

## Rational design of domestic biosand filters

Michael Kubare and Johannes Haarhoff

### ABSTRACT

A biosand filtration (BSF) unit is an intermittently operated slow sand filter designed for household use. This paper reviews the practical application of BSF, identifies the important design considerations and proposes a systematic design procedure. The media properties, water requirements, filter cycle time and water temperature are identified as the most important design input parameters. The resultant specifications are the water dosage volume, water production rate and media bed dimensions. We propose two parameters for characterising the filtration rate, namely the *initial* and *average clean* bed filtration rate. Mathematical expressions for these two parameters and the filtration time are derived. Guideline values for the filtration rate and the ratio of the pore volume to the water dosage volume are established and used as design checks. It is noted that the filtration rate is determined solely by the properties of the water temperature and the media—customary constraints posed by the bed area and the bed depth had been eliminated. Therefore the heart of BSF design lies in the careful and appropriate selection of the filter media. The design procedure proposed is illustrated with an example for a typical rural household in Venda, South Africa.

**Key words** | biosand filtration, filter media, home treatment, point-of-use treatment, slow sand filtration

**Michael Kubare**  
**Johannes Haarhoff** (corresponding author)  
Department of Civil Engineering Science,  
University of Johannesburg,  
P. O. Box 524, Auckland Park, 2006,  
Johannesburg,  
South Africa  
Tel.: +27 11 559 2148  
Fax: +27 11 559 2395  
E-mail: [jhaarhoff@uj.ac.za](mailto:jhaarhoff@uj.ac.za)

### INTRODUCTION

The central supply of piped drinking water has brought relief and convenience to a large part of the world's population. Those that are currently unserved, however, are increasingly problematic because of the small concentrations of users in remote, difficult to reach localities. Relying only on costly and resource-intensive centralised solutions such as piped treated water will leave hundreds of millions of people without safe drinking water far into the future (Mintz *et al.* 2001). The emphasis must therefore also shift towards self-sustaining, decentralised and affordable technologies that target the poorest and most vulnerable. Access to safe drinking water can be accelerated by provision of affordable technologies for point of use (POU) water treatment and storage in combination with improved hygiene behaviour. One of the most promising and accessible technologies emerging for POU drinking water treatment is biosand filtration (BSF).

The BSF unit is an intermittently operated slow sand filter (SSF) at small scale. The filter consists of a bed of fine sand supported by a layer of gravel enclosed in a box with appurtenances to deliver and collect the water. When water is poured onto the top of the filter, particulate matter is trapped at the surface, where a biological layer (also called the *schmutzdecke*) develops after a period of filter ripening. The biological layer is responsible for trapping and partly eliminating sediments, pathogens and other dissolved impurities from the water. Within the gravel support layer below the filter media are under-drains to remove the filtered water. Although designed primarily to improve microbial and aesthetic water quality, BSF has proven to be more versatile resulting in the development of adapted versions for enhanced removal of arsenic and fluoride (Hillman 2007).

As with most new innovations, the early development of BSF was marked by empirical designs, continuously

doi: 10.2166/aqua.2010.008

refined after practical experiences worldwide. BSF technology has now developed to the point where it should be translated into rational engineering design criteria. As there are no established comprehensive design criteria for BSF, the reproducibility and comparison of results from one setting to another is problematic. For example, in a demonstration project in Lao People's Democratic Republic, the microbiological performance of the BSF units was found to be sub-optimal compared to other field studies but it was not clear whether this was due to improper fabrication, media selection or the use of the filter (Clasen 2008). The primary purpose of this paper is therefore to provide a systematic review of the technical design considerations in order to propose a rational BSF design procedure for home use.

Once the design parameters have been established, all that remains is to suggest motivated guideline values for the respective parameters. This paper will suggest a first set of tentative guidelines, derived from the successful case studies reported in the literature. These studies provide a valuable starting point, but the suggested guidelines are not necessarily optimal—optimal guidelines will only be possible after many more systematic studies are available.

## PRACTICAL EXPERIENCE WITH BIOSAND FILTRATION

BSF had been promoted extensively for household use in developing countries, leading to its introduction in at least 36 countries with more than 500,000 people currently using the technology (Elliott *et al.* 2008). Application of BSF has been mainly through small-scale demonstration projects and during emergencies caused by natural disasters or war. Table 1 summarises some of the BSF projects that have been implemented in various countries.

