Comparative treatment performance and hydraulic characteristics of pumice and sand biofilters for point-of-use water treatment

K. Ghebremichael, L. D. Wasala, M. Kennedy and N. J. D. Graham

ABSTRACT

This study has investigated the comparative treatment and hydraulic performance of biosand filters (BSFs) of pumice and sand filter media, with *Escherichia coli* and turbidity as the principal indicators of water quality. The study has also assessed the effect of resting time on *E. coli* and turbidity removal. The performances of three filter columns consisting of sand, pumice, and sand/pumice dual media with a bed depth of 80 cm were evaluated over 4 months continuously. The columns were charged twice daily with local canal water. The pumice and the dual media filters achieved 24 and 14%, respectively, greater volume production per cycle compared to that of the sand filter. The pumice filter had consistently lower filtrate turbidity than the other filters with about 98.5% turbidity removal. Average *E. coli* removals were similar for all filters and corresponded to 0.9–1.8 log units for unripened media, and 1.4–3.3 log units for ripened media. It was observed that resting time of more than 4 h was necessary to achieve significant *E. coli* removal. Hydraulic and water quality profiles indicated that schmutzdecke development in the pumice layer was not effective as in the sand bed.

Key words | biosand filter, *E. coli*, pumice, resting time, turbidity

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INTRODUCTION

The biosand filter (BSF) is a point-of-use water treatment technology which is being deployed increasingly in developing countries (Stauber *et al*. 2006; Elliott *et al*. 2008; Sobsey *et al*. 2008; CAWST 2012). The BSF is an intermittently operated slow sand filter (SSF) at household scale. The design is modified in order to ensure that the intermittent operation does not adversely affect the schmutzdecke during the resting time. This is achieved by raising the filtrate discharge pipe to about 5 cm above the surface of the filter bed so that the filter bed is always immersed.

Previous studies have indicated that a ripened BSF can produce a filtrate turbidity of less than 1 NTU (Buzunis 1995) and remove up to 90% viruses, 99.9% protozoa and helminths (Stauber *et al*. 2009) and up to 99.99% *Escherichia coli* (Elliott *et al*. 2008). While it is believed that the resting time is important to the removal of microorganisms (Elliott *et al*. 2008, 2011), it remains unclear what should be used as a minimum resting time. Baumgartner *et al*. (2007) reported that a minimum resting time of 6–12 h was required in order to achieve a 1.3 log reduction of *E. coli*.

The initial filtration rate in BSF normally ranges from 0.4 to 0.7 m/h, which is higher than for SSF (0.2–0.4 m/h). Since the resting time in BSF improves microbial removal, higher initial filtration rates may not be of significant concern (Kubare & Haarhoff 2010). Charge volume equal to the bed pore volume ensures that the charged water remains within the bed for the entire resting time.

In practice, only sand has been used as the filter media in BSF and the relatively low porosity of sand leads to a small bed pore volume (small charge volume) and a high rate of head loss development (frequent clogging). Users would prefer a BSF that is capable of treating a larger volume at a greater filtration rate and longer filter run length. These limitations may reduce the acceptability of

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BSF and users may resort to other, unsafe water sources. To overcome these and improve BSF performance, an alternative media, pumice, has been evaluated, which is reported to improve turbidity removal and reduce the rate of head loss development (Farizoglu *et al.* 2003). In an earlier study it was observed that BSF with pumice media had consistent and better turbidity removal, had lower head loss build up and higher filtration rate compared with sand (Ghebremichael *et al.* 2011). However, it is not clear if the pumice media would achieve similar bacterial removal compared to sand.

The objective of this research was to investigate the hydraulic and treatment performance of laboratory-scale BSF with different media comprising sand alone, pumice alone and dual layers of sand and pumice. The comparison was quantified in terms of production volumes per cycle, rate of head loss development, turbidity removal and *E. coli* removal. The effect of resting time on the performance of BSF was also investigated.

