Microbial and chemical assessment of ceramic and BioSand water filters in rural Cambodia

H. M. Murphy, M. Sampson, K. Farahbakhsh and E. McBean

ABSTRACT

Unless significant advances are made in the water and sanitation sector, it is unlikely that Cambodia will meet the United Nations Millennium Development Goal (MDG) target #7 for water and sanitation. Point-of-use technologies (POU), also termed "household water treatment technologies", have been identified as successful options for providing safe water to rural households. Ceramic water filters and BioSand filters are two major POU technologies that are currently implemented across Cambodia. This paper presents data on the microbial performance of these two technologies in the field on various Cambodian source waters. In addition, data are presented on the occurrence of nitrite in treated water. Results showed that 61% and 88% of BioSand filters and ceramic filters, respectively, produced water in the low risk range for *E. coli* as defined by the WHO (0–10 CFU/100 mL). In addition, 83% of BioSand filters and 75% of ceramic filters were not meeting the WHO guideline value for chronic exposure to nitrite in drinking water (0.2 mg/L).

Key words | BioSand filters, Cambodia, ceramic filters, household water treatment, nitrification, point-of-use water treatment

H. M. Murphy (corresponding author)
K. Farahbakhsh
E. McBean
School of Engineering,
University of Guelph,
50 Stone Road,
East Guelph, Ontario N1G 2W1,
Canada
E-mail: *murphy@uoguelph.ca*;
        khosrowf@uoguelph.ca;
        emcbean@uoguelph.ca

M. Sampson (Deceased)
Resource Development International
    Cambodia (RDIC),
Royal Brick Road,
Kandal,
Cambodia

INTRODUCTION

Cambodia is currently ranked 129th out of 177 countries on the Human Development Index (HDI). According to the World Bank, unless significant advances are made in the water and sanitation sector, it is unlikely that Cambodia will meet the United Nations (UN) Millennium Development Goal (MDG) target #7 for water and sanitation. This target's aim is to "halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation" (UN 2006). Point-of-use technologies have been identified as successful options for providing safe water to rural households (Sobsey 2002).

Currently, there are two POU systems commonly implemented around Cambodia and worldwide: ceramic water filters and BioSand filters (Clasen *et al.* 2006; Duke *et al.* 2006; Stauber *et al.* 2009). Although these filters have been widely implemented, to date there are very few refereed journal publications that critically evaluate the performance

of these systems in the field. The bulk of the research conducted up to now has been on the health impact in terms of diarrhoeal disease reduction that may be attributed to the use of these technologies at the household levels. Brown (2007) and Liang *et al.* (in press) and others have found up to 49% reduction of diarrhoeal disease can be achieved in households which use one of these filters compared to those that do not. While the health benefits of using these technologies and reduction of microbiological contamination have been fairly well documented, little research has focused on other potential contaminants that these technologies could be removing from water supplies, such as fluoride, iron, manganese, nitrate, or nitrite, or how these parameters could be impacting the performance of the technology.

The objective of this paper is to present data from a study of BioSand and ceramic filters on the microbial performance of these systems in the field on various

Cambodian source waters. In addition, data will be presented on the occurrence of nitrate and nitrite in treated water. This research is important as it addresses unanswered questions regarding whether these systems are capable of providing microbiologically and chemically safe water that meets WHO guidelines.

METHODS

Ceramic filter design

Ceramic filters are made from porous fired clay. The ceramic filters examined in this study were produced by Resource Development International- Cambodia (RDIC). Their ceramic filter design originated from a group called Potters for Peace (PFP) who developed ceramic filters in Nicaragua (Lantagne 2001a,b). The RDIC design consists of local clay, ground rice husk, and silver nitrate. The rice husk is used to increase the filtration rate through the filter, while the silver nitrate is applied on the surface of the filter after firing to act as a biocide. The rice husk burns out in the firing process and allows increased porosity. Brown (2007) and Lantagne (2001a,b) reported that microbial removal efficiencies of 2–6 log, 0.5–5 log and 4 to 6 log can be achieved for bacteria, viruses and protozoa, respectively. However, in the field, Brown et al. (2007) observed on average only a 1.7 log reduction of E. coli. This low reduction was attributed to post-treatment contamination in the treated water storage containers (Brown et al. 2007; Murphy et al. 2010). Figure 1 illustrates the filter configuration. The average filtration rate for these filters is 2 L per h, which varied depending on the turbidity of the raw water. The ceramic filter can hold approximately 11 L of water while the plastic receptacle stores 20 L of treated water. To date, RDIC has produced approximately 90,000 ceramic filters which have been sold across Cambodia.

BioSand filter design

The BioSand water filter (BSF) is a household, intermittently operated, slow sand filter (Figure 2). The design was adapted from traditional slow sand filters by Dr. Manz at the

Figure 1 | Ceramic filter.