The initial critical need of BSF is the provision of microbiologically safe drinking water to prevent the transmission of diarrhoeal diseases such as cholera, typhoid fever, amoebic and bacillary dysentery. The ability of BSF to improve microbial water quality, and the consequent reduction in diarrhoeal diseases in users, has therefore been the focus of most research on the effectiveness of this technology (Biosand 2006).

In addition to improving the microbial quality of water, BSF has also proved effective in removing pathogens, parasites, turbidity and some metals. Laboratory evidence suggests that the filter can remove up to 90% of viruses, >99.9% for protozoan parasites and helminths, and >75% of iron and manganese (Stauber *et al.* 2009). Consistently high removal rates of *E. coli* of 95–98% (Stauber *et al.* 2006) and 98.5% (Baker & Duke 2006) have been reported. Turbidity removal has been reported to be around 85% (Baker & Duke 2006; Stauber *et al.* 2006) with effluent turbidity values of <1 NTU (Buzunis 1995). Faecal coliform removal rates of 70.5% (Fewster *et al.* 2004) and 96% (Buzunis 1995) have been reported in field and laboratory studies, respectively; 80% removal of heterotrophic bacterial populations, >99.9% removal of *Giardia lamblia* cysts, 99.98% removal of *Cryptosporidium* sp. and 50–90% removal of organic and inorganic toxicants have been demonstrated in laboratory studies (Palmateer *et al.* 1999). Similar to other filtration technologies, BSF is not effective in the removal of colour or dissolved compounds.

During a six-month-long field study in Haiti in 2005, a 47% lower incidence rate of diarrhoeal diseases was observed for households using the filter compared with households not using any form of POU technology (Stauber *et al.* 2009) while an earlier study reviewed a considerably lower incidence of diarrhoea per child per year of 1.7 when drinking BSF water compared with 4.8 when drinking unfiltered water (Stauber *et al.* 2006).

For any technology to achieve widespread and sustained use, it must meet the acceptability criteria of the targeted users. Some of the criteria that should be met by household water treatment devices for developing countries include: (1) observable improvement in water quality in the form of taste, smell and appearance; (2) easy to operate and maintain; (3) affordable and durable; (4) manufactured using local skills and materials; (5) no use of energy; (6) should produce enough water for the household; (7) the technology should be sustainable; and (8) should be robust enough to perform well under varying operating conditions. CAWST (2007) claims that BSF was the most affordable, efficient and easy-to-use of all the household drinking water treatment systems they had identified and evaluated in field studies.

**Table 1** | Examples of BSF projects implemented around the world

| Place                            | Implementing organisation   | Application  | Year      | Reference   |
|----------------------------------|---|--|-----------|---|
| Artibonite Valley, Haiti         | Community Development Division at Hospital Albert Schweitzer                  | 2,000 BSF units installed in 107 households  | 1999–2004 | Duke <i>et al.</i> (2006)   |
| Machakos District, Kenya         | Medair  | 2,000 BSF units sold to individual households between 1999 and 2003  | 1999–2003 | Fewster <i>et al.</i> (2004)  |
| Ethiopia                         | Samaritan's Purse, Canada through the Ethiopian Kale Heywet Church            | 1,300 BSF units installed in eight villages during 1999–2001. 8,000 BSF installed during 2003–2006   | 1999–2006 | Earwaker (2006)   |
| Cambodia                         | Hagar and Cambodia Global Action supported by Samaritan's Purse International | Hagar installed over 20,000 BSF units since 2001. CGA installed over 2,600 BSF units since 2002. Cambodia has largest number of BSF units in the world: 21,000 households using BSF in the country | 2001–2002 | Liang <i>et al.</i> (2007)  |
| Honduras                         | Pure Water for the World  | 8,400 BSF units installed in 135 communities   | 2000      | CAWST (2007)  |
| Nicaragua                        | Various   | 2,600 BSF units installed  | 1999–2004 | Vanderzwaag (2007)  |
| Dominican Republic               | Various   | More than 8,000 BSF units (concrete version) have been installed   | 2000–2008 | Stauber <i>et al.</i> (2009)  |
| Lumbini District, Nepal          | Individuals   | 12 BSF units introduced in homes and schools of five different villages of the district  | 2000      | Lukacs (2002)   |
| Nicaragua                        | USAID   | BSF units distributed to provide safe drinking water after the country had been hit by hurricane Mitch   | 1998      | <a href="http://www.biosandfilter.org">http://www.biosandfilter.org</a> |
| Darfur, West Sudan               | Medair  | BSF units distributed to provide safe drinking water to people displaced by war  | 2003      | <a href="http://www.biosandfilter.org">http://www.biosandfilter.org</a> |
| Lao People's Democratic Republic | Nam Saat and CAWST  | Demonstration project during which 320 BSF units were installed in two rural communities   | 2008      | Clasen (2008)   |

