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Evaluation of an Innovative Sand Filter for Small System Drinking Water Treatment

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Evaluation of an Innovative Sand Filter for Small System Drinking Water Treatment

by

Christopher A. Impellitteri, Ph.D. and Craig L. Patterson, P.E.
U.S. Environmental Protection Agency
Cincinnati, OH

Nur Muhammad, Ph.D., P.E. and Rajib Sinha, P.E.
Shaw Environmental & Infrastructure (E&I), Inc.
Cincinnati, OH

Fred Stottlemyer
International Rural Water Association
White Hall, MD

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Abstract

Results of evaluation of an innovative sand filter that uses the concepts of both slow and rapid sand filtration are presented in this article. The system uses a low-cost “Drum Sand Filter” (DSF) that consists of a 55-gallon drum filled with layers of sand of varying size. A low-cost “Drum Flocculator” (DF) and tablet chlorination are incorporated before and after the DSF, respectively, to enhance the filter performance and to provide a final barrier against microbial contamination. The results of the evaluation demonstrated that the DSF with the DF and tablet chlorination is very effective in removing turbidity and the selected microbiological contaminants including *Escherichia coli, Bacillus subtilis,* Total and Fecal Coliform and Polystyrene Latex (PSL) beads, a surrogate for Cryptosporidium. The DF/DSF system evaluated in this work is meant to provide a low-cost system in order to provide basic water treatment for locations where such treatment is not available.

Keywords
Drum flocculator; Drum sand filter; Microbiological contaminant; Small community; Tablet chlorinator; Turbidity

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Acronyms and Abbreviations

B. subtilis	*Bacillus subtilis*
DF	drum flocculator
DSF	drum sand filter
E. coli	*Escherichia coli*
EPA	U.S. Environmental Protection Agency
gpm	gallon/minute
HOCl	hypochlorous acid
HPC	heterotrophic plate counts
IRWA	International Rural Water Association
L	liter
lpm	liter/minute
LRV	log removal value
LT2ESWTR	Long Term 2 Enhanced Surface Water Treatment Rule
m	meter
$m^3/m^2/hr$	cubic meter/square meter/hour
mg	milligram
mL	milliliter
mm	millimeter
MLSS	mixed liquor suspended solids
MSD	Metropolitan Sewer District
NTU	Nephelometric Turbidity Unit
POE	point-of-entry
POU	point-of-use
PSL	Polystyrene Latex
PVC	Polyvinyl Chloride
PWS	Public Water System
SDWA	Safe Drinking Water Act
T&E	Test and Evaluation
µm	micron

1.0 INTRODUCTION

Safe drinking water is essential for good public health. Contamination of drinking water by microorganisms is a major cause of human illness world-wide. Between 1971 and 2003, more than 600 waterborne disease outbreaks were recorded in the United States and most of the outbreaks resulted in serious illness and even death (U.S. EPA, 2003). Therefore, properly designed water treatment systems, either large or small, are of critical importance to protect public health. Drinking water regulations present a challenge to all U.S. water utilities, especially for communities with small systems where resources and funding are limited. Small water treatment systems are larger than Point-of-Use (POU) (2-8 L/person/day) and Point-of-Entry (POE) (100-150 L/person/day) units, but with a distinctly smaller capacity than centralized public water systems (PWS) (Peter-Varbanets *et al*., 2009). EPA defines small systems as those serving between 25 and 10,000 people (U.S. EPA, 2003). The capacity of a small system cannot be unequivocally defined, but usually varies between 1,000 L/day and 10,000 L/day (Peter-Varbanets *et al*., 2009). The Safe Drinking Water Act (SDWA) established standards for drinking water systems and required EPA to assess treatment technologies relevant to small systems. Many small water utilities are interested in evaluating low-cost technologies for drinking water.

One possible technology is a low cost "Drum Sand Filter" (DSF). With this technology, a simple drum is filled with layers of fine sand supported by coarser sand and associated pipe work arranged to force the water to flow downward through the filter. A low-cost flocculation unit using a simple "Drum Flocculator" (DF) is incorporated before the sand filter to enhance the filtration performance of the system. A low-cost disinfection process using tablet chlorination is incorporated into the effluent stream as a final barrier against microbial contamination. This innovative sand filtration system utilizes concepts of both slow and rapid sand filtration. This technology could be used for short-term measures to provide a safe supply of drinking water from unsafe polluted water sources. The small basic treatment system described here could also serve small systems for longer periods of time if adequately maintained and operated. This option should be sustainable until a longer-term safe and cost-effective supply is available to the population. A series of turbidity and microbial challenge tests were conducted on a pilot system set up at the U.S. EPA Test & Evaluation (T&E) Facility in Cincinnati, Ohio. The objective of the tests was to evaluate the performance of the system and the efficacy of different chemical coagulants. This paper summarizes the results of the tests conducted on the innovative coagulation/sand filtration system and critically evaluates its potentials for drinking water treatment for a small community.

2.0 METHODS AND MATERIALS

2.1 System Description

2.1.1 Drum Sand Filter

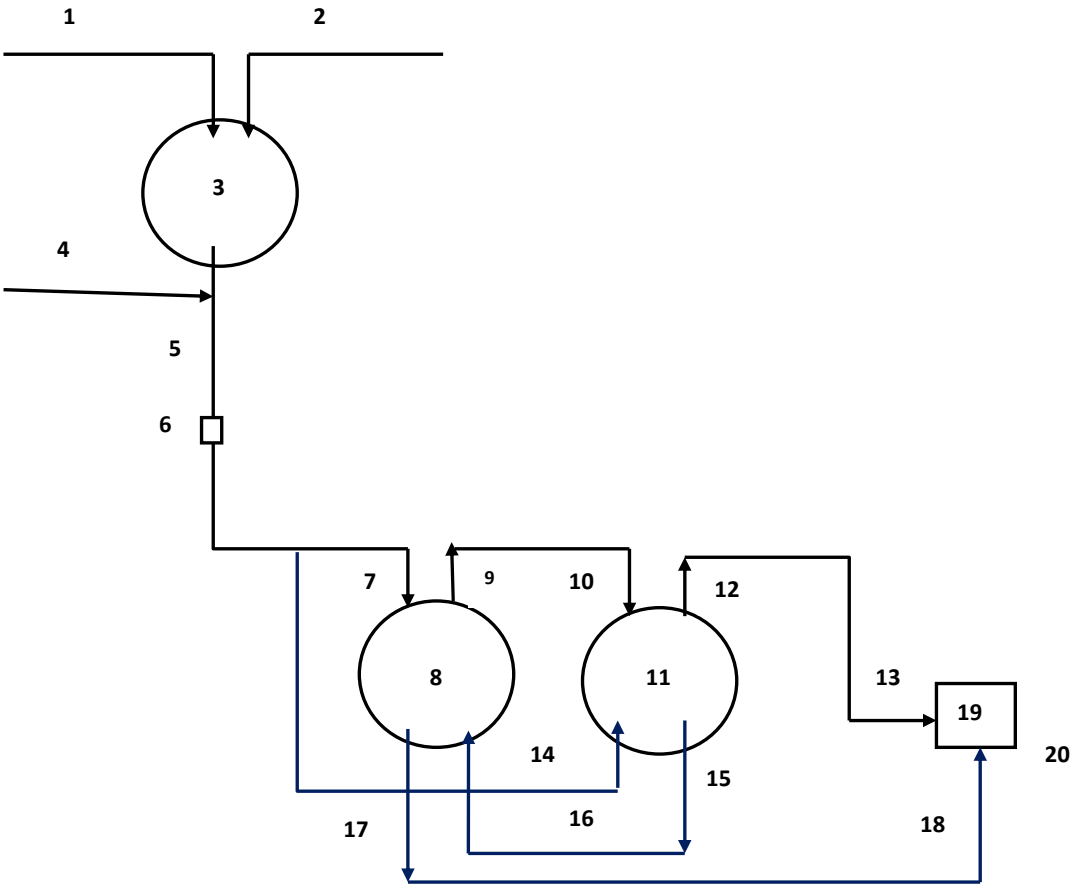
The DSF consists of fine sand supported by different layers of coarser sand and gravel in a 208-L (55-gallon) drum. Table 1 presents the filter configuration established by a series of tests

during preliminary studies. The overall configuration of the DSF utilizes sand sizes typical of those used in slow sand filtration systems (0.15 mm – 0.45 mm) (Ellis, 1985; Muhammad *et al*., 1996). The bottom layer consists of coarse sand that serves a dual role; filtration and support for the finer sand. The rate of filtration of the DSF is 0.75 $m^3/m^2/hr$ (1.0 gpm) which is faster than the recommended range of 0.10 m/hr to 0.30 m/hr for slow sand filtration (Ellis, 1985; Muhammad *et al*., 1996). The depth of the DSF (0.6 m) is noticeably lower than the recommended range of 1.2 m to 1.4 m for slow sand filters (Ellis, 1985), and close to the minimum possible depth of 0.48 m for a slow sand filter (Bellamy *et al*., 1985). The depth of the DSF is within the recommended range of 0.6 m to 0.75 m for a rapid sand filter (Schultz & Okun, 1984). The DSF system consists of two drum sand filters in series.