MATERIALS AND METHODS

Materials

For the laboratory tests raw water was collected from a canal in Delft, The Netherlands (see Table 1 for quality characteristics). The canal water was charged to the columns when its temperature has been brought to room temperature (20 °C). In order to investigate bacterial removal of the BSF, the canal water was spiked with cultured *E. coli* to a final concentration of approximately 1×10^6 CFU per 100 mL.

Table 1 | The quality characteristics of Delft canal water at 20 °C

Parameter	Numerical value
Dissolved oxygen, mg/L	8.9 ± 0.53
Dissolved organic carbon, mg/L	13.05 ± 1.76
pH	8.06 ± 0.07
Electrical conductivity, μS/cm	1,000.5 ± 34.64
Turbidity, NTU	8.7 ± 4.09
Ammonium-nitrogen, mg/L	0.34 ± 0.20
Nitrate-nitrogen, mg/L	3.88 ± 0.55

The effective size and uniformity coefficient of the sand (Filcom Bv, The Netherlands) and pumice (Aqua Techniek, The Netherlands) were 0.32 mm and 1.75, and 0.28 mm and 1.78, respectively. Prior to use the filter media were thoroughly washed with tap water and the pumice was soaked for about 72 h. The pumice was reported to have bulk and material densities of 360 and 2,400 kg/m^3, respectively (Aqua Techniek, The Netherlands). By measurement, the bed porosity of the pumice media was found to be approximately 0.48, and from this the grain porosity of the pumice was calculated to be 0.37.

Experimental method

Three BSF columns each made from PVC tubing of 10 cm internal diameter were used: Column A contained 80 cm sand, Column B had 40 cm pumice on top of 40 cm sand and Column C contained 80 cm pumice. Each media was supported by shallow layers of coarse sand and gravel. Piezometers and sampling ports were installed at different depths of each column to monitor the hydraulic and water quality profiles. The filtrate discharge pipe was positioned at a level of 5 cm above the filter media to ensure that media was always fully immersed and a depth of 5 cm of supernatant water was maintained above the media surface during resting time (no flow). The columns were charged twice a day for more than 4 months. The charge volume for each column was equal to the bed pore volume. The bed pore volumes of the sand, pumice/sand and pumice columns were 2.5, 2.7 and 3.0 L, respectively. Initial filtration rates were measured about 5 min after charging, by timing the collection of known discharge volumes. In order to study the effect of resting time on *E. coli* and turbidity removal, the charged volumes were allowed to remain in the filter bed for different time periods until the next charging event; resting times of 1.5, 4, 20 and 22.5 h were investigated. Corresponding performances for longer resting times of 72 h (over weekends) were also evaluated.

Analytical methods

Turbidity, head loss, filtration rates and *E. coli* concentrations were measured at the influent, effluent and/or intermediate points daily (and in some cases twice a day).

Turbidity was measured using a bench top photometer (Dr Lange, Trübungsphotometr LTP-4, Düsseldorf, Germany) and dissolved oxygen (DO) was measured as needed from different depths using a portable DO probe meter (WTW Oxi 340i, Weilheim, Germany). *E. coli* concentrations were estimated using the plate count method after 10-, 100- and 1,000-fold dilutions and inoculation on chromocult plates. The plates were incubated at 35–37 °C for 22–24 h and the colony counts were expressed in CFU/100 mL.

RESULTS AND DISCUSSION

Hydraulic aspects

Over a sequence of filter runs, the average initial filtration rate in the pumice column was consistently high (1.12 ± 0.03 m/h) in comparison to the dual media (pumice/sand) column (0.90 ± 0.05 m/h) and sand column (0.67 ± 0.03 m/h) (Figure 1), reflecting mainly the more porous nature of the pumice media. The measured initial clean bed filtration rates for the media were consistent with estimates determined using the Ergun equation (Kubare & Haarhoff 2010) assuming laminar flow.