BSF technology had been favourably accepted by users, on a number of counts:

- Considerable improvement in taste, odour and appearance of the water was evident (Vanderzwaag 2007).
- Like other filtration technologies, BSF does not introduce chemicals into the water. Chemicals such as chlorine may affect its acceptability due to objections about taste and odour (Clasen 2008).
- The health of the family was perceived to have improved after using the filter (Vanderzwaag 2007).
- BSF is able to operate well under a wide range of conditions, such as temperature, pH and turbidity.
- Among the features that have made BSF widely accepted is the ease of fabrication from local materials. It is thus more affordable and presents an opportunity for local entrepreneurs; it is durable and robust with no ongoing

costs and is simple to clean and maintain. The concrete version of the filter costs between US\$10 and US\$30 depending on local conditions (CAWST 2007). By using materials less heavy and expensive than concrete, such as plastic or metal where they are available, BSF units may even be cheaper.

Evidently, BSF meets the acceptability criteria of its target users, thus potentially encouraging routine use without extensive intervention to promote behavioural change. In a survey of 107 households using BSF for treatment of drinking water in Haiti (Baker & Duke 2006), a high level of satisfaction (>95%) among users of BSF was reported regarding ease of use and operation; quantity of water produced by the filter; appearance, taste and smell of the water after treatment; and health improvements from use of BSF. Regarding the sustainability of BSF, a remarkable 97% of the BSF units were still in use 5 years after installation, which confirmed the high level of satisfaction among the users and durability of BSF. Similar high levels of satisfaction among users have been reported in other field studies (Liang *et al.* 2007).

## TYPICAL OPERATION OF DOMESTIC BIOSAND FILTERS

A typical BSF unit will be positioned in the home, together with two plastic containers of equal volume. The one container will be used to bring water from the source into the home, while the other container will be empty. At periodic intervals (typically in the morning and in the evening), the water from the first container will be carefully emptied into the BSF unit, through a diffuser plate into the submerged headspace above the filter media. The diffuser plate dissipates the initial force of the water to prevent the disturbance of the media surface and the biological layer. At the same time, the empty container is positioned below the BSF outlet to collect the filtrate. The water added will raise the water level in the headspace and the unbalanced head between the headspace and outlet will start filtration. At first, the head difference between the water level and the outlet will be large and the filtration rate will be at its maximum. As the water level drops, the rate will exponentially decrease. By the time all the excess water has drained away, the collecting container should be full and ready for use.

After installation, the filter media should be clean and the filtration time will be fairly rapid. A start-up time of 2–3 weeks for new media is recommended to allow for the development of the biological layer before the water is suitable for drinking (CAWST 2007; Hillman 2007). As the media gets blocked and the biological layer on the media surface develops, the filtration rate will slow down. Eventually, the media blocking will reach a point when the filtration time becomes intolerably long, which signals the need for filter cleaning. It is obvious that very dirty raw water will lead to rapid media blocking—a maximum raw water turbidity of less than 30 NTU had been recommended to ensure acceptably long periods between media cleaning, or else a sedimentation step should be included (CAWST 2007). Stauber *et al.* (2006) noted a 25% decrease in filter flow rate during 25 days of operation with low turbidity influent water.

The cleaning of the media bed is achieved by controlled agitation of the top few centimetres of media. This procedure involves manually stirring the top layer of the sand by hand ensuring that the sand grains rub against each other in order to release the trapped solids. The solids captured in the media will now be suspended in the water in the headspace above the media. This water is scooped off with a small cup and discarded until all the dirty water had been disposed of. This gentle maintenance procedure has the advantage of leaving enough biofilm on the media grains to shorten the subsequent start-up time. The filter may be returned to use immediately, but it is recommended that the filter be flushed (i.e. filter to waste) for 2 days following this maintenance procedure (Elliott *et al.* 2008). Removal of the top few centimetres for thorough washing or disposal, as practised for large, conventional slow sand filters, is not recommended as this will result in longer start-up time which is not convenient for users with no alternative water sources.

## DESIGN CONSIDERATIONS

### The filtration rate

The filtration rate, or hydraulic loading, is the key design parameter for all filtration processes. When working with constant-rate processes, the filtration rate is simply the flow rate divided by the area of the media surface. BSF is not

a constant-rate process, as the filtration rate slows down rapidly as the water level in the headspace drops—a change observed over a time-scale of minutes. Moreover, the filtration rate will become progressively slower as the media gradually blocks—a change observed over a time-scale of days or weeks.