Table 1 - Media Configuration of the 'Drum Sand Filter'

Media	Size	Depth (mm)
Sand	Global No. 560 (Effective size = 0.15 mm)	175
Sand	Global No. 8 (Effective size = 0.20 mm)	175
Sand	Global No. 7 (Effective Size = 0.48 mm)	100
Sand	Global No. 5 (Effective Size = 1.10 mm)	150

Figure 1 shows the schematic layout of the DSF System. If the inlet valve of the first filter is fully open and the design flow rate is not achieved, the filter is becoming clogged. At this stage, the order of the filters is reversed by placing the cleaner second filter as the lead filter and the dirtier first filter as the lag filter that allows longer operation of the system prior to cleaning. The blue lines in the schematic layout show the reversing of the filters. When both filters become dirty, they are cleaned one at a time keeping the other one operational. When both filters are cleaned and re-installed, the new operational cycle starts.



Legend: 1 – Feed Water Tube; 2 – Coagulant Tube; 3 – Drum Flucculator (DF); 4 – Microbial Injection Tube; 5 – Outlet Tube from DF; 6 – Flow Meter; 7 – Influent Tube for Drum Sand Filter (DSF) 1 (Series Configuration); 8 – DSF 1; 9 – Effluent Tube from DSF 1; (Series Configuration) 10 – Influent Tube for Filter 2 (Series Configuration); 11 – DSF 2; 12 – Effluent Tube from DSF 2 (Series Configuration); 13 – Feed Tube to Chlorinator from DSF 2 (Series Configuration); 14 – Influent Tube for DSF 2 (Reversed Series Configuration); 15 – Effluent Tube from DSF 2 (Reversed Series Configuration); 16 – Influent Tube for DSF 1 (Reversed Series Configuration); 17 – Effluent Tube from DSF 1 (Reversed Series Configuration); 18 – Feed Tube to Chlorinator from DSF 1; 19 – Chlorinator; 20 – Final Effluent

Figure 1 - Schematic Layout of the DF-DSF System

A 50 mm diameter effluent PVC pipe connected to a fine stainless steel strainer (20 µm pore size) was inserted into the coarser sand media to extract the effluent water. The stainless steel strainer was fine enough to prevent the finer sand media from entering the effluent pipe. A tablet chlorinator was connected to the outlet pipe to disinfect the filtered water. The final filter set-up is depicted in Figure 2.

Figure 2 - Drum Sand Filter Set-up

2.1.2 Chemical Coagulation and Drum Flocculator

Three different coagulants were used during this study: alum, ferric chloride and chitosan. The doses of alum (10 mg/L), ferric chloride (4 mg/L) and chitosan (3 mg/L) were determined by jar tests conducted on source water with a turbidity of 10 nephelometric turbidity units (NTU). Turbidity challenges that included monitoring heterotrophic plate counts (HPC) and natural particles (2 – 5 µm) were conducted using all three selected coagulants. Microbial/surrogate tests were conducted using one conventional coagulant, alum and the emerging coagulant, chitosan; no microbial challenge tests were conducted using ferric chloride. A drum flocculator was used to mix the coagulants with the influent water in this study. This low-cost and sustainable method of flocculation in a simple drum was developed by the International Rural Water Association (IRWA) (Maryland, U.S.A.). A stock solution of the selected coagulant was mixed with deionized water and added to the flocculator at a specific rate to achieve the desired concentration. The feed water mixed with coagulant flows through an inlet tube to the sand filter. The flocculator was located at 3.7 m (12 feet) above the sand filter to provide enough head to achieve a feed flow rate of 3.8 Lpm (1.0 gpm). Microbial contaminants were injected into the inlet tube using a peristaltic pump to achieve the desired inlet concentrations. Figure 3 shows the DF setup at the T&E Facility. The contact time of the coagulants in the DF was 55 minutes.

Figure 3 - Drum Flocculator Setup

2.1.3 Disinfection

A tablet chlorinator, that generates chlorine by dissolving a chlorine tablet, (Severn Trent Services, model: 200) was connected to the effluent pipe to disinfect the final product. The generation of chlorine depends on a number of factors including the contact surface, flow rate and the age of the tablet. Figure 4 shows the chlorine tablet feeder.

Figure 4 - Chlorine Tablet Feeder

An automatic chlorine injector that uses a pre-set injection ratio to draw a hypochlorite solution was also considered as an alternate option for disinfection. However, as the sand filter was fed from the drum flocculator by gravity, the pressure in the influent line was not enough to extract the chlorine solution from the injector. Therefore, the tablet chlorinator was used in the present study.

2.2 Test Plan and Conditions

2.2.1 Turbidity Challenges

For evaluating turbidity removal performance of the DSF, surface water was obtained from the Mill Creek (source water adjacent to the U.S. EPA T&E Facility) and mixed with dechlorinated potable water in an 18,927-liter 5000-gallon) tank to produce matrix water with an influent target turbidity level of 10 NTU. Grab samples (100 mL) from the influent and effluent streams were collected at hourly intervals for approximately 5 hours. A HACH turbidity meter (Model 2100P) was used to measure the turbidity of the grab samples.

2.2.2 Microbial Challenges

To evaluate specific bacteria removal, the system was challenged with three different species: 1) *Escherichia coli (E. coli)*, a common normal flora in the gut, 2) *Bacillus subtilis (B. subtilis)*, a bacteria that goes from a vegetative stage to a spore stage depending on environmental conditions, and 3) Total and Fecal Coliform, indicator organisms for fecal pollution. For establishing the performance of the system in removing heterotrophic bacteria, HPC of the influent and effluent samples were determined during the turbidity challenges.

Freeze-dried *E. coli* (ATCC 15222™) was obtained from American Type Culture Collection (Manassas, Virginia) and the stock was re-constituted by adding 1 mL nutrient broth. The mixture was then transferred into 100 mL nutrient broth and incubated in a shaker incubator at 36 ^{0}C and 170 rpm for 20 – 24 hours. The culture was analyzed using IDEXX Colilert-18 Method (IDEXX, 2003) and the concentration was ~ 1.0×10^{9}/mL. A sub-culture, using 1 mL of the stock in 100 mL of nutrient broth, was prepared by incubating the mixture as described above for the challenge tests. Grab samples for *E. coli* were analyzed using the IDEXX Colilert-18 Method (IDEXX, 2003).

B. subtilis aerobic spores were used to fulfill two roles in the testing, both as a chlorine-resistant surrogate and as a *Cryptosporidium* surrogate. *B. subtilis* spores were obtained from Raven Laboratories (Omaha, Nebraska). Grab samples for *B. subtilis* were analyzed in accordance with methods described by Rice *et al.* (1994) using heat shock and standard membrane filtration.

For total and fecal coliform tests, the system was challenged with mixed liquor suspended solids (MLSS) collected from the aeration basin of the Metropolitan Sewer District (MSD) wastewater treatment plant located adjacent to the U.S. EPA T&E Facility. The concentrations of total and fecal coliform of the MLSS were ~1.0×10^{6}/mL and ~ 5.0×10^{4}/mL, respectively.

Grab samples for the total and fecal coliform were analyzed using Standard Methods 9222B and 9222C, respectively (APHA, AWWA and WEF, 2005).

To provide indirect and secondary measures of microbial removal, the removal of heterotrophic bacteria was monitored during turbidity challenges. Grab samples (100 mL) for HPC from the influent and effluent streams were collected twice during each experiment and analyzed using the IDEXX SimPlate method (IDEXX, 2002).

To evaluate the performance of the DF/DSF in removing *Cryptosporidium*, the system was challenged with PSL beads having a mean size of 2.83 µm. PSL bead stock was obtained from Polysciences Inc. (Warrington, PA). Grab samples (1 L) were centrifuged directly without filtration and analyzed using a hemacytometer following U.S. EPA Method 1622 (U.S. EPA, 2001). As the influent bead concentrations were reasonably high, the samples were centrifuged directly. Although the effluent beads concentrations were low, the grab samples were centrifuged to keep the method consistent with that used for influent samples. A 1 µm membrane filter was tested for collection of beads from the effluent as an alternative sampling method. However, the effluent pressure was not adequate to flow through the membrane.

To provide an indirect and secondary measure of protozoa removal, the removal of particles in the size range of 2-5 µm (that encompasses the size of *Cryptosporidium parvum*) was also determined during the turbidity challenges. Grab samples (100 mL) for particle counts from the influent and effluent streams were collected twice during each experiment and analyzed using a HIAC Royco (Model 9703) Particle Analyzer. The particle count data in the size range of 2 – 5 µm for the influent and effluent were compared.