During the start-up period, the filter run length for the sand, dual media and pumice columns were 29, 54 and 55 days, respectively. The initial filtration rates started declining (indicating ripening) after 2 weeks for the sand column and after 1 month for the dual media and pumice columns. The subsequent filter runs were shorter compared to the start-up period as the columns ripened quickly owing to the seeding effect from the first run. Starting with the second filter cycle, all three columns had similar run lengths of 18–20 days (Figure 1). The shorter filter run times of the pumice after the initial run may be due to the accumulation of biological deposits within the grain pore spaces during the first run which were not fully removed during the subsequent cleaning operations. Thus, although after cleaning enough deposits were removed to enable the initial filtration rate (and initial head loss) to return to the same maximum value, the ripening process (growth of biological deposits) proceeded rapidly such that the decline in filtration rate (and corresponding head loss development) in all filter types were similar.

Although in subsequent filter runs the pumice bed behaved similarly to the sand bed in terms of filter run lengths, the production volume per run/cycle of the dual media and pumice columns were greater compared to the sand. Based on the initial bed pore volume, the sand, dual media and pumice columns were charged with 2.3, 2.5 and 3.0 L each time and the corresponding water productions per run/cycle were 47, 54 and 60 L. The time needed to collect about 95% of the charged volume was 55, 70 and 115 min for the pumice, dual media and sand columns, respectively. These filtration times corresponded to the ripening period when the filtration rates were high. After ripening and clogging, the filtration rates declined significantly and the filtration times increased. The length of the filtration period is of importance for acceptance by users, and needs to be short enough to avoid users abandoning the BSF technology and returning to traditional untreated sources; Fewster *et al.* (2004) reported that a

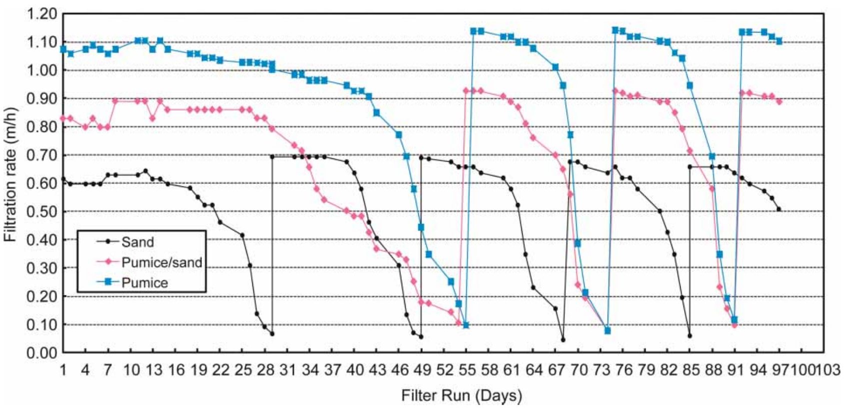

Figure 1 | Temporal variation of initial filtration rate for four consecutive filter cycles.

maximum filtration time of 2 h would be acceptable. The higher production volume and shorter filtration time of pumice media are important because users can treat a sufficient amount of water per charge in a shorter time. Moreover, treating a larger amount of water per charge helps to provide sufficient water per day, thus reducing the frequency of charging. This approach improves the treated water quality due to the longer resting time (the effect of resting time on contaminants removal is discussed in detail later).

The pattern of head loss increase for each media corresponded closely with the decline in filtration rate (Figures 1 and 2). The effectiveness of the cleaning processes was evident from the consistency of the initial head loss and initial filtration rate during the sequence of filter runs/cycles (Figure 2). In all cases, filter runs were terminated when the head loss reached a limiting value, rather than on the basis of turbidity or *E. coli* breakthrough. As expected, it was evident that at the end of each filter run, when the filtration rate had declined significantly, the reductions in turbidity and *E. coli* concentrations were at their greatest.

Turbidity removal

The influent turbidity of the canal water, over the 4-month period, was in the range of 3.4–18.6 NTU. The ripened filters were able to reduce the turbidity to less than 1 NTU which is similar to the reported values in the literature (Elliott *et al*. 2008; Katusabe 2010). The average filtrate turbidity from the sand, dual media and pumice columns were 0.7 ± 0.3, 0.6 ± 0.2 and 0.4 ± 0.1 NTU, respectively.

