

Reconsidering ‘appropriate technology’: the effects of operating conditions on the bacterial removal performance of two household drinking-water filter systems

Jill Baumgartner^{1,2}, Susan Murcott³ and Majid Ezzati¹

¹ Harvard School of Public Health, Boston, MA, USA

² University of Wisconsin, Madison, WI, USA

³ Massachusetts Institute of Technology, Cambridge, MA, USA

E-mail: majid.ezzati@harvard.edu

Received 12 February 2007

Accepted for publication 18 May 2007

Published 8 June 2007

Online at stacks.iop.org/ERL/2/024003

Abstract

We examined the performance of two household water treatment and safe storage (HWTS) systems, the Danvor plastic biosand filter and the Potters for Peace *Filtron* ceramic filter, under ideal as well as modified operating conditions using systematic and comparable measurements. The operating variables for the biosand filter were (i) pause times between filtration runs, (ii) water-dosing volumes and (iii) the effluent volume at which a filtered water sample was collected. For the ceramic filter we examined overflow filtration versus standard filtration. We used the bacterial indicators of total coliforms and *Escherichia coli* to quantify microbiological removal. With the biosand filter, a 12 h pause time had significantly higher total coliform removal than a 36 h pause time at the 20 l collection point (79.1% versus 73.7%; $p < 0.01$) and borderline significance at the 10 l collection point (81.0% versus 78.3%; $p = 0.07$). High-volume filtration (20 l) had significantly lower total coliform removal efficacy than low-volume (10 l) filtration at the 10 l collection point (81.0% versus 84.2%; $p = 0.03$). We observed a decreasing trend in total coliform removal by sample collection volume with the highest removal efficacy at the 5 l sample collection point (versus at the 10 and 20 l collection points). Using the ceramic filter, mean total coliform and *E. coli* removal were significantly lower ($p < 0.01$) in overflow filtration than in standard filtration. The findings indicate that operating conditions can reduce the effectiveness of the systems in a field-based setting and increase environmental risk exposure.

Keywords: water filter, technology, developing country, household water treatment and safe storage, point of use water disinfection

 Supplementary data are available from stacks.iop.org/ERL/2/024003

1. Introduction

Worldwide 1.1 billion people lack access to sufficient quantities of safe drinking water [1]. Unsafe drinking water, combined with insufficient water supply for sanitation and hygiene, is responsible for an estimated 4 billion cases of

diarrhoeal disease, 1.79 million diarrhoea deaths and 3.7% of the global burden of disease [1]. Improving access to clean water, an important policy imperative in international development for decades, is receiving renewed and increased attention; for example, goal 7 (target 10) of the Millennium Development Goals (MDGs) aims to ‘reduce by half the

proportion of people without sustainable access to safe drinking water’.

Access to safe water can in principle be achieved through centralized water treatment and/or point-of-use treatment. Widespread expansion of centralized water treatment (also referred to as ‘scaling up’) has been slow, particularly in urban fringes, poor rural areas and indigenous communities, largely due to the high cost and technical complexities of the required infrastructure [2]. Further, even when safe water is available through a communal source, which is a common form of water provision in many low-income communities, there remains a high risk of contamination between the time of collection and consumption in the home [3]. Household water treatment and safe storage (HWTS) interventions have therefore been considered low-cost and effective alternatives for reduction of diarrhoeal disease that can be implemented at the point of use [1, 4].

The effectiveness of an intervention in conditions of actual use and operation, referred to as community-based effectiveness, can be dramatically different from its efficacy in controlled laboratory or trial settings due to differences in the physical environment (e.g. water source characteristics) and user behaviour. Much of the previous HWTS literature has addressed the technical and economic feasibility of these systems, and how these factors impact household adoption. A separate body of research has established the role of hygiene behaviour in achieving significant reductions in the incidence or severity of diarrhoeal diseases [5–7]. However, there have been few studies on the role of behavioural parameters that determine operating conditions on the performance of HWTS systems in reducing exposure to unsafe water [8, 9], with just two studies identifying potential non-ideal behaviours, one of which quantified its effects on performance [10, 11].