For *B. subtilis*, *E. coli* and PSL beads, 2 mL of stock suspension with an approximate concentration of 10^9 cells or surrogates per mL was mixed with 1000 mL of 0.01% Tween 20 in a 2-L glass beaker. A sub-sample was collected to determine the actual concentration of the injection suspension. For total and fecal coliform, 1000 mL MLSS from the adjacent MSD wastewater treatment plant was used as the stock suspension. The 1000 mL MLSS suspension and the rinseate (1000 mL DI water) were added into the influent stream of the system using a peristaltic pump. The total injection time was approximately 120 minutes; the sand filter was operated for an additional 60 minutes to observe the presence of contaminant after stopping the injection. Samples from the influent stream were collected at 0, 5, 15, 30 and 60 minutes after the start of the injection. Initially, effluent samples were collected at the same sampling events as the influent samples and maximum effluent concentrations were observed at 60 minutes and remained consistent until 180 minutes. This led to the assumption of a lag time of 60 minutes between the influent and effluent, and effluent samples were collected at 60, 90, 120 and 180 minutes after the start of the injection for the subsequent experiments. The volume of grab samples for *B. subtilis* and *E. coli* was 100 mL and that for PSL beads was 1000 mL. The total and free chlorine concentrations of the effluent samples were determined using a HACH Spectrophotometer (Model 2400).

2.2.3 Data Analysis

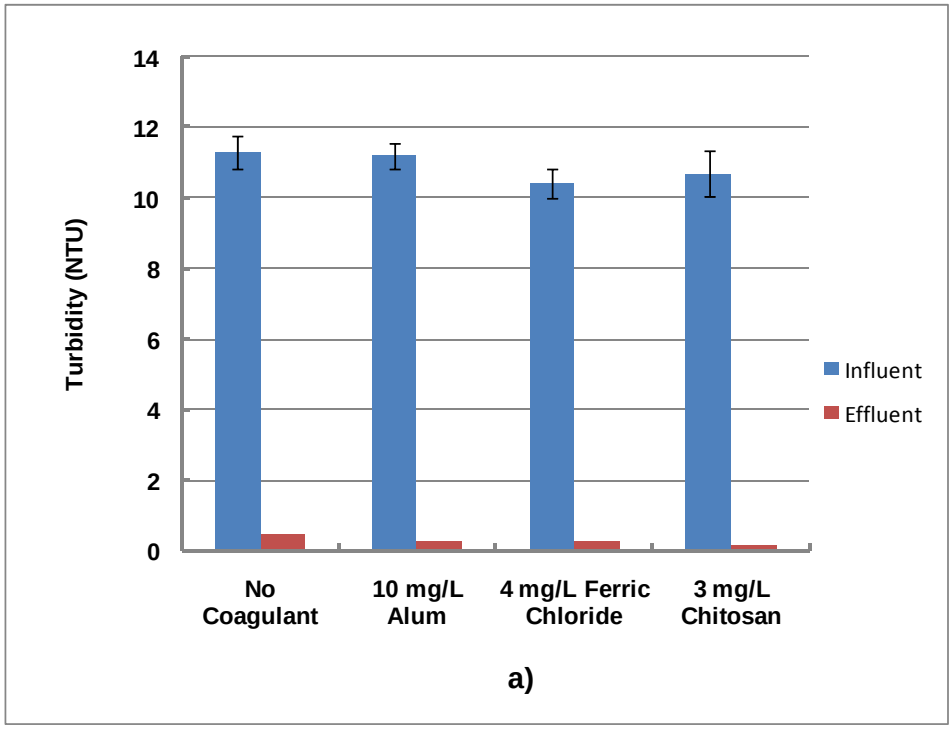
The average influent and effluent concentrations and percent/log removal of contaminants are presented graphically with standard error. Student's t-tests were conducted to compare the significance of the difference in performance of the sand filter at different coagulant conditions. Log removal values for challenge contaminants are presented as DSF log removal value (LRV) which is the removal by the DSF only, and total LRV which represents combined removal by the DSF and chlorination.

3.0 RESULTS AND DISCUSSION

3.1 Estimation of Turbidity Removal Performance of the DF-DSF System

3.1.1 Turbidity Challenges

Figure 5 shows the influent and effluent turbidity and percent removals of turbidity under different coagulant conditions. The influent and effluent data for turbidity represent the average of six grab samples collected during two turbidity challenges at each coagulant condition. For approximately similar influent turbidity (10.3 – 11.4 NTU), the average effluent turbidity was 0.45 NTU, 0.25 NTU, 0.25 NTU and 0.14 NTU for tests conducted with no coagulant, 10 mg/L alum, 4 mg/L ferric chloride and 3 mg/L chitosan, respectively. Statistical analysis indicates significant improvement of effluent quality due to the use of 10 mg/L alum (p value 0.0003), 4 mg/L ferric chloride (p value 0.0007) and 3 mg/L chitosan (p value 0.00008) as chemical coagulants. The use of 3 mg/L chitosan produced effluent with significantly lower turbidity than 10 mg/L alum (p value 0.00005) and ferric chloride (p value 0.0009). No statistically significant differences in removal performance were observed between 10 mg/L alum and 4 mg/L ferric chloride (p value 0.18).



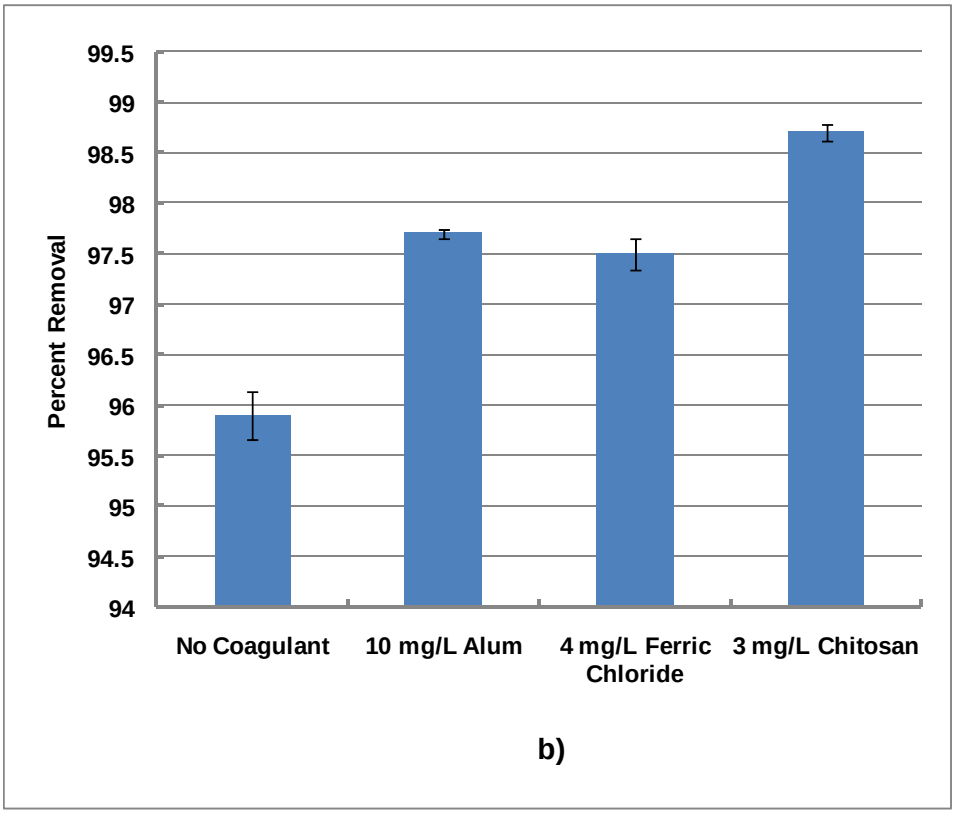


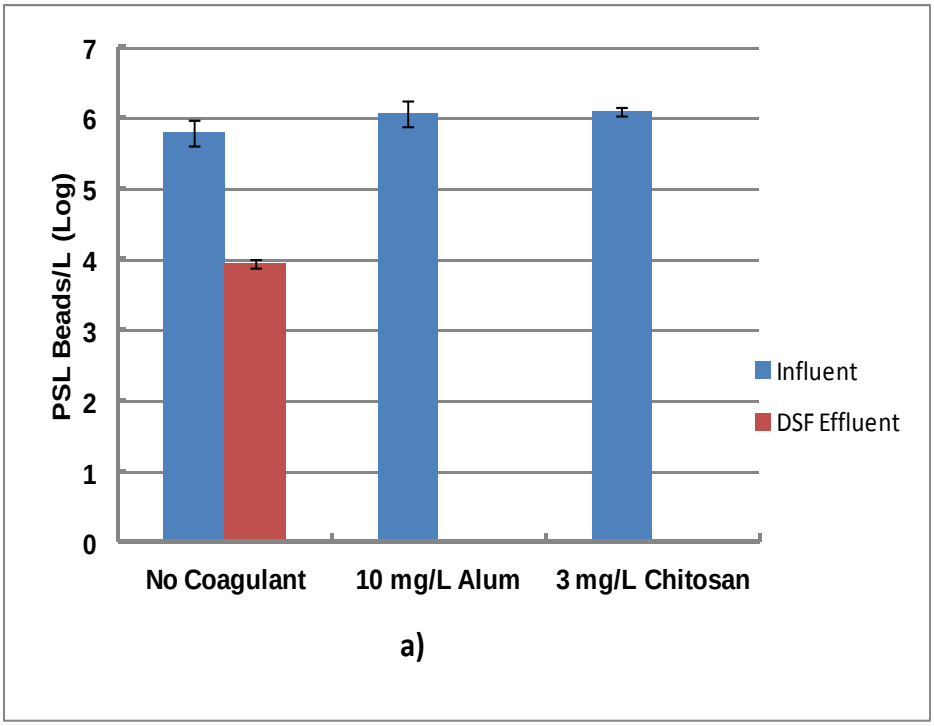
Figure 5 - a) Influent and Effluent Turbidity; b) Percent Removal of Turbidity at Different Coagulant Conditions

The effluent quality produced due to the addition of alum, ferric chloride and chitosan satisfied the Long Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) requirement of <0.30 NTU effluent turbidity (U.S. EPA, 2006). Chitosan was found to be very effective in reducing turbidity. This concurs with the findings reported in another study (Brown and Emelko, 2009).