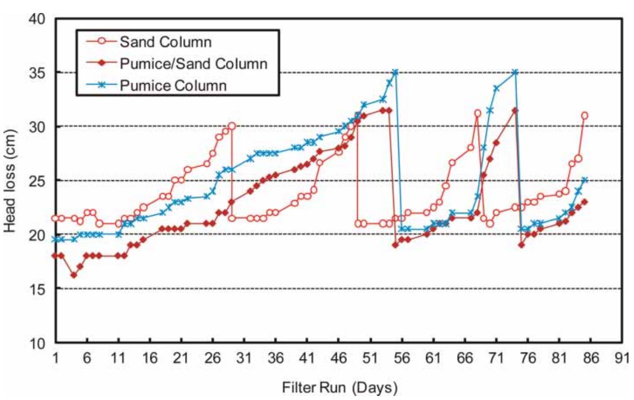

Figure 2 | Temporal variation of head loss curves for four consecutive filter cycles.

The filtrate turbidity from the pumice BSF was consistently below 1 NTU throughout the study period and was generally the lowest of the three media types (Figure 3). During the start-up phase, the sand and the dual media columns produced filtrate turbidities greater than 1 NTU for about 10–12 days. After each cleaning, the filtrate turbidity from the sand bed increased, indicating that this media requires a ripening period to produce low turbidity treated water. The greater performance of pumice to sand is believed to be due to the presence of pore spaces within the pumice grains, which provide a much greater surface area for particle capture, and which can retained the deposited solids; this advantage of pumice media has also been observed elsewhere (Farizoglu *et al*. 2003).

The need to obtain low filtrate turbidities during start-up or after each cleaning is important, especially in situations when a high concentration of microbial contamination is expected in the raw water. As the presence of microorganisms is closely associated with turbidity (LeChevallier & Norton 1992; Momba & Kaleni 2002), the lower filtrate turbidity with the pumice filter may be considered a significant advantage in terms of achieving low microbial concentrations. The presence of turbidity also influences the effectiveness of disinfection and thus the production of low turbidity water becomes important when users can not afford to wait until the BSF is fully ripened, especially during emergency situations.

E. coli removal

The results showing the removal of *E. coli* during several filter cycles indicated that the three media had similar

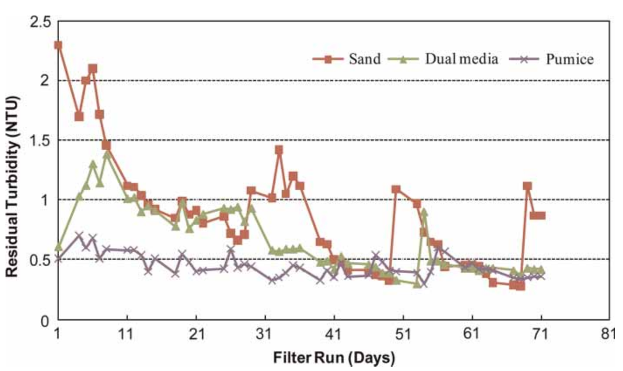

Figure 3 | Temporal variation of filtrate turbidity for each media over several filter cycles.

performances, as summarized in Figure 4. Statistical analysis indicated that there was no significant difference in *E. coli* removal between the sand and pumice columns ($p = 0.355$). In contrast, the *E. coli* removal by the dual media was slightly lower to that of sand and pumice, and the difference was statistically significant. The average *E. coli* removal in sand, dual media and pumice filters were 1.63 ± 0.45, 1.46 ± 0.37 and 1.68 ± 0.38 log units, respectively. For each filtration cycle, the results showed that the *E. coli* reduction improved with increasing days of filtration due to filter ripening. It is evident from Figure 4 that the *E. coli* removal followed a similar pattern to the head loss development, with the highest log removals observed towards the end of each filter run. The *E. coli* removal by the unripened filters was in the range of 0.9–1.8 log units and the corresponding range for ripened beds was 1.4–3.3 log units. Other studies based on laboratory experiments with sand filters have reported similar results (Duke *et al.* 2006; Stauber *et al.* 2006; Stauber 2007; Elliott *et al.* 2008). It should be noted that the results of tests with much longer resting times (72 h) are not included in Figure 4; these are discussed later.

