STAFF SUMMARY SHEET

	TO	ACTION	SIGNATURE (*Surname*), GRADE AND DATE		TO	ACTION	SIGNATURE (*Surname*), GRADE AND DATE
1	DFCE	coord	CIV DFCE	6			
2	DFER	approve	Torres, Col 14May13	7			
3	DFCE	action		8			
4				9			
5				10			

SURNAME OF ACTION OFFICER AND GRADE	SYMBOL	PHONE	TYPIST'S INITIALS	SUSPENSE DATE
Frank, O-4	DFCE	333-9118	tef	20130524

SUBJECT
Clearance for Material for Public Release USAFA-DF-PA- 344

DATE
20130510

SUMMARY

1. PURPOSE. To provide security and policy review on the document at Tab 1 prior to release to the public.

2. BACKGROUND.
Authors: Maj Timothy Frank (DFCE), C1C Matthew Scheie, C1C Victoria Cachro, C2C Andrew Munoz

Title: The effect of increasing grain size in biosand water filters in combination with ultraviolet disinfection

Circle one: Abstract Tech Report [✓ Journal Article] Speech Paper Presentation Poster
Thesis/Dissertation Book Other: ________________

Check all that apply (For Communications Purposes):

☐ CRADA (Cooperative Research and Development Agreement) exists

☐ Photo/ Video Opportunities ☐ STEM-outreach Related ☐ New Invention/ Discovery/ Patent

Description: The author experimented with biosand water filtration and UV disinfection to purify water to international drinking water standards.

Release Information: Maj Frank, et al. will submit this for possible publication in "Environmental Science and Technology" or similar.

Previous Clearance information: N/A

Recommended Distribution Statement: Distribution A: approved for public release, distribution unlimited

3. DISCUSSION. This paper represents work done during CE 499 fall 2012/spring 2013 by the three cadet authors with Maj Frank as the faculty advisor.

4. RECOMMENDATION. DFCE and DFER approve for public release.

TIMOTHY E. FRANK, Maj, USAF
Assistant Professor of Civil & Environmental Engineering

The effect of increasing grain size in biosand water filters in combination with ultraviolet disinfection

Timothy Frank[1], **Matthew Scheie**[1], **Victoria Cachro**[1], **Andrew Munoz**[1]

12354 Fairchild Drive, Suite 6J-117, United States Air Force Academy, Colorado, 80840 USA

E-mail: tefrank18@gmail.com

Abstract

We examined how sand grain size effects biological sand filtration and how the combination of biological sand filtration and ultraviolet (UV) disinfection effects water quality. Two biosand water filters were built: a control filter (d10 = 0.19, UC = 2.1) with maximum grain size of 0.70 mm in accordance with the Center for Affordable Water Technology (CAWST) guidance and an experimental filter (d10 = 0.80, UC = 1.5) with grain sizes ranging from 0.70mm to 2.0mm. Untreated water was manufactured and passed through each biosand water filter (BSF); the effluent was placed in clear polyethylene terephthalate bottles under longwave monochromatic UV light (365 nm) for disinfection. Water quality indicators of escherichia coli (e. coli) and turbidity were measured at three stages: untreated water, BSF effluent, and post-UV disinfection. Results show e. coli and turbidity removal characteristics of the control and experimental BSFs were not significantly different from one another. Although e. coli reduction was over 98% for each BSF, the high initial bacteria population resulted in effluent levels above World Health Organization drinking water guidelines. UV disinfection further reduced e. coli from both BSF's effluent to levels that met those guidelines. Additionally, both BSFs produced water that met turbidity guidelines. The data indicate existing grain size guidelines used in BSF construction may be relaxed without compromising water quality.

Keywords: biosand water filter, disinfection, grain size, water quality, developing country

1. Introduction

This study investigated low cost, sustainable means of purifying drinking water for use in developing countries. Over one billion people in developing countries do not have access to clean drinking water [1]. Further, the United Nations Children's Fund estimates 1.2 million children under the age of five die from diarrhea caused by waterborne pathogens each year [2]. In rural areas of developing countries or where municipal drinking water delivery systems are nonexistent, in poor repair, or unreliable, point-of-use water treatment methods can be an effective means of improving drinking water quality. When clean drinking water is available in developing countries, access typically involves long wait times and high cost [2]; both issues that point-of-use systems may be able to address.