3.2 Estimation of Cryptosporidium Removal Performance of the DF-DSF System Using Surrogates

3.2.1 PSL Beads Challenges

PSL beads (2.83 µm) were used as a surrogate for removal of *Cryptosporidium*. The LT2ESWTR dictates that a surrogate must have an effective size of 3 µm or smaller to demonstrate *Cryptosporidium* removal. Figure 6 shows the influent and effluent concentrations and LRVs of PSL beads at different coagulant conditions. The influent and effluent data represent the average of six grab samples collected during two PSL beads challenges at each coagulant condition. The sand filter performed effectively in removing 2.83 µm PSL beads with an average LRV of 1.85 that is close to the LT1ESWTR requirement (2.0 log) for *Cryptosporidium* removal (U.S. EPA, 2002). The average LRVs achieved by the DSF based on influent beads concentrations were >6.06 and >6.10 during challenges with 10 mg/L alum and 3 mg/L chitosan, respectively, that satisfied the LT2ESWTR requirement (> 5.5 log) for *Cryptosporidium* removal at the highest category of Bin 4 (U.S. EPA, 2006). The improvement in removal performance was statistically significant due to the addition of 10 mg/L alum (p value 0.000005) and 3 mg/L chitosan (p value 0.000002). No statistically significant difference in removal performance was observed between 10 mg/L alum and 3 mg/L chitosan (p value 0.47). The overall performance of the DF-DSF system in removing *Cryptosporidium* is either similar or superior to that of the conventional slow sand filter reported in another study (Bellamy *et al*., 1985).



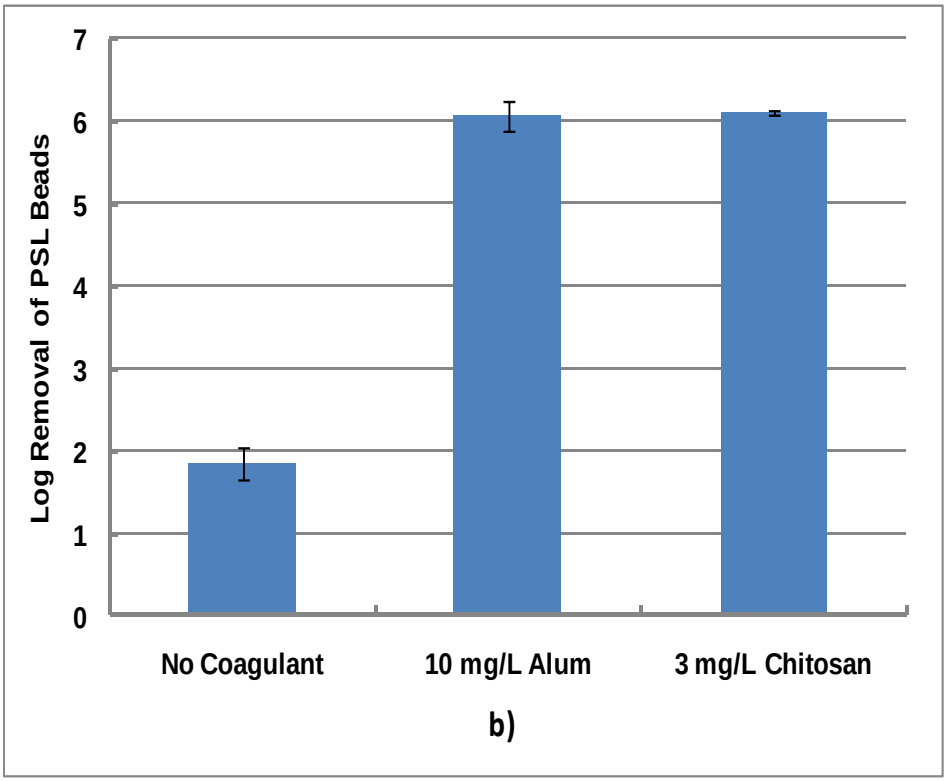


Figure 6 - a) Influent and Effluent Concentrations of PSL Beads; b) Log Removal of PSL Beads at Different Coagulant Conditions

3.2.2 *Particle Removal*

The particle count data were evaluated to obtain secondary information on the performance of the DSF. The influent particle counts were measured as available in matrix water. Figure 7 shows the percent removal of 2-5 µm size particles that mimic the size of *Cryptosporidium* oocysts, at different coagulant conditions. The data represent the average of four grab samples collected during two turbidity challenges at each coagulant condition. The sand filter achieved an overall 74.2% particle (2-5 µm) removal performance. Percent removal of particle counts increased significantly due to the addition of 10 mg/L alum (92.9%; p value 0.013), 4 mg/L ferric chloride (94.9%; p value 0.014) and 3 mg/L chitosan (96.5%; p value 0.006).

The removal of natural particles (2-5 µm) is noticeably lower than that for PSL beads indicating Cryptosporidium size natural particles to be a conservative surrogate for *Cryptosporidium* removal. This concurs with the findings of another study (Emelko *et al.,* 2005).