University of Calgary in the early 1990s (Palmateer et al. 1999). Slow sand filters function on the basis of two key principles: physical removal mechanisms and biological removal mechanisms. Particles present in the water are removed physically when they are too large to pass through the filter bed. Most biological removal occurs in the top layer of the filter in a biological film known as the "schmutzdecke". The schmutzdecke acts as a fine filter to remove small colloidal particles as well as a biological zone that degrades soluble organics and destroys harmful pathogens (Huisman & Wood 1974). Although the ability of slow sand filters to reduce microbial contamination in water is well documented, there is very little research documenting the performance of BioSand filters (Hendricks 1991; Duke et al. 2006; Stauber et al. 2006).
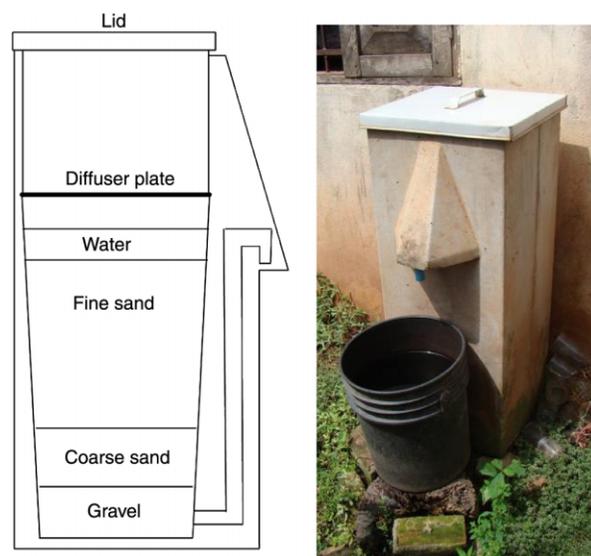

Figure 2 | BioSand filter.

BioSand filters are operated intermittently, with variable head and higher filtration rates when compared to traditional slow sand filters that are operated continuously with a constant head. The hydraulic loading rate of a BioSand filter is around 0.6 m/h, while the recommended filtration rates for a traditional slow sand filter for rural water supplies range from 0.1–0.2 m/h (Hendricks 1991; Lukacs 2001).

E. coli removal in the BSF has been documented to range between 0.5 to 2.0 log reduction in a laboratory setting and between no apparent *E. coli* removal to a 2.0 log reduction in field trials (Duke *et al.* 2006; Stauber *et al.* 2006; Baumgartner *et al.* 2007; Elliot *et al.* 2008). In an epidemiology study conducted in Cambodia by Liang *et al.* (in press), a 44% reduction in diarrhoeal disease was found between those who use a BioSand filter and those who do not. Very little research has examined the effectiveness of these systems on virus removal. Elliot *et al.* (2008) observed an average 0.5 log reduction of bacteriophage. The Manz BioSand filter has been implemented in 20 countries around the world (Duke *et al.* 2006). To date, approximately 25,000 have been installed throughout Cambodia by two local organisations: Hagar, and Cambodia Global Action (CGA) (Samaritans Purse 2009).

Household filter selection

A case study approach was used to assess the performance of ceramic and BioSand filters in rural Cambodia. Two communities were selected for study in September 2008. For the ceramic filters, a commune was selected where filters were sold door-to-door six months prior to the beginning of this research. An area of recent implementation was chosen for study to ensure that as many filters as possible could be located, since breakage rates are high (Brown *et al.* 2009). Seventy-four filters were sold in the region during this period. Instead of generating a random sample, attempts were made to locate the entire population. Of the 74 filters, 11 were not found, five were broken, two owners did not want to participate, and two filters belonged to households where no-one was at home at the time of visit. However, three additional filters were found in the same geographic region but they were in a village not specified by the manifest provided by RDIC.

For the BioSand filters, two villages were selected for study. The researchers were advised by the implementing organisation (CGA) that a total of 81 filters were installed in both villages. All 81 filters were located. The filters ranged in age from 1 year to 7 years. Of the 81 filters, 59 were still being used by households.

In total, water samples were collected and surveys were administered to 56 and 59 households still using their ceramic and BioSand filters, respectively, at the time of visit. The survey administered at each household inquired about household demographics, filter maintenance and cleaning, frequency of filling as well as a section for observations. The interviewer was required to make a series of observations at each household, for example: the state of the filters (broken, cracked etc), whether the filter was dirty inside and the condition and cleanliness of the treated water storage containers. In addition, for the BSFs, the filtration rate of the filter when completely full was recorded for each household.

Collection of water samples and analysis

Raw and treated water samples were collected in sterile autoclaved sample bottles and kept on ice until transported to the RDIC laboratory where they were analysed within 24 h for total coliforms (TC), *E. coli*, pH, turbidity, ammonia, nitrate and nitrite. These parameters were monitored as they were identified by RDIC (2007) as well as Feldman *et al.* (2007) as prevalent contaminants in Cambodia source waters and pose aesthetic or health concerns in water supplies. Although TCs have little health significance, especially in tropical environments, they are useful indicators of treatment; therefore they were monitored before and after treatment in the ceramic and BioSand filters (Hazen 2006). Ammonia was monitored because it can be an indicator of recent faecal contamination in water supplies and it can be converted by microorganisms to nitrite and nitrate through nitrification processes.