In general, the degree of *E. coli* removal observed in this study is comparatively lower to that typically found with a conventional SSF. Logsdon (2008) reported that an SSF can achieve 2–4 log reductions of bacteria and Bellamy *et al.* (1985) found average log reductions of 2–3.4 and 1.8–2.8 in total coliforms and fecal coliforms, respectively, in pilot SSFs. The higher microbial reduction by an SSF compared to a BSF may be explained by the difference in filtration rates used. For a sand bed the initial filtration rate of a BSF is about 0.6 m/h while the filtration rate for a SSF is in the range of 0.15–0.3 m/h. This inverse relationship between bacterial removal and filtration rate was demonstrated by Bellamy *et al.* (1985), who recorded log reductions of total coliforms of 3.4, 2.5 and 2.0, corresponding to filtration rates of 0.04, 0.15 and 0.4 m/h, in pilot SSFs. Another reason for the variation could be due to differences in the nature and development of the biological layer (schmutzdecke). In an SSF, which is operated continuously, the biological layer is expected to develop progressively in content and depth, leading to a steady improvement in treatment performance (e.g. *E. coli* removal) with time. With the BSF, however, the intermittent operation and variable filtration rate, with their impacts on the availability of substrate and oxygen, may substantially alter the development of the biological layer. Further study is needed to assess and compare the fundamental nature, and the temporal and spatial variation in the composition and concentration, of biomass in the BSF and SSF processes to better explain the differences in treatment performance.

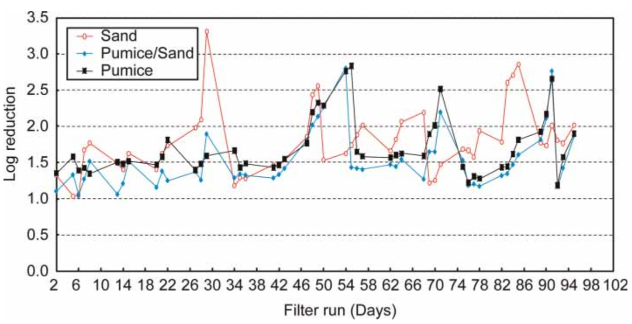

Figure 4 | Variation of *E. coli* removal (logarithmic reduction) with filter run time over several filter cycles.

Depth profiles

Profile studies indicated that in all the filter columns most of the contaminant removal and head loss development in ripened and clogging beds occurs in the top 5 cm of the beds (Figures 5(a)–(d), results of head loss not shown).

In a ripened and clogging pumice bed, more than 80% of turbidity removal occurred at the top 5 cm depth (Figure 5(a)). In the sand bed, however, the corresponding value for the clogging filter was 95% (Figure 5(c)). This may be due to variations in the extent of schmutzdecke development. For clean media, the removal of turbidity throughout the depth was greater for the pumice than the sand, and consequently there was less extent of further improvement in turbidity removal caused by the development of the schmutzdecke. Thus, the performance of the pumice filter is less dependent on the ripening process.

The *E. coli* profiles (Figures 5(b) and (d)) indicate that in ripened beds, bacterial removal by the sand column was concentrated in the top 5 cm layer, whereas in the pumice column, removal was distributed over a larger depth of the bed. For example, the percentage *E. coli* removal in the top 5 cm layers of ripened sand and pumice, compared to the full depth, were 85 and 44%, respectively. Although