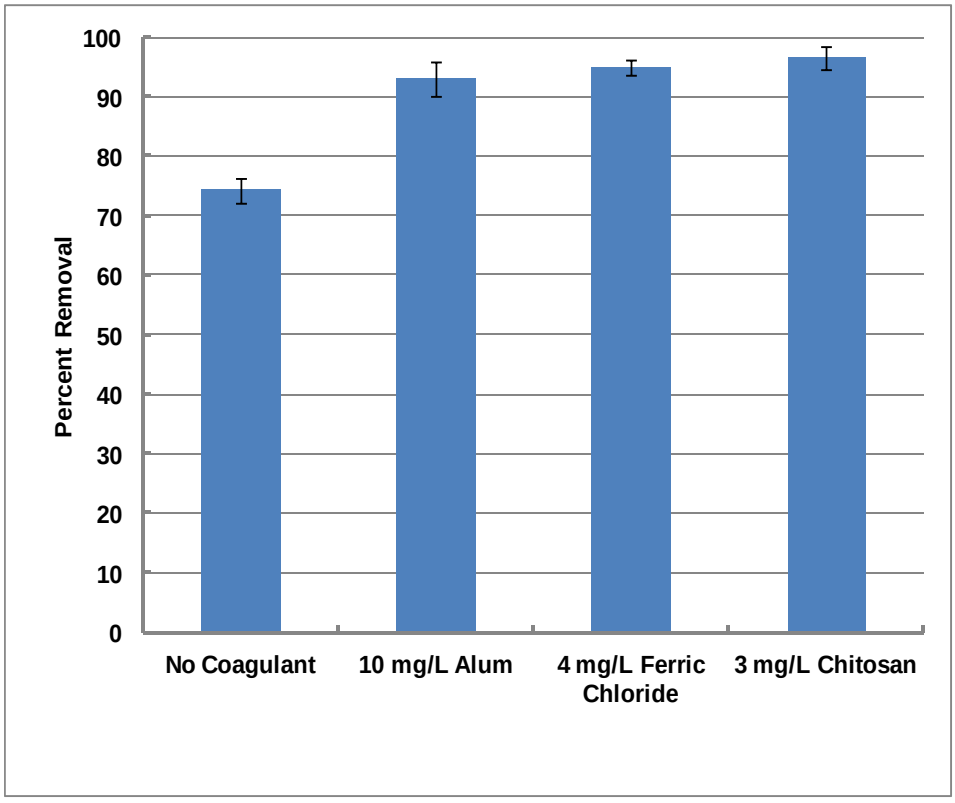


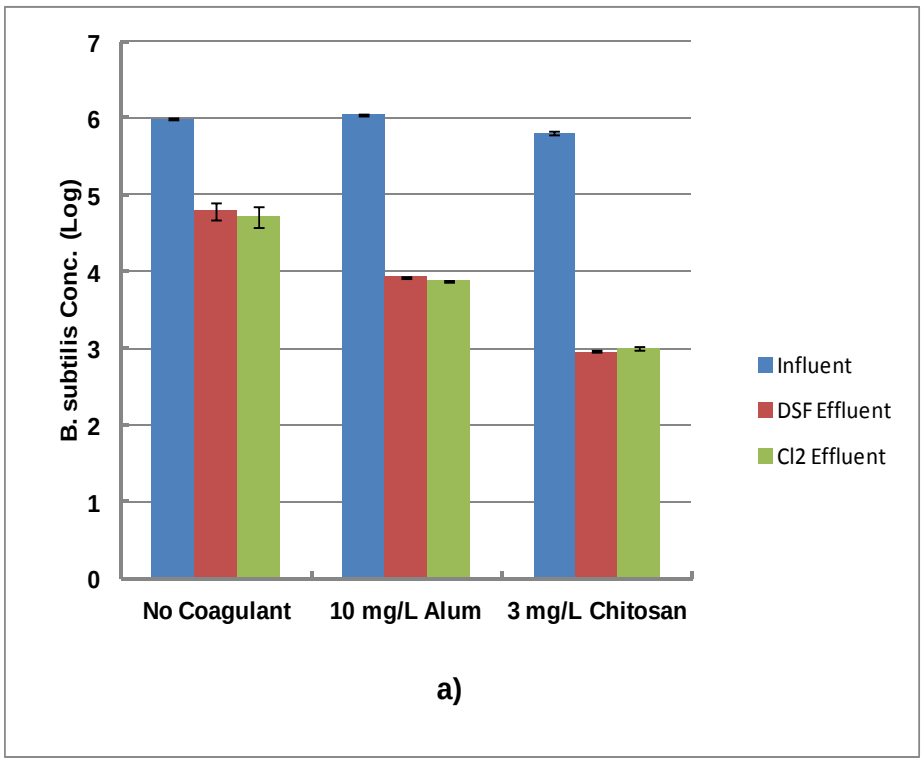
Figure 7 - Percent Removal of Particles at Different Coagulant Conditions

3.2.3 *B. subtilis Challenges*

Figure 8 shows the influent and effluent concentrations and LRVs of *B. subtilis* at different coagulant conditions. The influent and effluent data represent the average of four grab samples collected during the single *B. subtilis* challenge at each coagulant condition. Results showed that the performance of the sand filter was not adequate in removing *B. subtilis*; the LRV achieved was 1.19. Addition of 10 mg/L alum enhanced the performance of the sand filter significantly (p value 0.002); the LRV increased to 2.12. Significant improvement of the removal

performance was also observed due to addition of 3 mg/L chitosan (p value 0.008); the average LRV achieved was 2.85. The 3 mg/L chitosan was observed to be more effective than the 10 mg/L alum (p value 0.0002) in enhancing the removal performance. The free residual chlorine concentrations during the *B. subtilis* challenges varied between 0.6 and 2.0 mg/L. Post-chlorination was observed to be ineffective at inactivating *B. subtilis*. As sodium thiosulfate tablets were added to the sample bottles during sampling, no additional contact time was available for disinfection of the spores.

The LRVs for *B. subtilis* by the sand filter were noticeably lower than that for PSL beads indicating *B. subtilis* to be a conservative surrogate for *Cryptosporidium*. This concurs with the findings of another study (Muhammad *et al*., 2008) conducted on different drinking water treatment systems. The overall performance of the DF-DSF system in removing bacterial spores is superior to that of the conventional slow sand filter reported in another study (Heller *et al*., 2007).



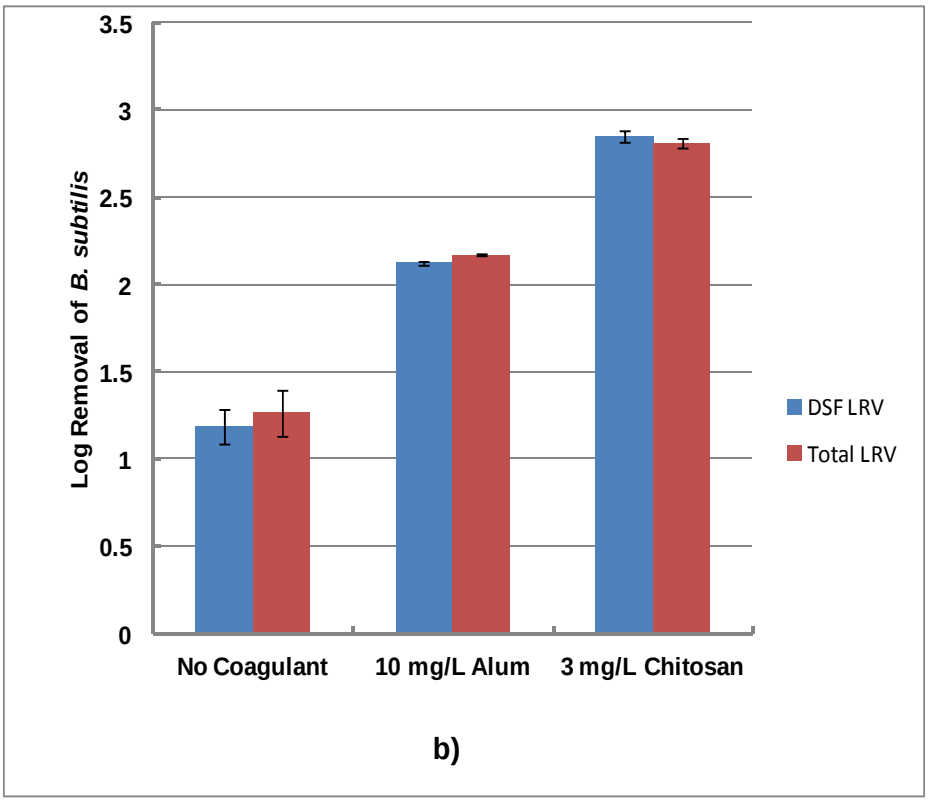


Figure 8 - a) Influent and Effluent Concentrations of *B. subtilis*; b) Log Removal of *B. subtilis* at Different Coagulant Conditions

3.3 Estimation of Bacteria Removal Performance of the DF-DSF System

3.3.1 HPC Removal

The HPC data were evaluated to obtain secondary information on the performance of the DSF in removing bacteria. The influent HPC concentrations were measured as available in matrix water. Figure 9 shows the removal of HPC at different coagulant conditions. The data represent the average of four grab samples collected during two turbidity challenges at each coagulant condition. The performance of the sand filter was not adequate in removing HPC; the LRV achieved was 0.13. Removal of HPC increased significantly due to the addition of 10 mg/L alum (0.705 log; p value 0.04) and 4 mg/L ferric chloride (1.25 log; p value 0.0007). No significant improvement of HPC removal was observed with the addition of 3 mg/L chitosan (0.87 log; p value 0.05). Post-chlorination was very effective in removing heterotrophic bacteria. The average free chlorine concentrations (HOCl) for turbidity challenges conducted with no coagulant, 10 mg/L alum, 4 mg/L ferric chloride and 3 mg/L chitosan were 5.15 mg/L, 2.50 mg/L, 2.15 mg/L and 0.98 mg/L, respectively. The overall LRVs during turbidity challenges at 3 mg/L chitosan were low due to relatively lower residual chlorine concentrations. The residual chlorine varied among different tests due to age of the tablet, contact surface and accumulation of tablet residue in the chlorinator effluent tube. The overall performance of the DF-DSF system in removing heterotrophic bacteria is similar to that of the conventional slow sand filter reported in another study (Palmateer *et al*., 1999).