Raw water samples were collected from concrete household storage containers, surface water sources near the household or directly from the well depending on how the household collected the raw water to feed their filter. Treated water samples were collected directly from the spouts of the BioSand and ceramic filters (Figures 1 and 2). The ceramic filter element sits inside a plastic water storage container that collects the treated water. This container is sealed off from the outside environment and the spout of the

system is located near the base of this container (Figure 2). The spout of the BioSand filter is located at the front of the concrete frame, meaning that samples were taken directly after treatment and not from the treated water storage container that a household would use with their BSF (Figure 1). It should be noted that the spouts were not sterilised prior to sample collection so the samples would be representative of the water a household would be drinking. In addition, samples were collected from both filters "as is", meaning that a freshly filtered sample was not collected. This was done to ensure that the samples collected were as representative as possible of household drinking water.

Total coliforms and *E. coli* were enumerated using the standard membrane filtration method as outlined in *Standard Methods for the Examination of Water and Wastewater 21st Edition* (2006). Samples were filtered aseptically through sterile 0.45 μm filters using a vacuum aspirator. The filters were then transferred using sterile forceps onto pre-dried Oxoid Differential Coliform Agar with BCIG (used for simultaneous detection of coliforms and *E. coli*) and incubated upside down for 18–24 h at 37°C. At this time, all pink and blue colonies were enumerated as coliforms and those colonies that were blue were counted specifically as *E. coli*. All microbiological samples were processed using two serial dilutions and each dilution was processed in duplicate. Ammonia, nitrate and nitrite were measured using a HACH DR/2400 Spectrophotometer using methods 8155, 8039, 8153 respectively as specified in the HACH DR/2400 manual (HACH Company 2004). All chemical parameters were measured in triplicate and an average was compiled. Turbidity was measured three times per sample using a HACH Turbidimeter, and pH was measured using an Oakton pH probe. Both the turbidity meter and the pH probe were calibrated weekly, prior to sample analysis.

RESULTS AND DISCUSSION

pH, turbidity and microbial water quality

BioSand filters

Source waters for the BioSand filters included: deep wells (>20 m), river, lake, rainwater and other (piped water or

rainwater mixed with any of the previously mentioned sources). The pH of these source waters ranged from 6.81 to 10.8, with an average of 7.67. pH values in the higher range (>8.0) are attributable to households who stored their water in large concrete jars before filtering the water through the BioSand filter. The calcium carbonate from the concrete likely leached out into the stored water, raising the pH. The turbidity ranged from 0.16 to 152 NTU depending on source water. As expected, surface waters had higher turbidity, whereas rainwater and groundwater had lower turbidity.

The box and whisker plot in Figure 3 illustrates untreated and treated water *E. coli* concentrations for all source waters. The median *E. coli* concentrations were significantly lower in well water than any of the other source waters. Given that water was often drawn straight from the well before filling the filter, microbial contamination was generally low in this source. Rainwater was commonly stored in large concrete water jars (1 m wide) often not including a cover or a safe method for water withdrawal (i.e. a dipper). Households utilised this water for many uses such as bathing, cooking, drinking, and cleaning. The water was not usually stored in a manner to limit microbial contamination. In addition, various methods of
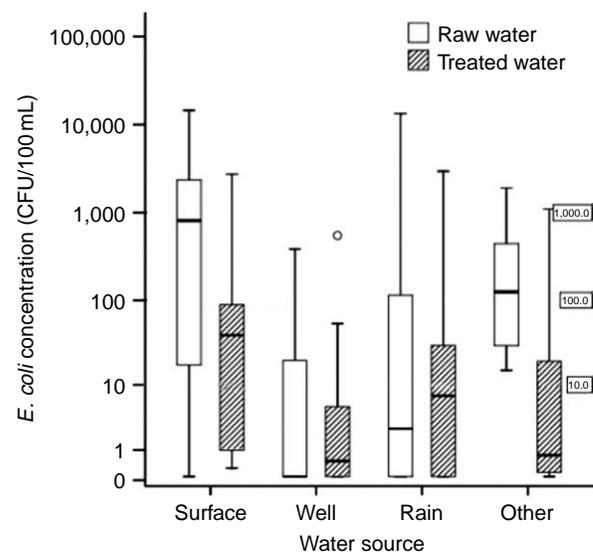
Figure 3 | Raw and treated water concentrations of *E. coli* for BioSand filters (boxes represent upper and lower quartiles, horizontal lines in each box represent median values, high and low values are represented by the error bars, and circles represent outliers). Surface water, 15 samples; Well water, 19 samples; Rainwater, 18 samples; Other sources, seven samples.

water extraction could contaminate the stored water supply, thus potentially explaining the high concentrations of *E. coli* observed for rainwater (Figure 3).