1.1. Biosand Water Filtration

The point-of-use biosand water filter (BSF) technology has been in existence for over 20 years and the Center for Affordable Water Sanitation Technology (CAWST) at the University of Calgary, Canada is an international champion for the technology. Previous laboratory and field studies have observed BSF effluent with e. coli and other bacteria removal rates greater than 90%, sometimes over 99% [3-8]. Additionally, studies have shown an even wider range of turbidity reduction, from almost none to 98% [6-8]. The CAWST BSF version 10 manual recommends using sand grains of 0.70 mm or less [9], but in personal communication with aid agencies experienced in manufacturing BSFs in developing countries, sand particles this small can be difficult to locate or isolate. Manufactured sieves with 0.70 mm openings are not universally available worldwide, and often times need to be imported or improvised. Window screens and mosquito nets have larger openings, but are more common in developing countries. Larger sand grains that might be isolated using these improvised methods, however, are unproven for BSF use.

Previous research has been done on sand grain size and its effects on the performance of BSFs and other slow sand filters. Jenkins, et al. explored the effect of two different effective sand sizes (0.17 mm and 0.52 mm) on the removal of fecal coliform and the MS2 virus in addition to turbidity reduction over a ten week period [4]. The smaller grained BSFs had a reduced flow rate which increased the sand's ability to mechanically trap particles. They concluded that sand grain size is a critical factor in the performance of BSFs and data indicated that the smaller grained BSFs significantly or near significantly improved bacteria removal from water when compared to the larger grained BSFs. Further, the smaller grained BSFs outperformed the larger grained BSFs in turbidity reduction. In a separate study, Bellamy, et al. studied the effects of sand size among other variables on total coliform removal in slow sand filters [10]. Experimental data concluded variation in either direction of an optimal effective sand size can reduce the effectiveness in removing bacteria. Based on a near-linear model they created, they optimized the effective size for the sand media to 0.28 mm, which was predicted to remove over 99.9% of total coliforms.

To the contrary, one study determined larger sand particles (0.30 to 1.8mm) removed more bacteria and bacterial spores than smaller sand particles (0.13 to 0.37mm) [11]. While a noteworthy result, this study was conducted on large scale slow sand filters, not point-of-use BSFs. More importantly, the author acknowledges the difference in effectiveness could have been attributed to differing chemical make-up of the sand between the two sand filters.

Our experimental BSF's effective grain size differed more drastically from the CAWST BSF manual's recommendations than these previous studies as we included sand grains between 0.70 mm and 2.0 mm in the filter media. Since BSFs use mechanical trapping, adsorption, predation, and natural death to remove bacteria from contaminated water, a BSF with larger sand grains would be expected to rely more on predation and natural death and less on mechanical trapping for bacteria removal. Furthermore, unlike many previous studies and as Stauber recommended [7], we not only aimed to measure percent reduction of bacteria and turbidity, but also to compare post-treatment water quality to international drinking water guidelines.

1.2. Ultraviolet Disinfection

In addition to determining the effect of grain size on BSF performance, we exposed samples of BSF effluent to ultraviolet (UV) light in order to simulate solar disinfection (SODIS) in a laboratory setting. SODIS is one of many forms of disinfection CAWST recommends post-filtration [9]. Through discussions with non-governmental aid organizations in developing countries, we discovered this additional step is not always carried out in the field since disinfection adds time, cost, and complexity to the water purification process.

Like biosand water filtration, much laboratory research and field studies have been done about SODIS. Despite that SODIS-only experiments have shown 3-log reductions or more of bacteria [12,13], Hunter analyzed 39 data sets from previous disinfection and filtration trials in developing countries, and concluded SODIS-only purification has little, if any, long term public health benefits [14]. Hirtle's research focused on various pretreatments to increase SODIS efficiency. Her results showed a roughing filter consisting of a 17 cm column of coarse sand prior to SODIS reduced both turbidity and e. coli 93% and 0.35-log, respectively [12]. Once the filtered water was placed in the sun, SODIS was significantly more effective in further reducing e. coli than without pretreatment. One limitation she discovered, however, was that despite SODIS being effective if turbidity was below 30 NTU, water needed to be consumed immediately after SODIS if turbidity was above 10 NTU due to regenerative properties of bacteria in turbid water. Therefore, the better the pre-treatment, the more effective SODIS can be.

Wilson also experimented with filtration as a pretreatment to SODIS. Using a 0.45 μm screen, she was able to virtually eliminate turbidity, which enabled a greater amount of UV light to be absorbed.