- One way of expressing the biosand filtration rate is to use the *initial clean bed filtration rate* (i.e. when the water level above the media is at a maximum) for *clean* filter media. The initial clean bed filtration rate is the instantaneous rate at the very start of the filtration period and is best calculated using equations developed later in this paper.
- Another expression of the biosand filtration rate is the *average clean bed filtration rate*, defined as the dosage volume divided by the time it takes for its complete filtration through *clean* sand media. This parameter can be experimentally measured, or calculated using equations developed later in this paper.
- The *maximum filtration rate* has been reported in the literature, which was measured just after the introduction of a charge. In the absence of an exact definition, the measurement of the maximum filtration rate is likely to be variable from one researcher to another and from one setting to another. This parameter is not further considered in this paper.

The difference between the initial and average clean bed filtration rates is significant, with the former as much as four times higher than the latter. This difference will be quantified using the methods developed further in this paper. Both of these are difficult to measure experimentally. The measurement of the initial clean bed filtration rate is normally done volumetrically, but during the finite time it takes to fill the container, the filtration rate has already dropped from the initial maximum. The measurement of the average clean bed filtration rate is complicated by the vague endpoint of the measurement—when exactly does the flow really stop in an asymptotic case?

Typical filtration rates for SSF range from  $0.1$  to  $0.3 \text{ m h}^{-1}$  with the units operating continuously. Because BSF is operated intermittently, some water is always stored in the media pores of the filter and undergoes further quality improvement during the resting period (Baumgartner *et al.*

2007; Elliott *et al.* 2008). Therefore, provided BSF is operated with adequate resting time, higher filtration velocities can be used in BSF compared with SSF. There are no published guidelines for the initial clean bed filtration rate. As a tentative starting point, a value between  $1$  and  $4 \text{ m h}^{-1}$  is suggested, which is gleaned from back-calculation using some reported case studies. Other researchers in this field are urged to critically consider this key parameter in their further work.

### The water depth in the headspace

The depth of the water above the media has to balance two concerns. The water depth, in combination with the diffuser plate, must allow the effective dissipation of the inlet energy of the water, to prevent the disturbance of the biological layer at the very top of the media. Also, the supernatant ensures that the filter can be operated intermittently by providing nutrients to the biological layer during the resting period. At the same time, the biological layer requires a constant supply of oxygen, which has to diffuse from the atmosphere through the water layer. The first concern suggests a large water depth, and the second concern calls for a small water depth. Field studies have reported a compromise water depth of about  $50 \text{ mm}$  (see Table 2). Practically, the water depth above the media is manipulated by adjusting the level of the filter outlet for plastic BSF units with external outlet tubes. For concrete BSF units with the outlet cast integral to the media housing, the outlet is not vertically adjustable. The only means of manipulating the water depth in the headspace is to increase or decrease the sand layer depth.

### Media depth

The biological layer develops in the top  $50$  to  $100 \text{ mm}$  of the media layer and is responsible for pathogen inactivation and the removal of organics from the influent water. The depth of the biological layer is controlled by the depth of the supernatant and influent water quality. The remainder of the fine media serves mainly to restrict migration of bacteria into the filtrate (by adsorption and starvation) and for this reason a minimum depth should be specified.