Treated water quality from the BioSand filters had an average pH of 8.54 with low and high values of 7.48 and 10.66, respectively. Turbidity was relatively low, ranging between 0.11 and 7.54 NTU. Given that the BioSand filters are constructed from cement, similar to the concrete water storage jars, the average increase in pH (+0.87) from raw water to treated water was likely caused by the leaching of calcium carbonate.

Treated water from the BioSand filters was frequently of good microbiological quality; however, in some cases, treated water contained more microbial contamination than the source water. The median concentrations of *E. coli* in treated well and rainwater were higher than the untreated sources (Figure 3). Eighteen of the 59 filters had treated water with higher *E. coli* concentrations than the source water. Of these 18, five contained *E. coli* in the high risk range (and higher) as identified by the WHO (101–1,000 CFU/100 mL), eight were in the intermediate range (11–100 CFU/100 mL) and five were in the low risk range (0–10 CFU/100 mL).

To demonstrate the removal capabilities of the BioSand filters in terms of *E. coli* concentrations, the log *E. coli* raw water concentrations were plotted against the log removal achieved (Figure 4). This figure illustrates that, even at an elevated raw water *E. coli* concentration, high bacterial removal can be achieved in these systems. The results also demonstrate that at low raw water *E. coli* concentrations no removal or the introduction of bacteria may occur via

contaminated spouts or re-growth of microorganisms in the standpipe (Figure 1), perhaps suggesting that these systems are not appropriate for waters of generally low microbial contamination (LeChevallier 1990). These waters include safely-stored rainwater and well water extracted from a protected well. Additionally, these sources often have lower turbidity and contain less organic matter. If the raw water turbidity and organic material are relatively low there is less biomass available for the schmutzdecke layer of the BioSand filter. With limited organic input, it is possible this system does not perform as well, given there is likely a lower diversity of micro- and macro-organisms in the schmutzdecke to consume bacteria and aid removal (Wotton 2002).

A linear regression analysis was performed and an R^2 of 0.58 was found, indicating a mild relationship between raw water concentration and log removal. It is believed that the fit of this linear model is not stronger because of various operational differences from one filter to another in the field. All the filters in this study had varying filtration rates and were filled at various time intervals, such as: multiple times a day, daily, or once every few days. It is believed that all of these factors contribute to the performance of the filter as found by Baumgartner *et al.* (2007). In addition, this mild relationship could be a reflection on the ability of the technology to perform consistently in the field from household to household and may indicate a lack of quality control between individual household implementations. Despite a low R^2 value, this positive linear relationship was found to be significant with a p value of 1.89×10^{-19} for a two-tailed t-test.
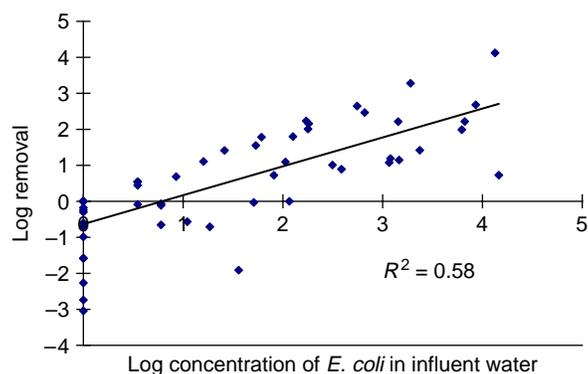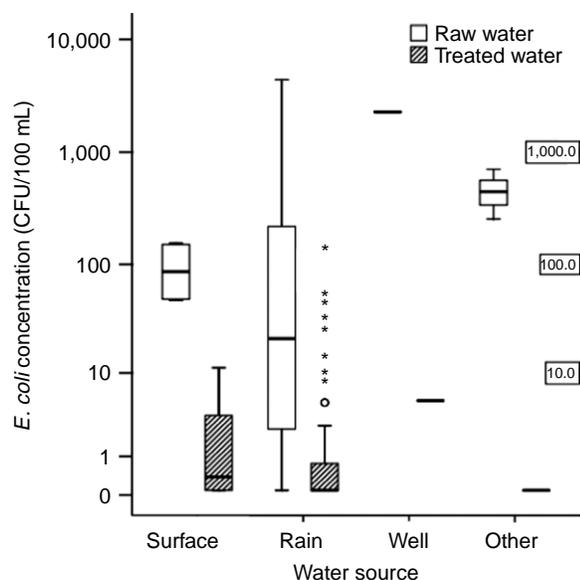
Ceramic filters

Source waters for the ceramic filters were of superior microbial quality to the source waters for the BioSand filters, as many households used rainwater which, if stored correctly, is free of many contaminants. The rainy season persisted longer than expected during the field study (2008); therefore, households were still using rainwater during the study even though it was expected that they would have already switched to another source of water. Source waters included deep well (>20 m), river, rain and mixed water. The pH of these source waters ranged from 7.05 to 10.53.