The more UV absorbance, the greater reduction in e. coli levels [15]. The use of a BSF as a pre-treatment for SODIS, unlike these previously mentioned filtration methods, would introduce the added benefits of a biological layer to the filtration process. A literature review did not uncover studies on biosand water filtration and UV disinfection conducted in series, and therefore, our project which paired these two viable water purification techniques in developing countries may be unique.

1.3. Hypotheses

The research goals for this project were to determine if sand grains above the CAWST recommended maximum size of 0.70 mm could be used in a BSF to improve drinking water quality and make the water safe enough to drink. Additionally, we tested the effectiveness of biosand filtration as a pretreatment to UV disinfection. To support these goals, we constructed two full-scale BSFs: one per the CAWST version 10 manual (the control BSF) and one using grain sizes from 0.70 mm to 2.0 mm (the experimental BSF). Contaminated water was filtered through each BSF and samples of the effluent were placed under UV light. Based on previous research mentioned above, we devised three hypotheses for our experiments:

- We believed the BSF with the smaller grain size would reduce e. coli and turbidity more than the BSF with larger grain size.
- Additionally, we believed UV disinfection would further reduce e. coli levels in the water that passed through each BSF.
- Finally, we believed the combination of biosand water filtration and UV disinfection would produce water quality meeting World Health Organization (WHO) guidelines, even using the experimental BSF. We estimated increasing the grain size would raise BSF effluent turbidity, but not by enough to exceed guidelines. Further, based on previous studies of bacteria reduction by biosand water filtration and UV exposure, when used in series, we expected they would reduce e. coli levels enough to meet drinking water guidelines.

2. Methods

2.1. Study Design

The sand used for the filter media in both BSFs was sourced in Colorado, USA, and was angular quarry sand. Per the CAWST manual, we sieved and washed the sand to remove excess fines and organic material. The control BSF contained particles that passed the 0.70 mm sieve, and the experimental BSF contained particles that passed the 2.0 mm sieve, but was retained on the 0.70 mm sieve. Sieve analysis determined the control BSF's sand media had an effective size of 0.19 mm and uniformity coefficient of 2.1, both in accordance with the CAWST manual. The experimental BSF's sand media had an effective size of 0.80 mm and uniformity coefficient of 1.5.

To grow the biological layer, a 20 l solution of 10% raw wastewater and 90% dechlorinated tap water was introduced to each BSF daily for 21 days. Prior to mixing with wastewater, the tap water was naturally dechlorinated through evaporation over a 48 hour period. It was stored in 20 l buckets and agitated twice in the 48 hour period. Free chlorine was measured using a HACH CN-66 Test Kit and shown to be below 0.1 ppm after this dechlorination process. With such a low amount of chlorine, any residual would be overwhelmed by the bacteria in the raw wastewater. The raw wastewater was gathered from a local wastewater treatment plant weekly and stored in sealed containers at 5 degrees Celsius until used. The raw wastewater and dechlorinated tap water mixture was stirred for 30 seconds to combine, and then poured all at once into each BSF.

Dose volume can have a large effect on the performance of the BSF as noted in previous studies [3,5]. Smaller dose volumes are likely to cause bacteria to die naturally from lack of oxygen or light because some water will remain in the sand pore space and not get flushed out from batch to batch.

Therefore in practice, smaller doses, less than 70% of the media's pore volume, will lead to better BSF performance [5], albeit yielding a smaller volume of treated water. We used a 20 l dose volume as this mirrors WHO's definition of basic access to water per capita per day [1].

Research has shown the longer the pause period between doses, the more effective the BSF is in reducing bacteria [3,4]. Like smaller dose volumes, longer pause periods allow for more natural death of the bacteria. Since water does not continuously flow through BSFs, there is a maximum practical limit to the pause period in order to maintain the health of the biological layer. The CAWST manual recommends a maximum of 48 hours; we used a 24 ± 2 hour pause period between doses. Again, this reflects the 20 liters per day definition of basic access to water.

The biological layer may take up to 30 days to ripen depending on the water source [9]. Previous studies have either grown the biological layer for a predetermined number of days or measured the bacteria-reducing performance of the BSF until it plateaued [3,4,7]. Our influent was fairly bacteria-laden (average of 41,000 CFU/ml) and we grew the biological layer for 21 days through daily doses of the wastewater/dechlorinated tap water mixture before collecting experimental data.

