for fine sand may also
553 have contributed to block-level variations in overall performance. These additional parameters
554 that may affect filter performance variability should be fully considered and processes developed
555 to address them within BSF implementation and construction projects, especially those involving
556 on-going large-scale filter production and distribution activities.

557 *4.7 Implications for developing country design, local manufacturing, and operation*

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

569 Pause time and increased residence time have emerged as highly beneficial for improving
570 removal performance on all four outcomes. Pause time may be particularly important for
571 avoiding viral shedding by allowing sufficient time for adsorbed and attached viral particles to

572 decay or be consumed before addition of the next batch. Thus, for a batch of treated ISSF water
573 for drinking purposes, the residence time should be maximized in daily use routines by allowing
574 for a pause time between feeds used for drinking. This implies instructing users to use either the
575 morning batch for drinking if the filter idle time is longest at night, or the evening batch if the
576 idle time is longest during the day, in households which require more than one 20 L batch a day.

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

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

592

593 **5.0 Conclusions**

- 594
- Across the 18 filter units and 10-week test duration, including both long and short
595 residence time operation, the ISSF was capable of removing 96% of bacteria (1.4 log
596 fecal coliform), 71% of viruses (0.54 log MS2 bacteriophage), 89% of turbidity and
597 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
598 comparable to that obtained with more expensive 2-layers of crushed manufactured sand
599 recommended in current BSF field design.
 - Sand size emerged as the most important design factor in this study. Controlling sand
600 size in filter production and maintaining quality control of filter packing during
601 installation to achieve the low hydraulic loading rates required for sufficient residence
602 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 –
603 0.30 log, independent of the residence time effect of the sand size change, with a less
604 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
605 can be expected to increase removal of bacteria by 0.29 log, viruses by 0.67 to 0.77 log,
606 turbidity by 3.85 percentage points, and reduce effluent turbidity by 0.40 NTU, compared
607 to short residence time operation in which no pause occurs. Pause time may be
608 particularly important for avoiding viral shedding by allowing sufficient time for
609 adsorbed and attached viral particles to decay or be consumed before addition of the next
610 batch.
 - The best design and operation combines fine sand with long residence time operation,
611 delivering marginal increases in mean removal of 0.63 log bacteria and 0.72 log viruses
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616

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

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

631

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638

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Figures

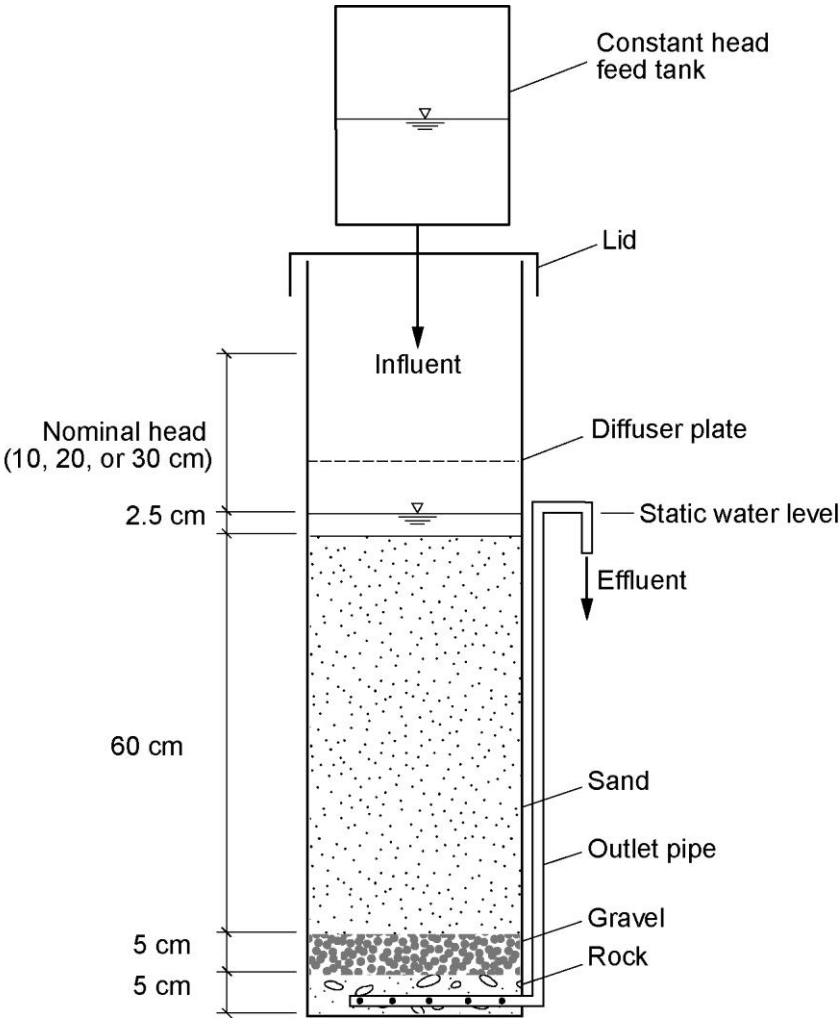


Figure 1. Experimental intermittent slow sand filter

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 – d₁₀ 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 d₆₀ to d₁₀ 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 \pm S.D. (N) ^b Min – Max	5.18 \pm 0.48 (96) 4.40 – 5.99	6.77 \pm 1.21 (96) ^c 4.94 – 8.05	24.19 \pm 12.4 (96) ^c 12.93 – 58.57
2 Mean \pm S.D. (N) Min – Max	5.18 \pm 0.48 (114) 3.94 – 5.84	4.96 \pm 0.53 (114) 4.04 – 6.27	12.99 \pm 7.9 (126) 5.51 – 37.60
3 Mean \pm S.D. (N) Min – Max	5.16 \pm 0.49 (120) 4.12 – 5.84	4.95 \pm 0.51(120) 4.15 – 6.37	11.89 \pm 5.4 (132) 5.36 – 26.27
Combined Mean \pm S.D. (N) Min – Max	5.17 \pm 0.48 (330) 3.94 – 5.99	5.48 \pm 1.14 (330) 4.04 – 8.05	15.62 \pm 10.1(354) 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 \pm S.D. (N) ^a Min – Max	24.1 \pm 15.8 (61) 8 – 58	16.6 \pm 4.0 (31) 12.33 – 23.75	7.9 \pm 6.1 (30) 2.17 – 21.75
2 Mean \pm S.D. (N) Min – Max	22.8 \pm 14.5 (86) 8 – 67	14.6 \pm 3.0 (40) 12.17 – 24.62	4.2 \pm 1.4 (46) 2.27 – 6.83
3 Mean \pm S.D. (N) Min – Max	26.9 \pm 16.9 (98) 8 – 67	15.7 \pm 4.1(46) 12.17 – 26.92	4.3 \pm 1.4 (52) 2.32 – 6.83
Combined Mean \pm S.D. (N) Min – Max	24.8 \pm 15.9 (245) 8 – 67	15.6 \pm 3.8 (117) 12.17 – 26.92	5.1 \pm 3.5 (128) 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

Block		Long Batch Outcomes			
		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)
Block		Short Batch Outcomes			
		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	Log10 MS2 Removal p-value	Turbidity % Removal p-value	Effluent Turbidity p-value
		1	2	3	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	2-factor analysis Long Batch	3-factor analysis All Batches
				1	2	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		-0.034	NS	-0.026
	(C) Days Since Maint.	1 additional day		NS	-0.0038 ^d	-0.0048

a – Sand paired difference Bonferoni 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