**Table 2** | Typical design values for the SSF and BSF

| Parameter                                       |                                 | Filter type |              | Reference*  |
|---|---------------------------------|-------------|--------------|---|
|   |                                 | SSF         | BSF          |   |
| Media properties                                | Effective dia. ( $d_{10}$ , mm) | 0.1–0.3     | 0.15–0.3     | CAWST (2007), Lukacs (2002), Hillman (2007) and Manz <i>et al.</i> (1993) |
|   |                                 |             | 0.19–0.22    |   |
|   | Uniformity coefficient          | <3.0        | 1.5–3.0      | Lukacs (2002), CAWST (2007) and Hillman (2007)                            |
|   |                                 |             | 3.5–4.0      | Elliott <i>et al.</i> (2008)  |
| Filtration velocity ( $v$ , $\text{m h}^{-1}$ ) |                                 | 0.1–0.3     | 0.6          | Lukacs (2002), CAWST (2007) and Hillman (2007)                            |
|   |                                 |             | 0.16–0.6     | Lukacs (2002)   |
|   |                                 |             | 0.5–1.1      | Elliott <i>et al.</i> (2008)  |
|   |                                 |             | 2 (maximum)  | Fewster <i>et al.</i> (2004)  |
| Filtration time ( $t_F$ , h)                    |                                 | 0           | 12           | Baumgartner <i>et al.</i> (2007)  |
| Resting time ( $t_R$ , h)                       |                                 |             | 18–24        | Elliott <i>et al.</i> (2008)  |
|   |                                 |             | 6–12         | CAWST (2007)  |
|   |                                 |             | 50 (maximum) | Lukacs (2002), Duke <i>et al.</i> (2006), CAWST (2007) and Hillman (2007) |
|   |                                 |             | 20–70        | Elliott <i>et al.</i> (2008)  |
| Supernatant depth ( $s$ , mm)                   |                                 | –           | >0.4         | Elliott <i>et al.</i> (2008)  |
|   |                                 |             | >0.46        | Hillman (2007)  |
| Media depth ( $L$ , m)                          |                                 | 0.6–1.0     | 50           | Elliott <i>et al.</i> (2008)  |
| Gravel support (mm)                             |                                 |             | 50           | Elliott <i>et al.</i> (2008)  |
| Under-drain (mm)                                |                                 |             | 50           | Elliott <i>et al.</i> (2008)  |
| Start-up time (days)                            |                                 |             | 14–21        | CAWST (2007) and Hillman (2007)   |

\*The references refer to the values for BSF. Values for the SSF have been obtained from Fox *et al.* (1994) and Campos *et al.* (2002).

### The volume of the media

As alluded to earlier, the water stored in the media pores of the filter undergoes further quality improvement during the resting period. To fully exploit this phenomenon, the pore volume within the media bed must be such that water poured onto the BSF unit will not appear at the outlet until the next dosage of raw water. An important design consideration is therefore that the media volume should have an adequate pore volume to contain at least the entire dosage volume.

The retention time of the water within the pores of the media bed is strongly dependent upon the plug flow characteristics of the BSF unit. With complete plug flow, all water will have the same retention time in the media. With some axial dispersion due to the tortuous flow paths through the porous media, the water leaving will have a range of retention times. Although tracer tests performed on full-scale

BSF units indicated a high degree of plug flow, because of the variability in media porosity, the likelihood of significant settling of media after loading and hydraulic short-circuiting, a safety factor should be applied. Experimental evidence suggests that the removal of *E. coli* bacteria was compromised when the dosage volume was more than 70% of the pore volume (Elliott *et al.* 2008). From this, it is suggested that the media volume should have  $1/0.7 = 1.4$  times more pore volume than the dosage volume.

### The grading of the filter media

The treatment efficiency of the SSF is attributed to its fine effective media size, biodegradation in the biological layer and low filtration velocity (Campos *et al.* 2002). Therefore, ideally the media for BSF should have similar physical

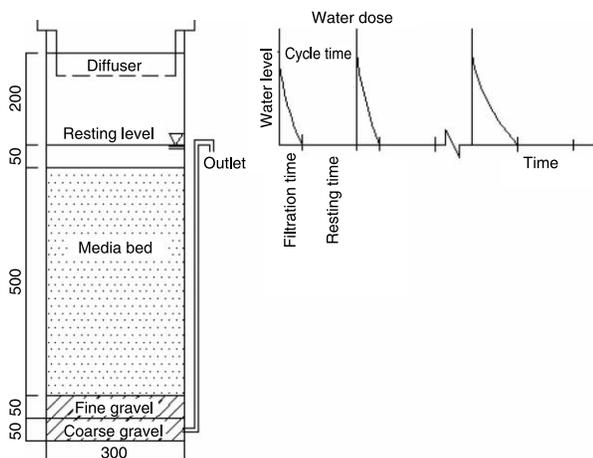
properties to that used in the SSF, namely an effective size in the range of 0.1 to 0.3 mm (Campos *et al.* 2002). Media that is too coarse will result in an initial filtration rate which is too high with unacceptable turbidity in the filtrate. The media reported from field studies of BSF indicate a similar media size range between 0.15 and 0.3 mm (see Table 2).

Of similar importance is the uniformity coefficient (UC) of the media, defined as  $d_{60}/d_{10}$ . For rapid sand filtration, which is washed by fluidisation, a narrow window for grain size has to be specified with the UC typically less than 1.4. For SSF, the media is cleaned by scraping and narrow media grading is less important. For SSF, an UC of up to 3 is normally acceptable. For BSF, where the filter is manually washed, narrow media grading is even less important and a lenient limit of up to 5 had been proposed (see Table 2).