Starting on Feb 4, 2013, we began the data collection phase of the experiment. Throughout this phase, each day, we filtered 20 l of the wastewater/dechlorinated tap water mixture through a 297 μm sieve then poured it into each BSF. Flow rate varied throughout our experiment, but averaged 0.19 l/min for the control BSF (min = 0.05 l/min, max = 0.39 l/min) and 0.60 l/min for the experimental BSF (min = 0.49 l/min, max= 0.71 l/min). We completed a total of eight test runs through March 13, 2013. As the flow rate dropped, we conducted maintenance using the wet harrowing method; we wet harrowed the control filter three times and the experimental filter once. We waited at least seven days from wet harrowing before starting another test run; this seven day period has been shown to be sufficient to allow the biological layer to heal enough to only have a modest effect on turbidity and bacteria removal [4]. While a reduced flow rate itself will not hinder BSF performance, it becomes unpractical if the user has to wait hours for a 20 l batch to filter through the BSF.

Each test run consisted of pouring a 20 l sample of water into each BSF, pausing 24 ± 2 hours, and taking the first 500 ml of effluent from each BSF directly from the outlet tube as the next day's influent was poured. When the effluent is taken has an effect on water quality [3], and taking the first 500 ml of effluent (versus taking a mid-dose sample) ensured the water was from the previous day's dose and had been in the BSF for the last 24 hours. We placed the 500 ml sample directly in a clear polyethylene terephthalate (PET) bottle that had been triple-rinsed with deionized water. PET bottles have been shown to block UV light with wavelengths smaller than 340 nm, while allowing longerwave UV light to pass through generally at a 60% transmittance rate or better [16]. Bottles that transmit shortwave UV light would be work better for SODIS [16], but these shorter wavelengths (290 nm to 320 nm) are strongly attenuated by the atmosphere [17].

The bottles sat under longwave monochromatic UVA (365 nm) light for 24 ± 2 hours on top of a flat surface coated in foil, which would potentially increase optical inactivation of bacteria [17]. Monochromatic lamps inactivate e. coli differently at various fluencies and do not perfectly mimic natural sunlight [18]. Further, monochromatic UVA light generally leads to less bacteria inactivation than polychromatic sunlight [19], therefore our UV disinfection results would be more conservative than if we had used natural sunlight or polychromatic lamps. UV light affects various cell functions at different fluencies [20], but past research has shown 3-log reduction of e. coli with approximately 2000 kJ/m^2 of irradiation [18]. This corresponds to a few hours of direct sunlight depending on location and weather conditions. We used three UVGL-25 handheld UV lamps placed three inches above the bottles to produce an average irradiation of 1820 kJ/m^2 as calculated using manufacturer's specifications and validated with an Ideal Industries, Inc 61-340 Multimeter with Apogee SU-100 UV light sensor. While under UV lamps, the bottles were kept at room temperature, thus temperature was not expected to contribute to bacteria inactivation as previous studies had shown to occur at much higher temperatures [17,18].

2.2. Water Quality Testing

It is widely understood that there is a strong correlation between the presence of e. coli and the presence of other waterborne pathogens [3,7,16,21]. We measured e. coli levels in the water at three stages of our experiment: untreated water, BSF effluent, and post-UV disinfection. To do this, we used IDEXX Laboratories, Inc. products. Colilert® was added to a 100 ml sample, stirred to combine, and placed into a Quanti-tray®/2000. The tray was sealed and incubated at 35.5 degrees Celsius for 24 to 28 hours before the e. coli population could be read under a longwave UV lamp using the most probable number method. The untreated water e. coli levels were determined by a 100x dilution sample using a sterile buffer made from sodium dihydrogen phosphate prepared according to WHO guidelines [1]. BSF effluent and post-UV disinfection samples were undiluted for e. coli testing.

In addition to e. coli, turbidity is an important measure of water quality because particulates can protect microorganisms and can stimulate bacteria growth [1]. We measured the turbidity of both the untreated water and BSF effluent. We did not measure turbidity post-UV disinfection as disinfection would not affect turbidity. To measure turbidity, we took a 5 ml sample and used a PASCO® PASPORT PowerLink PS-2001 coupled with DataStudio software, which was calibrated before each use.