We examined the performance of two HWTS systems, the Danvor plastic biosand filter and the Potters for Peace *Filtron* ceramic filter, under ideal as well as modified operating conditions using systematic and comparable measurements. Laboratory studies conducted in controlled environments have established faecal coliform or *Escherichia coli* (*E. coli*) removal rates of 93–99% [12–14] for the biosand filter and 99.9% for the *Filtron* ceramic filter [15]. However, the bacterial removal of the biosand filter in developing country settings has been less than ideal, varying from less than 60% to 99.9% removal [14, 16–21]. Similar variation in bacterial removal is reported for field studies on the *Filtron* ceramic filter [22, 23]. The variable performance of the systems in household settings mirrors the situation for other household environmental technologies, such as alternative cooking stoves [24, 25].

This study establishes systematic evidence for the robustness of the two HWTS technologies to specific environmental and behavioural conditions, which can be used to inform the choice and delivery of interventions, for example in contributing to the MDGs’ safe water target. In addition to its application to HWTS interventions, this study provides an example of an analysis that helps design, evaluate and deliver environmental health technologies to resource-poor settings based on systematic evaluation of actual performance

of the technology in reducing environmental risk exposure, and therefore contributes to our definition of ‘appropriate technology’, which has thus far primarily utilized design and operation, and not outcome-based indicators of technology performance.

2. Methods

2.1. Study design

We conducted a series of experiments on the biosand and ceramic filters that included ideal operating procedures as well as selected operating conditions that deviated from ideal use, yet still fell within each system’s current recommended usage guidelines. The parameters examined were based on field experiences observing how each unit may be used, and are shown in figures 1(a) and (b).

To reflect these operating conditions, experiments with the plastic biosand filter included the following (figure 1(a)).

- *Scenario 1 (infrequent filtration and high water dosing volume)*: 36 h pause period, water dosing volume of 20 l, sample collection points at 5, 10 and 20 l.
- *Scenario 2 (frequent filtration and high water dosing volume)*: 12 h pause period, water dosing volume of 20 l, sample collection points at 5, 10 and 20 l.
- *Scenario 3 (frequent filtration and low water dosing volume)*: 12 h pause period, water dosing volume of 10 l, and sample collection points at 5 and 10 l.

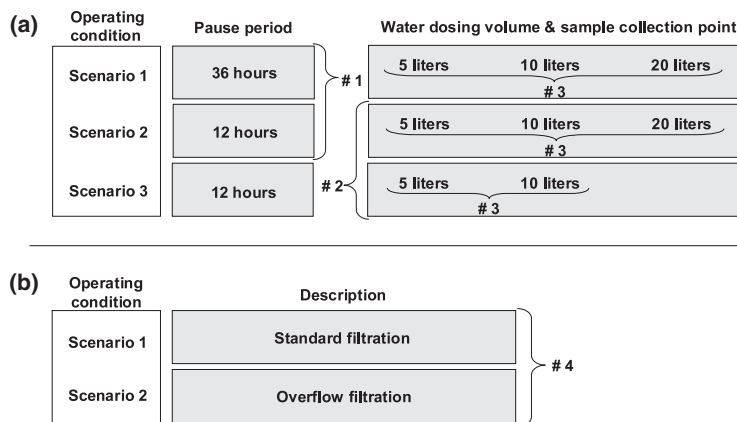
Access to water supply services is defined as the availability of at least 20 l per capita per day (lpcd) from an improved water source within 1 km of the user’s dwelling, a portion of which is used as drinking water [26]. The water dosing volumes used for experiments were based on estimates for the minimum drinking water requirements; 3.0 lpcd to maintain adult hydration and 5.5 lpcd for lactating women engaging in moderate physical activity in above-average temperatures [27, 28]. Comparison of the bacterial reduction between scenarios 1 and 2 addresses the question of how filtration frequency affects bacterial removal, and comparison of scenarios 2 and 3 addresses the question of how water dosing volume affects bacterial removal. Comparing bacterial reduction across the sample collection points in each scenario addresses the question of the variation of the filter’s removal effectiveness throughout a filter run.