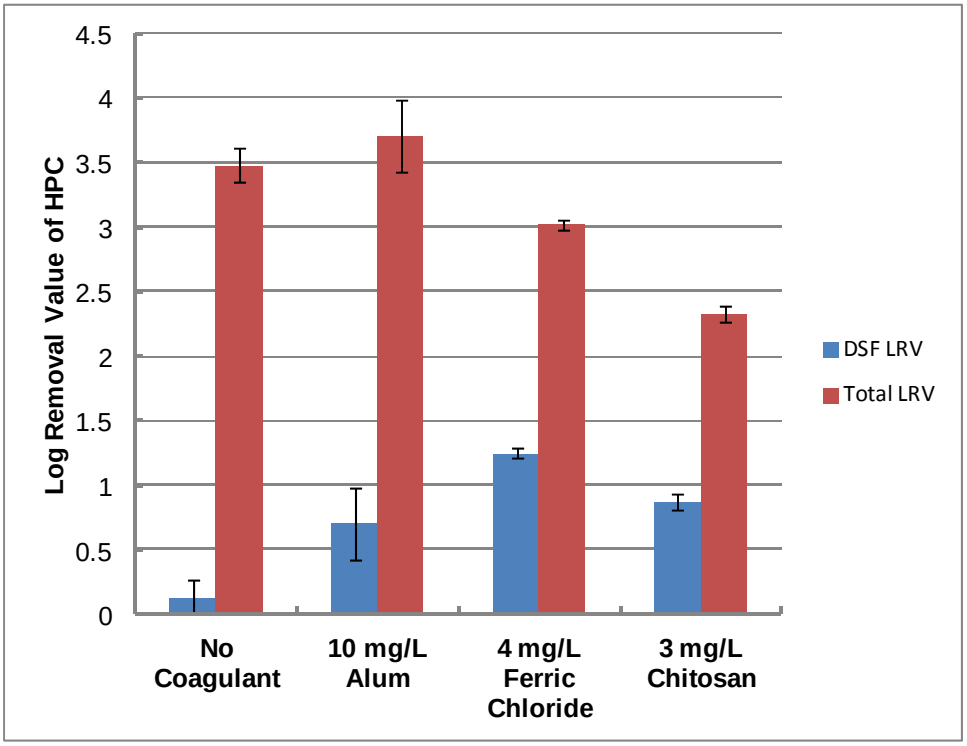


Figure 9 - Removal of HPC at Different Coagulant Conditions

3.3.2 E. coli Challenges

Figure 10 shows the influent and effluent concentrations and LRVs of *E. coli* at different coagulant conditions. The influent and effluent data represent the average of eight grab samples collected during two challenges at each condition. Results showed that the performance of the sand filter was moderate in removing *E. coli*; the LRV achieved was 2.4. Addition of 10 mg/L alum enhanced the performance of the sand filter significantly (p value 0.0002); the LRV increased to 3.70. No significant improvement in removal of *E. coli* was observed due to the addition of 3 mg/L chitosan (p value 0.29); the average LRV achieved was 2.6. Backwashing followed by prolonged flushing of the sand filter between the *E. coli* challenges conducted with 3.0 mg/L chitosan did not result in noticeable improvement of performance. The sand filter was re-packed for the total and fecal coliform challenges.

The free residual chlorine concentrations during the *E. coli* challenges varied between 0.5 and 1.9 mg/L. Nearly complete inactivation of *E. coli* was achieved by post-chlorination despite the addition of sodium thiosulfate tablets in the samples.

The performance of the DF-DSF system in removing *E. coli* is similar to that of conventional slow sand filter reported in another study (Ellis, 1985); however, the overall performance of the system including chlorine disinfection is noticeably superior than the conventional slow sand filter.

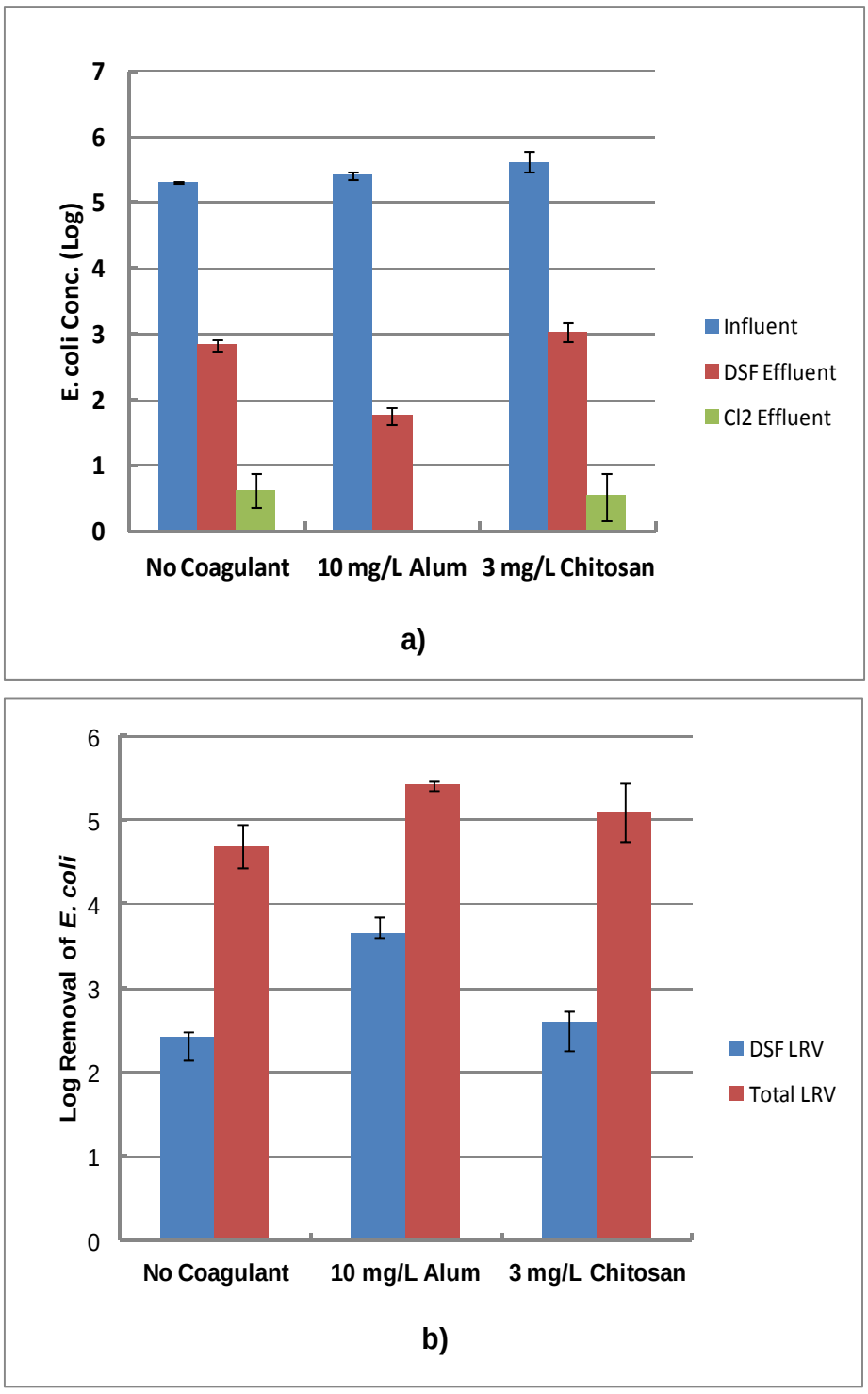
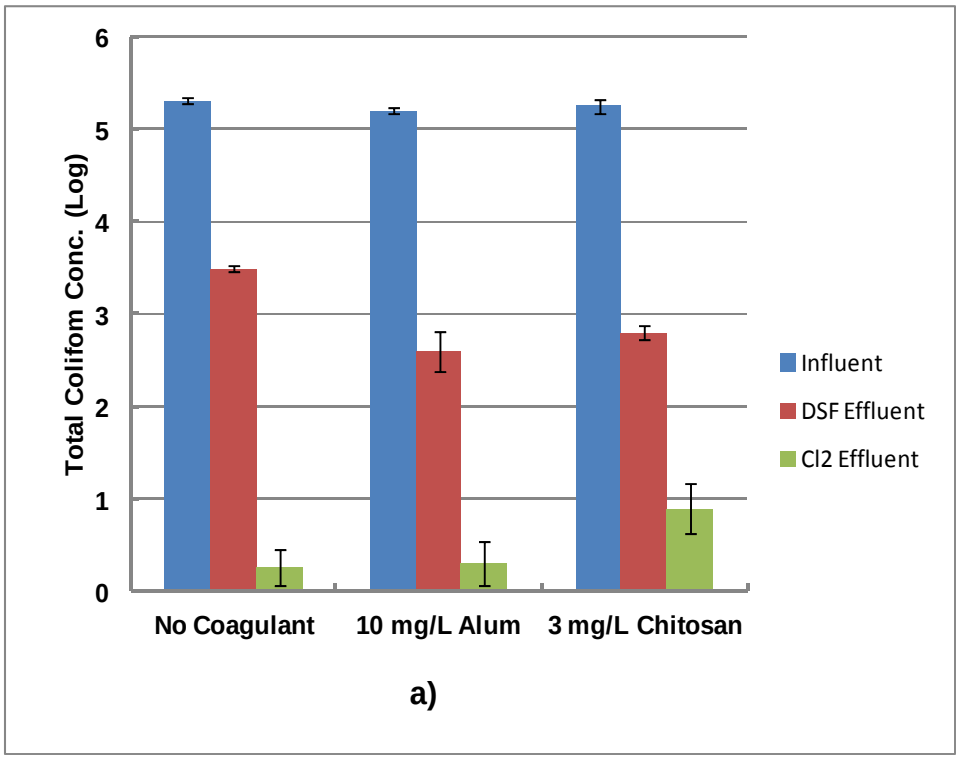


Figure 10 - a) Influent and Effluent Concentrations of *E. coli*; b) Log Removal of *E. coli* at Different Coagulant Conditions

3.3.3 Total and Fecal Coliform Challenges

Figure 11 shows the influent and effluent concentrations and log removals of total coliform at different coagulant conditions. Figure 12 shows the influent and effluent concentrations and log removals of fecal coliform at different coagulant conditions. The influent and effluent data represent the average of eight grab samples collected during two challenges at each condition. Results show that the performance of the sand filter was moderate in removing total coliform and fecal coliform; the LRV for total coliform and fecal coliform were 1.80 and 1.45, respectively. Addition of 10 mg/L alum enhanced the performance of the sand filter significantly in removing total coliform ((p value 0.004) and fecal coliform (0.005); the LRV of total coliform increased to 2.60 and that for fecal coliform increased to 2.75. Addition of 3 mg/L chitosan improved the performance of the sand filter significantly in removing total coliform (p value 0.003) and fecal coliform (p value 0.02); the average LRV for total coliform increased to 2.45 and that for fecal coliform increased to 2.62. No significant differences were observed between alum and chitosan at the selected doses in removing total coliform (p value 0.12) and fecal coliform (p value 0.30).