3. Results and Discussion

We used an ANOVA to test each hypothesis. When comparing effluent e. coli and turbidity between the two BSFs, we found no significant difference in performance of either water quality parameter ($p >> 0.05$ for both cases). This was unexpected, and while the mean percent reduction of both e. coli and turbidity was slightly greater in the control than the experimental BSF, the relatively small sample size ($n = 8$) precluded statistical significance. E. coli reduction for the control was 98.7% ($\sigma = 0.0148$) and 98.4% ($\sigma = 0.0245$) for the experimental BSF. The turbidity reduction was 75.4% ($\sigma = 0.182$) for the control and 74.8% ($\sigma = 0.131$) for the experimental BSF. Table 1 shows the average water quality measurements at each stage of testing for both BSFs.

Table 1. Comparison of average water quality indicators between BSFs and across the three stages of water quality testing.

	Control BSF		Experimental BSF	
	E. coli (CFU/ml)	Turbidity (NTU)	E. coli (CFU/ml)	Turbidity (NTU)
Untreated water	39,400	19.9	42,700	18.3
BSF effluent	251	4.43	304	4.20
Post-UV disinfection	<1.00	N/A[a]	<1.00	N/A[a]

[a] Turbidity of post-UV disinfected water was not tested.

Secondly, and as expected, we concluded UV disinfection significantly reduced e. coli from each BSF's effluent. In every case, UV exposure virtually eliminated e. coli bacteria, reducing concentrations to less than 1 CFU/ml. Therefore, in both stages of the water purification process (biosand filtration and UV disinfection), the bacteria levels were significantly reduced. This reduction occurred when we used both the control and experimental BSFs.

Finally, we believed the combination of biosand water filtration and UV disinfection would produce water quality meeting WHO guidelines, even for the experimental BSF. WHO drinking water guidelines suggest a maximum e. coli concentration of 10 CFU/ml and maximum turbidity of 5 NTU [22]. Though, communities in developing countries that have consumed turbid water for generations may be accustomed to the color and taste, and it has been suggested that the maximum acceptable turbidity level in rural Africa might be near 15 NTU [6]. Both the experimental and control BSFs alone were able to meet WHO turbidity guidelines but neither was able to meet e. coli guidelines. After UV disinfection, and as expected, effluent from both BSFs produced water that met e. coli guidelines with all samples reading less than 1 CFU/ml, as previously mentioned.

Besides the experimental BSF statistically performing equally as well as the control, we noticed a benefit of using the larger grained BSF. It required less maintenance and maintained its flow rate much better than the smaller grained BSF throughout our study. This could be due to us not pre-screening (with a 297 μm screen) the untreated water during the 21-day biological layer growth period and partially clogging the pore space in the control BSF. However, in practice when fine screens are not used and highly turbid water may exist, this benefit of larger sand grains with respect to flow rate and maintenance may be a consideration.

4. Conclusions

Our experimental BSF with sand grains between 0.70 mm and 2.0 mm did not perform significantly differently in removing e. coli or turbidity from contaminated water. These results provide a level of confidence to those who find it difficult to locate or isolate sand grains within CAWST specifications. Additionally, we have shown that UV treatment of BSF effluent is extremely effective in reducing e. coli post-BSF filtration. Furthermore, in conjunction with UV (solar) disinfection, biosand filtration can produce water that meets international drinking water guidelines, even with larger sand grains.

Our results present promise for using larger grains as BSF sand media, but pose questions for further study. Long term effects of larger grained BSFs need to be determined: Does performance remain consistent over time? As we saw in our experiment, due to the larger pore volume, maintenance may not be required as often. When long-term maintenance is required, however, is the wet harrowing method effective or are pore spaces throughout the sand column clogged to the point where it needs to be replaced? If locating or isolating small sand grains can be a limiting factor in standard BSF construction, perhaps a computational model can be established where effective size and uniformity coefficient can be varied to match field conditions such that effluent water quality can be predicted.

Additionally, can we ever confidently state BSF effluent without disinfection is safe for consumption (meeting WHO guidelines)? Conflicting prior results whether greater influent bacteria concentrations yield similar or increased percentage of bacteria removal [3,23] make it unclear if an initial e. coli concentration can be back-calculated from a maximum desirable effluent concentration of 10 CFU/ml using the percent e. coli reduction from our experimental BSF. Our untreated water e. coli concentration was relatively high (42,700 CFU/ml), and if 98.4% reduction is indifferent consistent for any untreated water condition, an initial e. coli concentration of about 625 CFU/ml or less might not need disinfection post filtration. Research with a more moderate level of bacteria influent than what we used would have to be done to confirm this estimate.