The experiments for the *Filtron* ceramic filter included (figure 1(b)):

- *standard filtration*: with influent volume less than the filter’s capacity;
- *overflow filtration*.

Filter overflow is an important potential limitation to the effectiveness of the ceramic filter because the place where the filter lip fits onto the rim of the collection receptacle is not tightly sealed, allowing for water to seep through, hence potentially increasing the bacterial load of the filtered water.

We did not perform tests on water dosing volume or filtration frequency for the ceramic filter because the bacterial removal mechanisms of the ceramic filter, specifically small



Research questions:

- #1: Does filtration frequency and the intermittent “pause period” affect the biosand filter’s bacterial removal effectiveness?
- #2: Does the water dosing volume, the volume of water poured in each filter run, affect the biosand filter’s bacterial removal effectiveness?
- #3: Does the biosand filter’s bacterial removal effectiveness vary at different “sample collection points” during a single filter run?
- #4: Will overflowing the ceramic filter affect its bacterial removal effectiveness?

Figure 1. Schematic of experiments for (a) biosand filter and (b) *Filtron* ceramic filter.

pore size and its colloidal silver coating, are relatively insensitive to these factors in the short term. We also did not test the removal efficacy of the ceramic filter at various sample collection points because bacterial removal is not very sensitive to this parameter with a relatively constant flow rate.

Using one unit of each filter type, we implemented each biosand filter experiment in a sequence of 16 identical trials and each ceramic filter experiment in a sequence of 10 identical trials (see supplementary online material for experimental procedures; available at stacks.iop.org/ERL/2/024003). We used membrane filtration to detect *E. coli* and total coliforms because it allows the measurement of bacterial indicators as a continuous variable, hence quantifying bacterial removal in each trial (see supplementary online material for detailed methods and discussion of implications). *E. coli* serves as an indicator of faecal pollution; total coliforms, though not useful as an index of faecal pathogens, can be used as an indicator of the effectiveness of treatment and performance of the biofilm [29].

2.2. Statistical analysis

Bacterial removal for each trial was the ratio of total coliform and *E. coli* counts from samples of filtered water to those of unfiltered water.

We examined normal probability plots, histograms and skewness and kurtosis measures for all trials related to each experiment to test if the data were normally distributed. We used Bartlett’s test for equal variance. Neither the normality nor the equal variance assumptions were violated.

For the biosand filter, we used unpaired two-sided means tests with equal variance to compare the mean bacterial

removal of the biosand filter under different scenarios. We used one-way analysis of variance (ANOVA) to test the null hypothesis that bacterial removal efficacy at various 5, 10 and 20 l collection points was equal. We used paired *t*-tests for comparison of bacterial removal in standard versus overflow filtration with the ceramic filter because we compared bacterial removal before and after overflow filtration on the same filter unit.

Previous research has indicated a negative association between bacterial removal efficacy of the biosand filter and the bacterial content of the source water [12]. We examined whether the proportional reduction in the bacterial indicators was affected by the bacterial content of the unfiltered source water using Pearson correlation coefficients between bacterial content of source water and bacterial removal efficacy of the filter. We also regressed the removal efficacy of the filter in the first set of experiments (scenario 3) against the order of trial to examine whether the biofilm, or *schmutzdecke*, was fully developed when experiments began. If the biofilm was not yet mature, bacterial removal efficacies would have increased over time.

3. Results and discussion

3.1. Biosand filter

The Pearson correlation coefficient between bacterial removal and the bacterial content of the unfiltered source water was 0.12 ($p = 0.18$) and 0.18 ($p = 0.35$) for total coliform and *E. coli*, respectively. This implies that the proportional reduction in bacteria was not affected by the bacterial concentration of the source water. The regression coefficient for the relationship

Table 1. Total coliform removal (%) by the biosand filter under different operating condition scenarios and at different sample collection points.