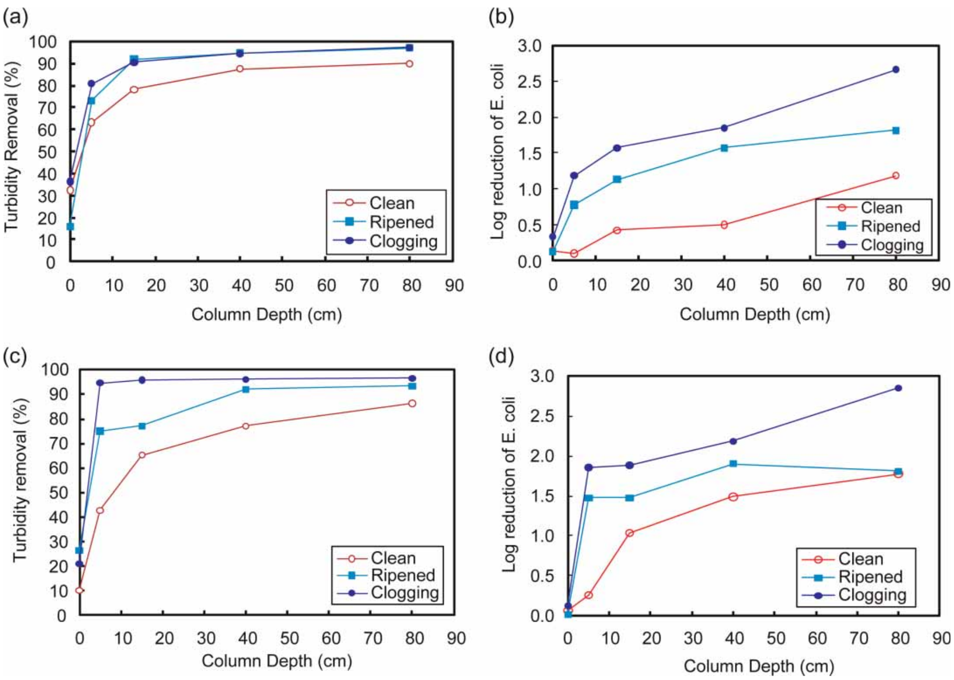

Figure 5 | Example of turbidity and *E. coli* removal-with-depth profiles for sand and pumice media under different filter bed conditions of clogging; (a) and (b) pumice bed; (c) and (d) sand bed.

the head loss development and turbidity removal of the ripened pumice bed were greatest in the top layer, the relatively low *E. coli* removal (~1 log) may suggest some deficiencies in the development and nature of the schmutzdecke. For both sand and pumice filters *E. coli* removal over the total bed depth was similar. Since the full bed depth was important in achieving the greatest *E. coli* removal, it is important to ensure in practice that there is an adequate bed depth for the BSF and that this should be determined on the basis of microbial removal rather than turbidity removal alone.

Effect of resting time

Several studies have indicated the importance of resting time for treatment efficiency, stability of the biological layer and the amount of water production per cycle (Baumgartner *et al*. 2007; Elliott *et al*. 2008; Kubare & Haarhoff 2010). From the perspective of microbial removal, longer resting times are desirable. Too long a resting time, however, can affect the microbial stability depending on the depth of the water column (which affects oxygen transfer) and the availability of nutrients. We have observed that increasing the resting time improves the *E. coli* removal performance. This may be attributed to the longer contact time available for predators (e.g. protozoa) to scavenge on the bacteria, and the natural die-off of *E. coli* when the water is allowed to remain in the bed in the absence of sufficient oxygen and nutrients. In this study, resting times of 1.5, 4, 20, 22 and 72 h were investigated. Figures 6(a)–(d) show the variation of *E. coli* removal for different resting times over several filtration cycles.