Acknowledgements

The authors would like to the thank the United States Air Force Academy Department of Civil and Environmental Engineering for their financial support and laboratory space and equipment, especially Dennis Scott and Heidi Hunter. We must thank also thank Alice and Kent Meyer for assistance with tools and machinery during BSF construction, and IDEXX Laboratories, Inc. for the complimentary use of a Quanti-Tray Sealer® 2X. This research was funded in part by a grant from the Air Force Office of Scientific Research.

References

[1] WHO 2002 *The World Health Report: Reducing the Risks, Promoting Healthy Life* www.who.int/whr/2002/en

[2] UNICEF 2012 *The State of the World's Children* www.unicef.org/sowc2012

[3] Baumgartner J, Murcott S and Ezzati M 2007 Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems *Environmental Research Letters* 2 024003

[4] Jenkins M, Tiwari S and Darby J 2011 Bacterial, viral and turbidity removal by intermittent slow sand filtration for household use in developing countries: experimental investigation and modeling *Water Research* 45 18 6227-39

[5] Elliott M, Stauber C, Koksal F and DiGiano F 2008 Reductions of e. coli, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter *Water Research* 42 10-11 2662-70

[6] Earwaker P 2006 Evaluation of household biosand filters in Ethiopia University of Cranfield, Silsoe

[7] Stauber C 2007 The Microbiological and health impact of the biosand filter in the Dominican Republic: a randomized controlled trail in Bonao University of North Carolina at Chapel Hill

[8] Duke W, Nordin R, Baker D and Mazumder A 2006 The use and performance of biosand filters in the Arbonite Valley of Haiti: a field study of 107 households *Rural and Remote Health* www.rrh.org.au/publishedarticles/article_print_570.pdf

[9] CAWST 2010 *Biosand Filter Manual* http://resources.cawst.org/package/biosand-filter-construction-manual_en

[10] Bellamy W, Hendricks D and Logsdon G 1985 Slow sand filtration: influences of selected process variables *Journal AWWA* 78 12 62-67

[11] Hijnen W, Schijven J, Bonné P, Visser A and Medema, G 2004 Elimination of viruses, bacteria and protozoan oocysts by slow sand filtration *Water Science and Technology* 50 1 147-54

[12] Hirtle L 2008 Exploring pretreatments for the solar water disinfection (SODIS) process University of Waterloo, Ontario, Canada

[13] Dejung S et al 2007 Effect of solar water disinfection (SODIS) on model microorganisms under improved and field SODIS conditions *Journal of Water Supply: Research and Technology* 56.4 245-56

[14] Hunter P 2009 Household water treatment in developing countries: comparing different intervention types using meta-regression *Environmental Science Technology* 43 8991-7

[15] Wilson S 2010 Impact of water quality on solar disinfection (SODIS): investigating a natural coagulant pretreatment on the photoinactivation of escherichia coli University of Toronto, Ontario, Canada

[16] Wegelin M et al 2001 Does sunlight change the material and content of polyethylene terephthalate (PET) bottles? *Journal of Water Supply: Research and Technology* 50.3 125-33

[17] McGuigan K, Joyce T, Conroy R, Gillespie J and Elmore-Meegan M 1998 Solar disinfection of drinking water contained in transparent plastic bottles: characterizing the bacterial inactivation process *Journal of Applied Microbiology* 84 1138-48

[18] Wegelin M, Canonica S, Mechsner K, Fleischmann T, Pesaro F and Metzler A 1994 Solar water disinfection: scope of the process and analysis of radiation experiments *J Water SRT* 43 3 154-69

[19] Berney M, Weilenmann H and Egli T 2006 Flow-cytometric study of vital cellular functions in escherichia coli during solar disinfection (SODIS) *Microbiology* 152 1719-29

[20] Bosshard F, Riedel K, Schneider T, Geiser C, Bucheli M and Egli T 2010 Protein oxidation and aggregation in UVA-irradiated escherichia coli cells as signs of accelerated cellular senescence *Environmental Microbiol*ogy 12 11 2931-45

[21] Downs K 2008 Biosand Filters (BSF) as an effective point of use technology: evaluation of microbial reductions in laboratory and field studies, Michigan State University

[22] WHO 2008 *Guidelines for drinking-water quality* http://www.who.int/water_sanitation_health/dwq/gdwq3rev/en/

[23] Bellamy W, Silverman G, Hendricks D and Logsdon G 1985 Removing giardia cysts with slow sand filtration *Journal AWWA* 77 2 52-60