Figure 4 | Linear regression analysis of raw water *E. coli* concentrations versus log removal for BioSand filters.
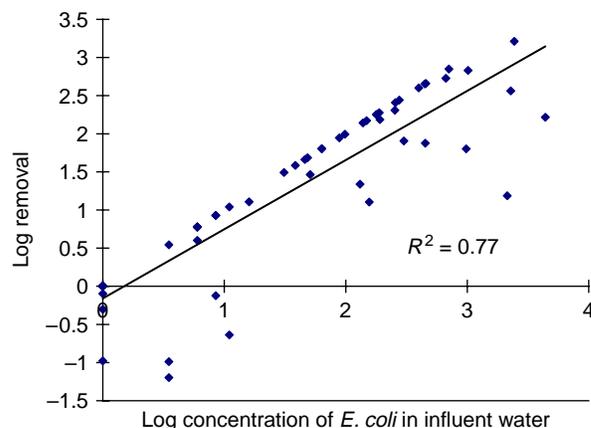
The turbidity of the raw water ranged from 0.34 to 30.1 NTU. The turbidity of these source waters was significantly lower than the BioSand filter source waters. Again, this is likely attributable to the fact that many households were using rainwater, which had low turbidity, to feed their ceramic filters. In Figure 5, raw and treated water *E. coli* concentrations are illustrated in a box and whisker plot.

Treated water pH ranged from 6.78–9.59 and turbidity ranged from 0.02 to 2.98 NTU. Turbidity and *E. coli* concentrations decreased through all the filters, thus indicating that the filters were working correctly (i.e. likely no breach in filter integrity). Treated waters from all filters were in the low to intermediate risk category for *E. coli* according to the WHO guidelines. This high quality of treated water may be attributed to the good quality of raw water into these systems.

Figure 6 illustrates the log *E. coli* raw water concentrations plotted against the log removal achieved. The same positive relationship was found for ceramic filters as BioSand filters. As raw water concentration of *E. coli* increases, the log removal capability for the ceramic filters increases as well. This shows that, even at higher raw water *E. coli* concentrations, high bacterial removal can be achieved in

Figure 6 │ Linear regression analysis of raw water *E. coli* concentration versus log removal for ceramic filters.
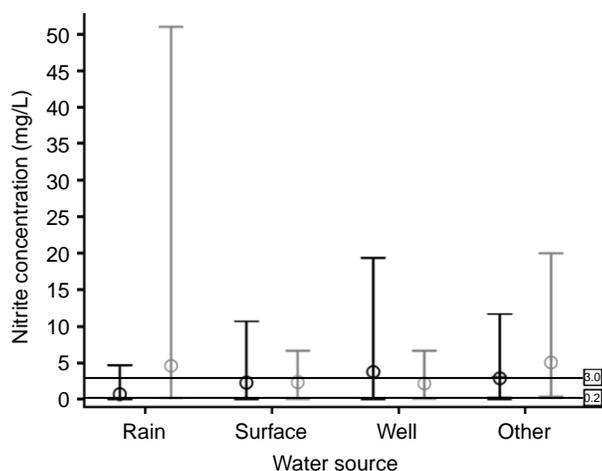
these systems. However, contrary to the BioSand filters, at a lower raw water concentration of bacteria, there are not as many filters achieving negative or zero removal, especially below a raw water concentration of 2 log *E. coli*.

The linear regression analysis performed gave an R^2 value of 0.77, indicating a stronger relationship between raw water concentration of bacteria and log removal than observed for BioSand filters. In addition, a two-tailed t-test revealed that this positive relationship is significant at a p value of 4.04×10^{-12}. This could be explained by the fact that all of the ceramic filters were fairly identical in terms of age and filtration rate and there was less variation observed for frequency of filling the filter from household to household. It is hypothesised that cases of lower log removal observed in Figure 6 are a result of improper cleaning of the plastic filtered water storage container, and not a function of the performance of the ceramic filters. Several authors have reported that contaminated storage containers may contribute to the increase in bacteria in household water supplies (Momba & Kaleni 2001; Jagals *et al.* 2003; Brown *et al.* 2007; Murphy *et al.* 2010).

Nitrite and nitrate

BioSand filters

Figure 7 illustrates the untreated and treated water nitrite concentrations observed for all BioSand filters. The results are grouped by water source and the figure shows the high and low values, as well as the average concentrations

Figure 5 │ Raw and treated water concentrations of *E. coli* for ceramic filters (boxes represent upper and lower quartiles, horizontal lines in each box represent median values, high and low values are represented by the error bars, and circles and stars represent outliers). Surface water, four samples; Well water, one sample; Rainwater, 48 samples; Other sources, four samples.