In general, log removals were higher for longer resting times (20 and 22 h). Statistical analyses indicated that in all filters the log removals of *E. coli* for 1.5 h resting time were significantly lower than for resting times of 20 and 22 h. On average, a difference of about 2 log units was observed. On the other hand, there was no statistically significant difference in *E. coli* removal between resting times of 4 and 20 h. Based on our results, a resting time of 4 h would be necessary to improve the filtrate quality significantly. The *E. coli* removal for a resting time of 72 h was the greatest (2.5–3.3 log units) although this may not be feasible in practice and may have a negative effect on the biological layer in the long term. Stauber (2007) compared the effect of resting time for *E. coli*, MS2 phage and

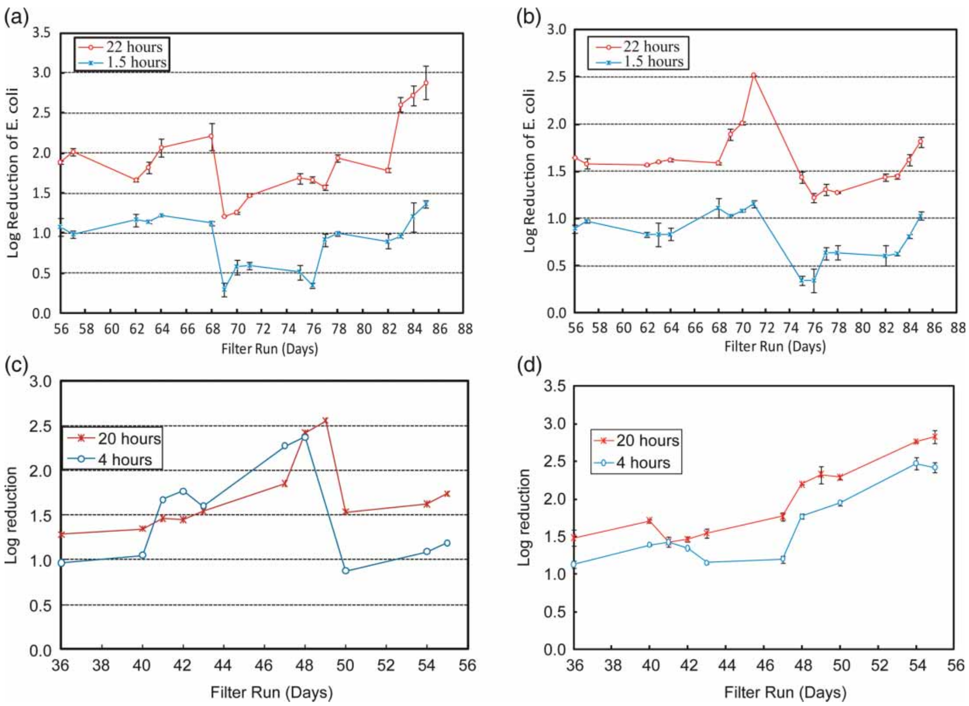

Figure 6 | Influence of resting time on *E. coli* removal: (a) sand 1.5 and 22 h; (b) pumice 1.5 and 22 h; (c) sand 4 and 20 h; (d) pumice 4 and 20 h.

PRD-1 and the results indicated that the reductions for water collected overnight were 2.2, 1.1 and 1.45 log units, respectively. The corresponding reductions for water samples collected on the same day were 1.9, 0.66 and 0.9 log units. Based on a comparison of echovirus type 12, bacteriophage and *E. coli* removal, Elliott *et al*. (2008) also reported that longer resting times gave a better performance.

In the case of turbidity removal it was observed that there was a small increase in the turbidity removal with resting time. However, the differences in turbidity removal with resting times when comparing the removal at 1.5 and 22 h, and at 4 and 20 h, were not statistically significant. The slightly better turbidity removal at longer resting times may be explained by the effects of particle sedimentation within filter pores and increasing opportunities for particle attachment to biofilms with increasing resting time.