Sample collection point	Operating conditions	n	μ (95% CI)	Min–max	p-value ^c
Scenario 1 versus scenario 2 (36 versus 12 h pause period) ^a					
5 l	12 h	16	95.9 (94.2, 97.6)	90.2–98.9	0.84
	36 h	15	95.7 (93.8, 97.5)	88.0–99.7	
10 l	12 h	16	81.0 (78.8, 83.2)	74.3–87.9	0.07
	36 h	16	78.3 (76.1, 80.5)	70.0–85.1	
20 l	12 h	16	79.1 (76.8, 81.4)	70.3–85.5	<0.01
	36 h	16	73.7 (70.2, 77.3)	58.3–83.2	
Scenario 2 versus scenario 3 (20 l versus 10 l water dosing volume) ^b					
5 l	10 l	14	96.5 (95.8, 97.1)	93.8–98.0	0.52
	20 l	16	95.9 (94.2, 97.6)	90.2–98.9	
10 l	10 l	14	84.2 (82.4, 86.1)	78.7–90.1	0.03
	20 l	16	81.0 (78.8, 83.2)	74.3–87.9	
Different sample collection points ^d					
5 l	Scenario 1: 36 h pause period and 20 l water dosing volume	15	95.7 (93.8, 97.5)	88.0–99.7	<0.01
10 l		16	78.3 (76.1, 80.5)	70.0–85.1	
20 l		16	73.7 (70.2, 77.3)	58.3–83.2	
5 l	Scenario 2: 12 h pause period and 20 l water dosing volume	16	95.9 (94.2, 97.6)	90.2–98.9	<0.01
10 l		16	81.0 (78.8, 83.2)	74.3–87.9	
20 l		16	79.1 (76.8, 81.4)	70.3–85.5	
5 l	Scenario 3: 12 h pause period and 10 l water dosing volume	14	96.5 (95.8, 97.1)	93.8–98.0	<0.01
10 l		14	84.2 (82.4, 86.1)	78.7–90.1	

^a The water dosing volume was held constant at 20 l.

^b The pause time was held constant at 12 h.

^c p-value refers to the statistical significance of the difference between bacterial removal of each pair of operating conditions; for the sample collection point experiments, it refers to the significance of ANOVA.

^d We removed two outliers from the biosand filter experiment using frequent filtration and low water dosing volume. Laboratory notes indicate that influent <5 °C was poured through the filter unit on the day these outliers were recorded. This low influent temperature increased the probability that bacteria passed through the biofilm during this trial [32].

between bacterial removal and the order of trial was also statistically non-significant ($p = 0.13$ at 5 l; $p = 0.33$ at 10 l). In other words, the bacterial removal efficacy did not increase as the trials progressed, indicating that the biofilm was fully developed prior to beginning the experiments.

Table 1 and figure 2 show the results for total coliform removal in the biosand filter experiments, organized by the hypotheses in figure 1(a). Results obtained for *E. coli* removal follow a pattern that mirrors the one shown for total coliform removal on average (see supplementary online material). *E. coli* removal results had larger variance because the *E. coli* count in each sample was, by definition, smaller than that of total coliform, leading to a larger stochastic error in the former data. As a result none of the differences in mean *E. coli* removal efficacy under different operating conditions were statistically significant.

3.1.1. Scenario 1 (36 h pause time) versus scenario 2 (12 h pause time). Scenario 1 (36 h pause time) had a higher total coliform removal than scenario 2 (12 h pause time) that was statistically significant at the 20 l collection point (79.1% versus 73.7%; $p < 0.01$) and of borderline statistical significance at the 10 l collection point (81.0% versus 78.3%;

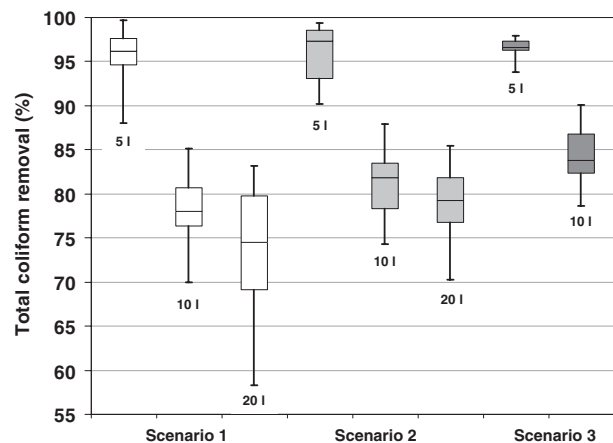


Figure 2. Total coliform reduction (%) by the biosand filter under different operating scenarios and at various sample collection points.