Figure 7 │ Nitrite concentrations for untreated and treated water from BioSand filters (bars represent high and low values, while the circles represent average values observed). Surface water, 15 samples; Well water, 19 samples; Rainwater, 18 samples; Other sources, seven samples. 1st series of bars in each group (bolded) represent untreated water; 2nd series of bars (grey) represent treated water.

observed. These results are compared to the WHO guideline values of 0.2 mg/L for chronic exposure to nitrite and the 3.0 mg/L acute exposure for infants (WHO 2007). Nitrite levels in treated water from numerous BioSand filters exceeded these WHO guideline values. In addition, 39 of the 59 filters saw an increase in nitrite and nitrate from the source water to the treated water. From Figure 7, average nitrite concentrations increased for households using rainwater or other source water. Overall, a decrease in nitrite was observed in households fed well water and no apparent change in nitrite concentrations was seen in households using surface water.

A matched paired t-test was conducted on the change in concentration of nitrite between untreated and treated water for all water sources. The differences between untreated and treated nitrite concentrations were calculated by subtracting effluent concentrations from influent. This data set was then transformed using a Box-Cox transformation so that the data best approximated a normal distribution. An average nitrite increase of 0.26 mg/L was found to be significant at the 99.9% confidence interval with a t-value of 9.18.

Treated water nitrate and ammonia concentrations were in the range of 0 to 27.72 mg/L NO_3^-, and 0 to 1.13 mg/L NH_3, respectively. Nitrate concentrations in treated waters never exceeded the 50 mg/L WHO guideline

value for acute exposure in infants (WHO 2007). In order to see if there was any relationship between increased nitrite concentrations and increased E. coli concentrations in filtered water for the BSF, the nitrite and E. coli values were correlated with one another. There was no apparent correlation between elevated nitrite levels and E. coli concentrations in treated water from the BioSand filters ($R^2 = 0.04$).

Ceramic filters

Figure 8 shows the nitrite concentrations observed in untreated and treated water for all ceramic filters. Similarly to Figure 7, the results are grouped by water source. Like the BSFs, nitrite levels in treated water from the ceramic filters also exceeded WHO guideline values. In addition, 34 and 16 filters saw an increase in nitrate and nitrite, respectively, from the source water to the treated water. From Figure 8, average nitrite concentrations increased for households using rainwater, surface water or other sources of water. The one filter using well water saw an average decrease in nitrite as it passed through the ceramic filter.

A matched paired t-test was conducted on the change in concentration of nitrite between untreated and treated water for all water sources. The difference between nitrite concentrations was calculated by subtracting the effluent
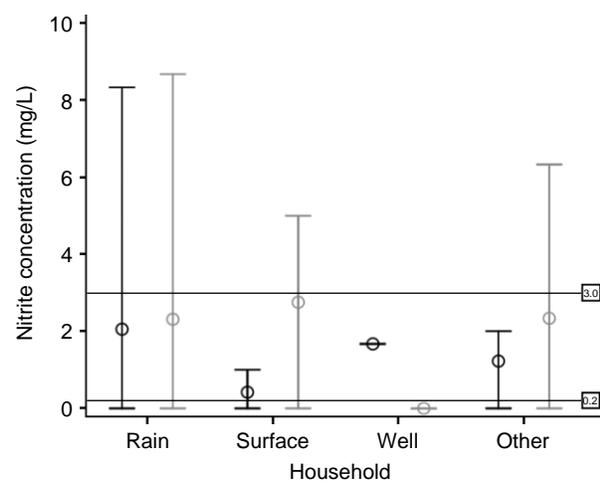
Figure 8 │ Nitrite concentrations for untreated and treated water from ceramic filters (bars represent high and low values, while the circles represent average values observed). Surface water, four samples; Well water, one sample; Rainwater, 48 samples; Other sources, four samples. 1st series of bars in each group (bolded) represent untreated water; 2nd series of bars (grey) represent treated water.

concentration from the influent. This data set was then transformed using a Box-Cox transformation so that the data approximated a normal distribution. The results revealed that an average nitrite increase of 0.42 mg/L was significant at the 99.9% confidence interval with a t value of 7.61.

In treated water, average nitrate concentrations ranged from 0 to 21.85 mg/L NO_3^- and ammonia levels were in the non-detectable range. In addition, to examine whether or not there was any relationship between increased nitrite concentrations and increased *E. coli* concentrations in filtered water from the ceramic filters, nitrite and *E. coli* concentrations were correlated with one another. There was no apparent correlation between elevated nitrite levels and *E. coli* concentrations in treated water from the ceramic filters ($R^2 = 0.0002$).