The free residual chlorine concentrations during the total and fecal coliform challenges varied between 0.5 and 1.9 mg/L. Nearly complete inactivation of total and fecal coliform was achieved by post-chlorination despite the addition of sodium thiosulfate tablets in the samples. The performance of the DF-DSF system in removing total and fecal coliform is similar to that of the conventional slow sand filter reported in several other studies (Muhammad *et al*., 1996; Eiilis, 1985); however, the overall performance of the system including chlorine disinfection is noticeably superior than the conventional slow sand filter.



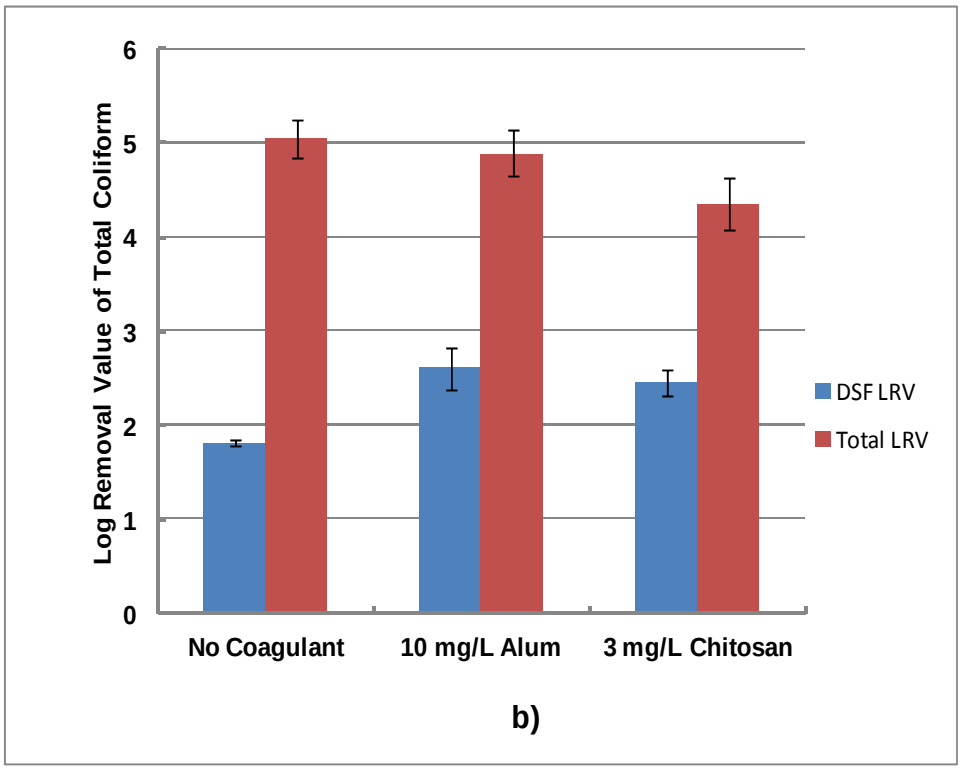
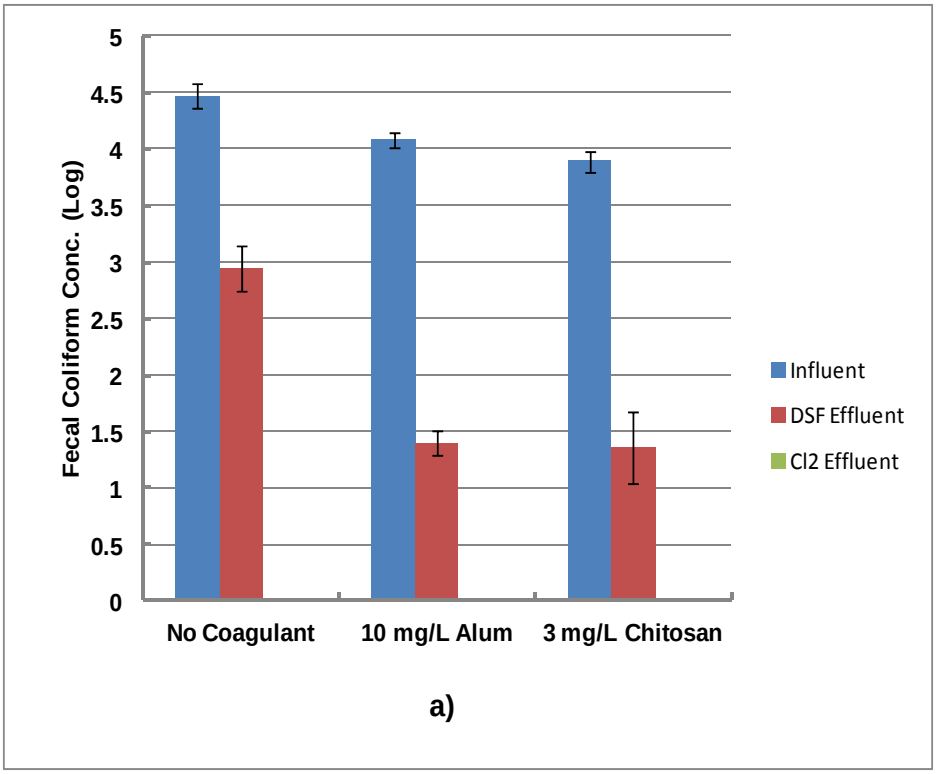


Figure 11 - a) Influent and Effluent Concentrations of Total Coliform; b) Log Removal of Total Coliform at Different Coagulant Conditions



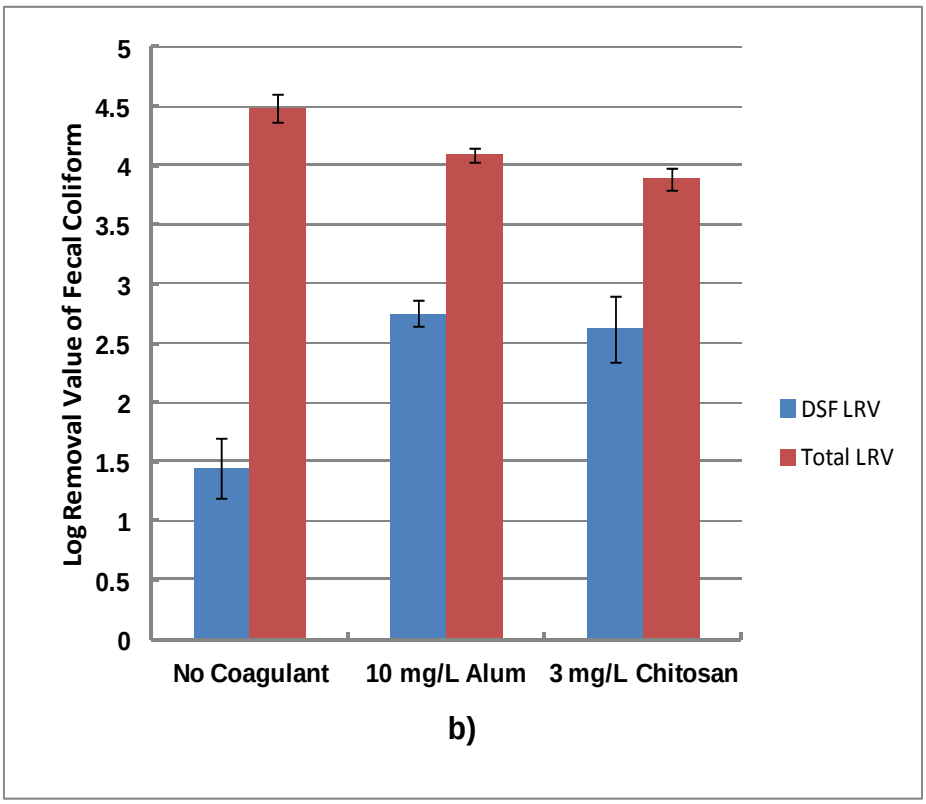


Figure 12 - a) Influent and Effluent Concentrations of Fecal Coliform; b) Log Removal of Fecal Coliform at Different Coagulant Conditions

3.4 Maintenance of the DSF

The treatment mechanism of the DSF is not biological in nature; the performance of the system was noticeably enhanced by the addition of coagulant in this study. Therefore, it is necessary to maintain the correct dose and proper mixing of coagulant during the operation of the system.