$p = 0.07$). This finding may be a consequence of decreased activity of microorganisms that live in the biofilm and consume the pathogens in the water, when the pause period becomes too long. Previous research, using a 24 h pause time, suggests

the survival (and hence the density) of microorganisms in the biofilm relies on inflow of contaminated source water [13]. Therefore less frequent inflow of contaminated source water (i.e. a longer pause period) may reduce the viability of the biofilm's removal function relative to more frequent filtration.

This mechanistic hypothesis is supported by results from the 5 l collection points. Samples collected at the 5 l collection point in scenario 1 (36 h) had longer contact with the sand held in the filter bed than those at the same collection point in scenario 2 (12 h). Typically, this longer contact would increase pathogen removal through either adsorption to the sand grains or natural death from nutrient starvation [30]. However, results in table 1 show that total coliform removal at 5 l sample collection point was almost identical for the two scenarios (95.7% versus 95.9%; $p = 0.84$). This is probably because the decreased efficacy attributable to fewer biofilm organisms may have offset any benefits gained from increased exposure to the sand grains at 5 l in scenario 1.

3.1.2. Scenario 2 (20 l water dosing volume) versus scenario 3 (10 l water dosing volume). We observed an inverse relationship between water dosing volume and bacterial removal. Scenario 2 (20 l) had a lower total coliform removal than scenario 3 (10 l) that was statistically significant at the 10 l collection point (81.0% versus 84.2%; $p = 0.03$), but not at the 5 l collection point (95.9% versus 96.5%; $p = 0.52$). The difference at 10 l may be an effect of the difference in hydraulic loading between the two experiments: using a high water dosing volume, water at 10 l is pushed through the biofilm and sand at a faster rate, resulting in less exposure to both of these bacterial removal mechanisms; at 5 l this is not observed because there is no difference in hydraulic loading or exposure time to the sand media between the two experiments.

3.1.3. Sample collection point. There was a decreasing trend in total coliform removal by sample collection point, with the highest removal efficacy at the 5 l sample collection point for all three scenarios. In scenario 3, there was a statistically significant decrease in total coliform removal at 10 l compared to 5 l (84.2% versus 96.5%; $p < 0.01$). In experiments using a 20 l water dosing volume, there was a decreasing trend in total coliform removal with increasing sample collection point (5, 10 and 20 l) in both scenario 1 ($p < 0.01$) and scenario 2 ($p < 0.01$).

Results from flow hydraulics tests using tinted water showed that filtrate at the 5 l collection point mostly, if not entirely, comprises influent from the previous trial held in the sand media during the pause period. Filtrate at the 10 l collection point largely comprises new influent whereas filtrate at 20 l entirely consists of new influent. These results support previous research indicating that a portion of the biological removal happens during the pause times when the source water has a longer contact time with the biofilm and pore media [12, 30]; as the sample is collected later in the filtration process, it has less contact with the pore media where some level of biological removal takes place.

Table 2. Comparison of *Filtron* ceramic filter total coliform and *E. coli* reduction (%).

Operating conditions	<i>N</i>	μ (95% CI)	Min–max	<i>p</i> -value ^a
Total coliform removal				
Standard filtration	10	99.4 (99.2, 99.6)	98.9–99.7	<0.01
Overflow filtration	10	47.8 (37.5, 58.2)	31.3–70.7	
<i>E. coli</i> removal				
Standard filtration	10	99.8 (99.6, 99.9)	99.3–100	<0.01
Overflow filtration	10	48.7 (37.1, 60.3)	26.7–81.5	

^a *p*-value refers to the statistical significance of the difference between bacterial removal using standard and overflow filtration.