Comparison to WHO guidelines and health implications

Table 1 shows the number of filters that produced water that met the low, medium and high risk WHO guidelines for *E. coli* exposure as well as the number of filters that did not meet the nitrite and nitrate guideline values. In general, ceramic filters produced water that had lower *E. coli* concentrations than the BSFs. This could be partly attributed to the fact that the ceramic filters were primarily fed rainwater which was of higher quality than the water sources feeding the BSFs in this study. In terms of nitrite exposure, more BSFs exceeded the chronic guideline than ceramic filters. In summary, 39.0% and 12.5% of BSFs and ceramic filters, respectively, were not meeting the low risk

exposure guideline for *E. coli*. For chronic nitrite exposure, 83% of BSFs and 75% of ceramic filters were exceeding the guideline value of 0.2 mg/L NO_2^-. Additionally, 29% of BSFs and 30% of ceramic filters surpassed the acute exposure guideline value for infants of 3.0 mg/L NO_2^-. The nitrate guideline of 50 mg/L was never surpassed in treated water from these filters.

Increases in nitrite and nitrate concentrations through these systems may indicate that biological nitrification may be occurring within some of these filters. Nitrification is a microbial-driven process by which bacteria in an aerobic environment convert ammonia to nitrite and then subsequently other bacteria convert nitrite to nitrate. Given that ammonia was present in concentrations ranging from 0–1.03 mg/L in water sources that fed both the ceramic and BioSand filters, it is plausible that nitrification may have been occurring to convert ammonia to nitrite and subsequently to nitrate. This may have occurred in the schmutzdecke layer in the BSFs and on the inner surface of the ceramic filters. If the ceramic filter is constantly filled with water and never left to dry out, and given that biofilms exist on all types of surfaces in contact with water, it is plausible that a biofilm exists inside the ceramic filter, especially since it has such a slow flow rate and users often re-fill their filter before it has run dry (Marshall 1992). According to Huisman & Wood (1974, p. 20), "nitrogenous compounds are broken down and the nitrogen is oxidized" in the schmutzdecke layer of the BSF, also implying that nitrification is possible in the BSF.

Increases in nitrate and nitrite are significant as these compounds may be harmful to infants, causing blue baby

Table 1 │ Number of BSF and ceramic filters that met the various WHO guidelines

WHO guideline	Number of BSFs	% of BSFs	Number of ceramic filters	% of ceramic filters
E. coli				
Low risk (0–10 CFU/100 mL)	36	61%	49	88%
Medium risk (11–100 CFU/100 mL)	15	25%	6	11%
High risk (101–1,000 CFU/100 mL)	4	7%	1	2%
>1,000 CFU/100 mL	3	5%	0	0%
Nitrite (NO_2^-) *and nitrate* (NO_3^-)				
$NO_2^- > 0.2$ mg/L (chronic exposure)	49	83%	42	75%
$NO_2^- > 3.0$ mg/L (infant acute exposure)	17	29%	17	30%
$NO_3^- > 50$ mg/L	0	0%	0	0%

syndrome. In addition, many of these filters are exceeding the chronic exposure guideline value of 0.2 mg/L for nitrite. If households are exposed to these waters chronically, they may be at risk for heart and lung complications (WHO 2007).

CONCLUSIONS

Given the various Cambodian source waters, both POU technologies have demonstrated the ability to significantly reduce the concentration of bacteria in the treated water. However, when raw water concentrations of bacteria were <1 log, no removal, or an increase in bacteria concentration, could be observed, indicating that perhaps POU technologies may be best suited for waters with higher microbial contamination, and that maintenance practices associated with these technologies are important to ensure safe water quality. Neither technology was capable of consistently supplying water with nitrite below WHO guidelines. It is recommended that further research be conducted on various source waters worldwide to explore the occurrence of nitrites and nitrates in treated waters from these systems.

ACKNOWLEDGEMENTS

REFERENCES

Baumgartner, J., Murcott, S. & Ezzati, M. 2007 Reconsidering 'appropriate technology': the effects of operating conditions on the bacterial removal performance of two household drinking water filter systems. *Environ. Res. Lett.* **2**, 1–6.

Brown J. 2007 *Effectiveness of ceramic filtration for drinking water treatment in Cambodia*. PhD Thesis, University of North Carolina, Chapel Hill, USA.

Brown, J., Sobsey, M. D. & Proum, S. 2007 *Improving Household Drinking Water Quality-Use of Ceramic Water Filters in Cambodia*. Water and Sanitation Program (WSP) Field Note. The World Bank, Phnom Penh, Cambodia.

Brown, J., Proum, S. & Sobsey, M. D. 2009 Sustained use of a household-scale water filtration device in rural Cambodia. *J. Water Health* **7**(3), 404–412.

Clasen, T. F., Brown, J. & Collin, S. M. 2006 Preventing diarrhoea with household ceramic water filters: assessment of a pilot project in Bolivia. *Int. J. Environ. Health Res.* **16**(3), 231–239.

Duke, W. F., Nordin, R. N., Baker, D. & Mazumder, A. 2006 The use and performance of BioSand filters in the Artibonite Valley of Haiti: a field study of 107 households. *Rural Remote Health* **6**(3), 570.