Filtrate quality during filtration

In a continuously operated filter process (for example an SSF), the filtration rate affects the filtrate quality and higher filtration rates typically result in inferior treated water quality. In the usual operation of a BSF, filtration rates are higher initially with the sudden application of the charge, and decline with time. Thus, it was expected that the treated water quality would be relatively poor initially, and then improve subsequently as the filtration rate declined. In order to check this, grab samples were taken for incremental volumes of filtered water and analyzed for turbidity and *E. coli* (Figures 7(a) and (b)). The results indicated that the residual turbidity decreased initially (<10 min) and then gradually increased with time (10–60 min), in contrast to what was expected (Figure 7(a)). Since the BSF operates intermittently, the first filtrate samples corresponded to the water remaining at the bottom of the filter bed during the resting period, which was assumed to be of good quality; therefore, the filtrate turbidity at the beginning of the run was low. The subsequent increase in turbidity with time may be explained by the detachment and flushing through of particles in the upper layers of the BSF, which were either weakly attached to the grains or were suspended in the filter pores. However, although the pattern shows a clear increase in turbidity with time, the magnitude was relatively minor and the overall change would not warrant changes in the operation of BSF.

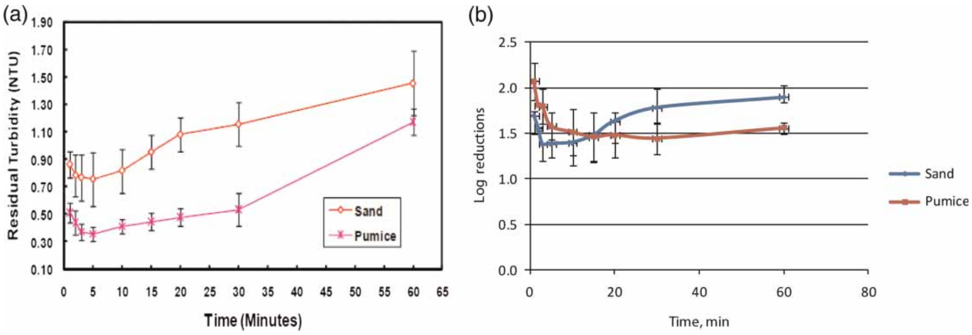

Figure 7 | Temporal variation of filtrate quality during a typical charge: (a) turbidity; (b) *E. coli*.

In the case of *E. coli* (Figure 7(b)) the influence of filtration rate was different in that initially the log removal was high, but subsequently declined in the first 5–10 min, and thereafter (>10 min) the log reduction increased (sand media) or remained approximately the same (pumice media). In this case, it is assumed that the water at the bottom of the bed and in the BSF supporting media would have a low microorganism concentration due to lack of oxygen and nutrients. The immediate and continuing increase in *E. coli* concentration observed in the period up to about 10 min may be explained by the higher filtration rate causing bacteria sloughing/detachment from biofilms on grain surfaces. With increasing time (>10 min), the decline in filtration rate would be expected lead to a reduction in *E. coli* numbers as observed. In their study Elliott *et al*. (2008) also reported that *E. coli* and virus removal decreased with time; this was attributed to attenuation during the resting time where the longer the water remained in the bed the greater the reduction.

CONCLUSIONS

BSFs normally use sand as the filter media and they have been shown to perform reasonably well as a household water treatment method. This study was carried out to enhance understanding of the process and to improve its performance. Thus, two main aspects have been considered: firstly, to evaluate the use of an alternative, high porosity media (pumice) to address the hydraulic limitations of sand media while maintaining a similar or better filtrate water quality; and secondly, to understand the effect of resting time on turbidity and *E. coli* removal. The results of an extensive period of experimental work involving parallel filter columns indicated that pumice was able to produce a similar quality of filtered water while giving an increase in the filtration rate (hence shorter treated water collection time) and a greater water production. Thus, the pumice media BSF produced about 30% more filtered water compared to the conventional sand BSF, which together with the reduced filtration time offer a significant improvement in the technology.

Earlier studies have referred to the importance of resting time. In this study the results of the tests involving different resting times indicated that 4 h or more would be necessary to achieve an adequate microbiological quality, while a resting time of only 1.5 h was unlikely to do so. It is recommended that users provide sufficient resting time (>4 h) to ensure that the physical and microbial quality of the filtered water is adequately high. Given the evidence that there may be some initial deterioration in the bacterial quality of the filtrate water after addition of a new charge of raw water, caused by the higher filtration rate, the number and volume of charges per day needs to be optimized in each case to achieve the maximum performance of the BSF unit.

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