3.2. *Filtron* ceramic filter

Mean total coliform and *E. coli* removal were significantly lower ($p < 0.01$) in overflow filtration than in standard filtration (table 2). In overflow filtration, filtrate contamination per 100 ml sample varies according to (a) the ratio of overflow to filtrate water in the collection receptacle and (b) the bacterial content of the filtered and unfiltered source water. Although removal efficacy differs according to these two factors, the quality of the filtrate water will always be compromised unless the unfiltered water is free of microbes. Further, while parasites and most bacteria are removed, one study suggests that viruses are able to pass through the pores of the ceramic filter version used in this study [15].

4. Conclusions

The results for the biosand filter illustrate the importance of achieving an optimal balance between the water dosing volume, pause time and the quantity of safe water required by households to meet daily needs. More research is required to determine the ideal combination of water dosing volume and pause time in order to maximize the filter performance without requiring users to adhere to a complex water dosing schedule. In the short term, filter implementers might consider advising households to either filter just the water volume held in the influent reservoir (approximately 5 l) or separately collect the initial 5 l of filtrate for consumption and use the remaining filtered water for other household needs. Alternatively, households could use a combination of HWTS technologies such as combining filtration with disinfection, for example with chlorination or solar disinfection in polyethylene terephthalate plastic bottles.

Finally, the user instructions and training manual for the ceramic filter currently fail to address how overflowing the unit may contaminate the filtrate. Both of these documents should inform users to cease filling the filter 3–5 cm below its lip as well as to avoid disturbing the unit during filtration to prevent unintentional overflow. Additionally, small changes to the design of the ceramic filter such as an extension of the filter lip would reduce the chance of overflow contamination without compromising the unit's durability or dramatically increasing its cost.

This research establishes how operating conditions that are affected by user behaviour can alter the bacterial removal

efficacy of two HWTS systems, thereby reducing their community-based effectiveness and increasing environmental risk exposure. Studies conducted in developing countries suggest that increased microbial contamination in water poses increased health risks [31]. Using scenario 3 (10 l water dosing volume every 12 h) as a reference, our results show that operating parameters such as pause time, water dosing volume and sample collection point for the biosand filter can double the level of bacterial contamination remaining in the filtered water, and thereby increase the risk of water-borne disease. Therefore, evaluation of an HWTS system should be accompanied by routine monitoring of operating conditions in the field and testing the robustness of technology performance to these conditions, to better inform the choice and delivery of environmental health technologies for specific environmental and behavioural settings.