Elliot, M. A., Stauber, C. E., Koksal, F., DiGiano, F. A. & Sobsey, M. D. 2008 Reductions of *E. coli*, echovirus type 12 and bacteriophages in an intermittently operated household-scale slow sand filter. *Water Res.* **42**(10–11), 2662–2670.

Feldman, P. R., Rosenboom, J. W., Saray, M., Navuth, P., Samnang, C. & Iddings, S. 2007 Assessment of the chemical quality of drinking water in Cambodia. *J. Water Health* **5**(1), 101–116.

HACH Company 2004 *DR/2400 Spectrophotometer Procedure Manual*. HACH Company, Loveland, USA.

Hazen, T. 2006 Fecal coliforms as indicators in tropical waters: a review. *Environ. Toxicol.* **3**(5), 461–477.

Hendricks, D. (ed.) 1991 *Manual of Design for Slow Sand Filtration*. AWWA Research Foundation, Denver, USA, p. 26.

Huisman, L. & Wood, W. E. 1974 *Slow Sand Filtration*. World Health Organisation, Geneva, Switzerland.

Jagals, P., Jagals, C. & Bokako, T. C. 2003 The effect of container-biofilm on the microbiological quality of water used from plastic household containers. *J. Water Health* **1**(101), 108.

Lantagne, D. 2001a *Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter–Report 1: Intrinsic Effectiveness*. Alethia Environmental, Allston, USA.

Lantagne, D. 2001b *Investigation of the Potters for Peace Colloidal Silver Impregnated Ceramic Filter–Report 2: Field Investigations*. Alethia Environmental, Allston, USA.

LeChevallier, M. 1990 Coliform regrowth in drinking water. A review. *J. AWWA* **82**(11), 74–86.

Liang K., Stauber C. E., Murphy H. M. & Sobsey M. D. (in press). *Independent Evaluation of the BioSand Water Filter in Rural Cambodia: Sustainability, Health Impact and Water Quality Improvement*. Water and Sanitation Program (WSP) Field Note. The World Bank, Phnom Penh, Cambodia.

Lukacs H. 2001 *From design to implementation: Innovative slow sand filtration for use in developing countries*. Masters Thesis. Massachusetts Institute of Technology, Cambridge, USA.

Marshall, K. C. 1992 Biofilms: an overview of bacterial adhesion, activity, and control at surfaces. Control of biofilm formation awaits the development of a method to prevent bacterial adhesion. *ASM Am. Soc. Microbiol. News* **58**(4), 202–207.

Momba, M. N. B. & Kaleni, P. 2001 Regrowth and survival of indicator microorganisms on the surfaces of household containers used for the storage of drinking water in rural communities of South Africa. *Water Res.* **36**, 3023–3028.

Murphy, H. M., Sampson, M., McBean, E. & Farahbakhsh, K. 2010 Influence of household practices on the performance of clay pot water filters in rural Cambodia. *Desalination* **252**, 145–152.

Palmateer, G., Manz, D., Jurkovic, A., McInnis, R., Unger, S., Kwan, K. K. & Dutka, B. J. 1999 Toxicant and parasite challenge of Manz intermittent slow sand filter. *Environ. Toxicol.* **14**, 217–225.

Resource Development International- Cambodia (RDIC) 2007 *Drinking water quality study of tubewells in Cambodia*. http://www.rdic.org/dwqipage.htm (accessed 7 October 2007).

Samaritans Purse Canada 2009 Personal Communication regarding sales and implementation of BioSand Filters in Cambodia.

Sobsey, M. D. 2002 *Managing water in the home: accelerated health gains from improved water supply*. Report WHO/ SDE/WSH/02.07. World Health Organisation, Geneva, Switzerland.

Standard Methods for the Examination of Water and Wastewater 21st edition 2006 American Public Health Association/ American Water Works Association/Water Environment Federation, Washington DC, USA.

Stauber, C. E., Elliot, M. A., Koksal, F., Oritz, G. M., DiGiano, F. A. & Sobsey, M. D. 2006 Characterisation of the biosand filter for *E. coli* reductions from household drinking water under controlled laboratory and field use conditions. *Water Sci. Technol.* **54**(3), 1–7.

Stauber, C. E., Ortiz, G. M., Loomis, D. P. & Sobsey, M. D. 2009 A randomized controlled trial of the concrete biosand filter and its impact on diarrheal disease in Bonao, Dominican Republic. *Am. J. Trop. Med. Hyg.* **80**(2), 286–293.

United Nations (UN) 2006 *Millennium Development Goals Report (2006)*. New York, USA. http://unstats.un.org/unsd/mdg/ Resources/Static/Products/Progress2006/MDGReport2006.pdf (accessed 27 January 2007).

World Health Organisation (WHO) 2007 *Nitrate and Nitrite in Drinking-Water: Background Document for Development of WHO Guidelines for Drinking-Water Quality*. WHO, Geneva, Switzerland.

Wotton, R. S. 2002 Water purification using sand. *Hydrobiologia* **469**, 193–201.