It is necessary to check the raw and finished water turbidity daily. If the raw water turbidity is >10 NTU, a pre-treatment unit is recommended to be incorporated before the DF-DSF system to avoid rapid clogging and frequent cleaning of the filter. If the finished water turbidity is >1 NTU, a full inspection of the system that include checking the flow rate, feed water turbidity, coagulant dose and short-circuiting or channeling of the sand bed is necessary.

Backwashing of the DSF is necessary when the flow rate declines due to clogging of the sand and the desired flow is no longer achieved. Although the flow rate did not decline during the operation of the unit in this study, backwashing was conducted after the completion of a specific contaminant challenge test to create clean conditions for the next contaminant challenge tests. Backwashing of the unit was conducted using clean water at a flow rate of 1 gpm for 30 minutes. Backwashing and flushing was conducted on the DSF to create clean conditions for challenge tests. Backwashing flow rate is recommended to keep to a minimum to avoid vigorous fluidization and loss of fine sand. After the completion of each challenge test, the DSF is recommended to be flushed using at least 3 bed volumes of water to maintain a stable sand bed condition.

Maintaining a uniform flow rate is very important to ensure better performance of the DSF. Sudden increase of flow rate may create short-circuiting resulting in a poor filtrate quality. It will also impact the generation of free chlorine in the tablet chlorinator.

As the concentration of residual chlorine generated using the tablet chlorinator depends on a number of factors including contact surface, flow rate and age of the tablet, it is recommended that the residual chlorine be checked at least twice a day. It is also recommended to check the accumulation of tablet residue in the outlet tube as it may cause high residual chlorine concentration.

4.0 CONCLUSIONS

Based on the results of turbidity challenges, the sand filter with the current configuration was effective in removing turbidity; for an influent turbidity of ~ 10.0 NTU, the effluent turbidity was consistently below 0.5 NTU without chemical coagulant. Significant improvement of effluent quality was observed due to use of chemical coagulants; the effluent turbidity was consistently below 0.3 NTU that satisfied the LT2ESWTR requirement (< 0.3 NTU) for turbidity removal.

The sand filter performed effectively in removing 2.83 µm PSL beads with an average LRV of 1.85 that was close to the LT1ESWTR requirement (2.0 log) of *Cryptosporidium* removal. The

system achieved >6.0 log removal of 2.83 µm PSL beads during challenges with chemical coagulants that satisfied the LT2ESWTR requirement (> 5.5 log) for *Cryptosporidium* removal at the highest category of Bin 4 for the DSF. The sand filter was found to be effective in removing *Cryptosporidium* size natural particles (2-5 µm), and the addition of chemical coagulants enhanced the performance significantly. The performance of the sand filter alone was not adequate (1.19 log removal) in removing *B. subtilis*. However, the addition of 10 mg/L alum (2.12 log removal) and 3 mg/L chitosan (2.85 log removal) enhanced the performance of the system significantly. The LRVs for *B. subtilis* and particle counts (2 – 5 µm) by the sand filter were noticeably lower than those for PSL beads indicating that the potential of *B. subtilis* and particle counts may be too conservative for consideration as a surrogate for *Cryptosporidium* in comparison with the PSL beads.

The performance of the sand filter was not adequate in removing heterotrophic bacteria without chemical coagulant; significant improvement was observed due to the addition of chemical coagulants. The system demonstrated moderate performance in removing *E. coli* (2.40 log), total coliform (1.80 log) and fecal coliform (1.45 log) without chemical coagulant. Significant improvements in the removal of *E. coli* were observed due to the addition of 10 mg/L alum (3.70 log) in feed water. No significant improvement was observed with the addition of 3 mg/L chitosan (2.60 log). Addition of 10 mg/L alum enhanced the performance of the sand filter significantly in removing total and fecal coliform; the LRV for total coliform (1.80 log) increased to 2.60 and that for fecal coliform (1.45 log) increased to 2.75. Addition of 3 mg/L chitosan improved the performance of the sand filter significantly in removing total and fecal coliform; the LRV for total coliform (1.80 log) increased to 2.45 and that for fecal coliform (1.45 log) increased to 2.62.

Post-chlorination was very effective in inactivating heterotrophic bacteria, *E. coli,* fecal coliform and total coliform; nearly complete inactivation of the microorganisms was achieved at 0.9 mg/L – 1.9 mg/L free chlorine with a low contact time. Post-chlorination was not effective in inactivating *B. subtilis* spores at concentrations of 1.0 – 2.0 mg/L, as the sampling strategy with sodium thiosulfate tablet in the bottle provided minimum contact time.

The performance of the DSF in combination with the selected coagulants and tablet disinfection process was excellent in removing turbidity and the selected microorganisms/surrogates, except *B. subtilis* spores. The system was easy to operate with no power and negligible chemical requirements. Based on the performance, ease of operation, and cost, the DF-DSF appeared to demonstrate good potential for drinking water treatment in very small communities (serving less than 100 people) and for emergency situations.

5.0 REFERENCES

APHA, AWWA and WEF (2005) 'Standard Methods for the Examination of Water and Wastewater', 21st Ed., APHA, AWWA & WEF Publication, Washington D.C., U.S.A.

Bellemy, W.D., Hendricks, D.W. and Longsdon, G.S. (1985) 'Slow sand filtration: Influences of selected process variables', *J. AWWA*, **77**(12), 62-66.

Brown, J.T. and Emelko, B.M. (2009) 'Chitosan and metal salt coagulant impacts on Cryptosporidium and microsphere removal by filtration'. *Wat. Res*., **43**, 331-338.

Ellis, K.V. (1985) 'Slow Sand Filtration', *CRC Crit. Rev. in Environ. Controls,* **15**(4), 315-354.

Emelko, M. B., Huck, P. M. and Coffey, B. M. (2005) 'A Review of *Cryptosporidium* Removal by Granular Media Filtration', *Jour. AWWA,* **97**(12), 101-115.

Heller, L., Viera, M. B. C. M., Brito, L. L. A. and Salvador, D. P. (2007) 'Association between the Concentration of Protozoa and Surrogates in Effluents of the Slow Sand Filtration for Water Treatment', *Brazilian Jour. of Microbiol.*, **38**, 337-345.

IDEXX (2003) 'Instruction Manual for Colilert-18 for *E. coli* Analysis', Maine, U.S.A.

IDEXX (2002) 'Instruction Manual for SimPlate for HPC Multi Dose', Maine, U.S.A.

Muhammad, N., Sinha, R., Krishnan, R., Piao, H., Patterson, C. L., Cotruvo, J., Cumberland, S. L., Nero, V. P. and Delandra, C. (2008) 'Evaluating Surrogates for *Cryptosporidium* Removal in Point of Use System', *Jour. AWWA*, **100**(12), 98 – 104.

Muhammad, N., Ellis, K.V., Parr, J. and Smith, M, D. (1996) 'Optimization of slow sand filtration. In *Reaching the Unreached: Challenges for the 21st Century', Proceeding of the 22nd WEDC conference*. New Delhi, India.

Palmateer, G., Manz, D., Jurkovic, A., McInnis, R., Unger, S., Kwan, K. K. and Dutka, B. J. (1995) 'Toxicant and Parasite Challenge of Manz Intermittent Slow Sand Filter', *Environ. Toxicol*., **14,** 217-225.

Peter-Varbanets, M., Zurbrugg, C. Swartz, C. and Pronk, W. (2009) 'Decentralized Systems for Potable Water and Potential of Membrane Technology', *Wat. Res.*, **43**, 245-265.

Rice, E. W., Fox, K. R., Miltner, R. J., Lytle, D. A. and Johnson, J. H. (1994) 'A Microbiological Surrogate for Evaluating Treatment Efficiency', In *Proc. AWWA Water Quality Technology Conference*. San Francisco, California, U.S.A

Schultz, C. and Okun, D. (1984) 'Surface Water Treatment for Communities in Developing Countries', Willey Publications, New York, U.S.A.

U.S. EPA (2006) 'The Long-Term 2 Enhanced Surface Water Treatment Rule (LT2ESWTR) Implementation Guidance', EPA-816-F-06-019, Washington, D.C.

U.S. EPA (2003) 'Small Systems Guide to Safe Drinking Water Act Regulations', EPA 816-R-03-016, Washington D.C., U.S.A.

U.S. EPA (2002) 'The Long-Term 1 Enhanced Surface Water Treatment Rule (LT1ESWTR) Implementation Guidance', EPA-816-R-04-008, Washington, D.C.

U.S. EPA (2001) 'Method 1622: *Cryptosporidium* in Water by Filtration/IMS/FA', Washington, DC, U.S.A.