References

- [1] WHO 2002 *Reducing the Risks, Promoting Healthy Life* (Geneva: The World Health Organization)
- [2] Bartram J, Lewis K, Lenton R and Wright A 2005 Focusing on improved water and sanitation for health *Lancet* **365** 810–2
- [3] Clasen T and Bastable A 2003 Faecal contamination of drinking water during collection and household storage: the need to extend protection to the point of use *J. Water Health* **1** 109–15
- [4] Clasen T, Roberts I, Rabie T, Schmidt W and Cairncross S 2006 Interventions to improve water quality for preventing diarrhoea *Cochrane Database Syst. Rev.* **3** CD0047943
- [5] Stanton B, Black R, Engle P and Pelto G 1992 Theory-driven behavioral intervention research for the control of diarrheal diseases *Soc. Sci. Med.* **35** 1405–20
- [6] Curtis V and Cairncross S 2003 Effect of washing hands with soap on diarrhoea risk in the community: a systematic review *Lancet Infect. Dis.* **3** 275–81
- [7] Curtis V, Cairncross S and Yonli R 2000 Domestic hygiene and diarrhoea—pinpointing the problem *Trop. Med. Int. Health* **5** 22–32
- [8] Agboatwalla M, Figueroa ME, Sarwari F, Ahmed A, Khanum Z and Nisa B 2005 Household perceptions, beliefs, and practices regarding safe water in Pakistan *World Health Organization Int. Symp. on Household Water Management (Bangkok, Thailand)*
- [9] Kincaid L and Figueroa M 2005 Perceived attributes of water and their effects on water treatment in Guatemala and Pakistan *World Health Organization Int. Symp. on Household Water Management (Bangkok, Thailand)*
- [10] (AED) Academy for Educational Development 2006 *Consumer Perception Study: Household-based Drinking Water Treatment Methods with Effectiveness Trials: Hygiene Improvement Project*
- [11] Clasen T, Saeed T, Boisson S, Edmondson P and Shipin O 2007 Household water treatment using sodium dichloroisocyanurate (NaDCC) tablets: a randomized, controlled trial to assess microbiological effectiveness in Bangladesh *Am. J. Trop. Med. Hyg.* **76** 187–92
- [12] Buzunis B J 1995 Laboratory report: conformational testing of an intermittently operated slow sand filter University of Calgary, Canada
- [13] Palmateer G et al 1999 Toxicant and parasite challenge of the Manz intermittent slow sand filter *Environ. Tox.* **14** 217–25
- [14] Stauber C E, Elliott M A, Koksall F, Ortiz G M, DiGiano F A and 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** 1–7
- [15] Lantagne D 2001 Investigation of the potters for peace colloidal silver impregnated ceramic filter *Report 1: Intrinsic Effectiveness: Alethia Environmental*
- [16] Lee T 2001 *Biosand Household Water Filter Project in Nepal* (Cambridge, MA: MIT Press)
- [17] Lukacs H 2002 *From Design to Implementation: Innovative Slow Sand Filtration for Use in Developing Countries* (Cambridge, MA: MIT Press)
- [18] Pincus M I 2003 *Safe Household Drinking Water via BioSand Filtration Pilot Project Evaluation and Feasibility Study of a BioSand Pitcher Filter* (Cambridge, MA: MIT Press)
- [19] Donison KS 2004 *Household Scale Slow Sand Filtration in the Dominican Republic* (Cambridge, MA: MIT Press)
- [20] Duke W F, Nordin R N, Baker D and 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** 570
- [21] Earwaker P 2006 *Evaluation of Household Biosand Filters in Ethiopia* (Silsoe, UK: Cranfield University)
- [22] Lantagne D 2001 Investigation of the potters for peace colloidal silver impregnated ceramic filter *Report 2: Field Investigations: Alethia Environmental*
- [23] Hwang R 2003 *Six Month Field Monitoring of Point-of-Use Ceramic Water Filter by Using H2S Paper Strip Most Probable Number Method in San Francisco Libre, Nicaragua* (Cambridge, MA: MIT Press)
- [24] Sinton J et al 2004 An assessment of programs to promote improved household stoves in China *Energy Sustainable Dev.* **8** 33–52
- [25] Agarwal B 1983 Diffusion of rural innovations: some analytical issues and the case of wood-burning stoves *World Dev.* **11** 359–76
- [26] WHO/UNICEF 2000 *Global Water Supply and Sanitation Assessment 2000 Report* (Geneva: The WHO/UNICEF Joint Monitoring Programme for Water Supply and Sanitation)
- [27] Gleick P H 1996 Basic Water Requirements for Human Activities: Meeting Basic Needs *Water Int.* **21** 83–92
- [28] Howard G and Bartram J 2003 *Domestic Water Quantity, Service, Level and Health* (Geneva: World Health Organization)
- [29] WHO 2004 *Guidelines for Drinking-Water Quality* 3rd edn (Geneva: World Health Organization)
- [30] Weber-Shirk M and Dick R 1997 Physical-chemical mechanisms in slow sand filters *J. Am. Water Works Assoc.* **89** 87–100
- [31] Sobsey M 2002 *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply. WHO/SDE/WSH02.07* (Geneva: World Health Organization)
- [32] Silhan J, Corfitzen CB and Albrechtsen HJ 2006 Effect of temperature and pipe material on biofilm formation and survival of *Escherichia coli* in used drinking water pipes: a laboratory-based study *Water Sci. Technol.* **54** 49–56