### The BSF use cycle and its production capacity

The typical use of a BSF over time is depicted in Figure 1. One *use cycle* consists of a *filtration period* (during which the downstream container is filled), followed by a *resting period* with no flow. As the filter media blocks, the filtration period will become longer, but the overall use cycle will probably stay the same, as it depends on the daily routine of the household.

BSF units with a tapered bottom have also been constructed but there is no evidence to suggest that this can improve the filter hydraulics or treatment efficiency—this is dictated mainly by construction and other practical



**Figure 1** | Schematic diagram of a BSF; the typical use cycle shows the progressive increase in the filtration time during use.

considerations. For concrete BSF units, this allows easy removal of the steel filter mould. For plastic filters, this allows them to be stacked for shipping (before the PVC outlet tube is attached).

The literature provides valuable guidance with respect to the required lengths of the filtration and resting periods, as summarised in Table 2. The filtration period, when the media is relatively clean, is a matter of minutes—an issue which will soon be further investigated. Of importance now is to note that the acceptability of BSF is compromised if the filtration period is too long. A maximum acceptable filtration time of two hours has been indicated in the literature (Fewster *et al.* 2004). This seems to be the resistance point for rural users, after which users become impatient and may skip the use of BSF altogether. The required resting period, by comparison, is much longer—from 6 to 24 hours. For practical purposes, the duration of the filtration time is so short in relation to the overall use cycle that one can assume that the resting period will be approximately equal to the overall use cycle.

The resting time is of importance from the perspective of treatment efficiency, the viability of the biological layer and the water production rate. The resting time provides the contact time for microbial removal processes and thus a long resting time will be desirable from this perspective. However, too long a resting period (which results in less frequent dosage of water) may reduce the viability of the biological layer because the survival of the microorganisms relies on the periodic inflow of source water for nutrients (Baumgartner *et al.* 2007). Additionally, too long a resting period will reduce the water production rate and thus fail to satisfy household water requirements. Therefore careful selection of the resting period is vital in order to balance these competing objectives.

Should one assume 12 hours for the resting period, it means that the BSF unit can be dosed twice a day—in the early morning and in the evening. The daily production capacity of a BSF for this scenario is thus twice the container volume. Should BSF be designed for a dosage volume of 20 litres, the daily production capacity is, at most, 40 litres per day.

The size of the household container is determined by other considerations. The vast majority of household containers are those which are primarily manufactured for

use in industry. Ergonomic considerations suggest a maximum industrial container size of between 20 and 25 litres. The household container thus has a volume of mostly between 20 and 25 litres. This explains the reported range of daily water production rate of 20 to 40 litres (one or two containers for the water dosage volume applied in field applications of BSF in developing countries; Sobsey 2002; Stauber *et al.* 2006; CAWST 2007; Elliott *et al.* 2008).

### MATHEMATICAL MODELLING OF HEAD LOSS THROUGH GRANULAR MEDIA

A key limitation for BSF design is to prevent an excessively high initial clean bed filtration velocity. It is therefore necessary to develop a simplified expression to relate the initial clean bed filtration velocity to the media properties. The starting point is the well-known Ergun Equation (AWWA 1991):

$$\frac{h}{L} = \left[ \frac{150 \cdot \mu \cdot (1 - \varepsilon)^2}{\rho \cdot g \cdot d^2 \cdot \psi^2 \cdot \varepsilon^3} \right] \cdot V + \left[ \frac{1.75 \cdot (1 - \varepsilon)}{g \cdot d \cdot \psi \cdot \varepsilon^3} \right] \cdot V^2 \quad (1)$$

where:

- $h$  = head loss through media bed (m)
- $L$  = depth of media bed (m)
- $V$  = filtration rate ( $\text{m s}^{-1}$ )
- $\varepsilon$  = media bed porosity (-)
- $\psi$  = average surface area sphericity (-)
- $d$  = geometric grain diameter (m)
- $g$  = gravitational acceleration ( $\text{m s}^{-2}$ )
- $\rho$  = density of water ( $\text{kg m}^{-3}$ )
- $\mu$  = dynamic viscosity of water ( $\text{kg m}^{-1} \text{s}^{-1}$ )

The attractive feature of the Ergun equation is that it has both laminar (1st term) and turbulent terms (2nd term). By comparing the relative magnitude of the two terms, the flow regime can be classified as predominantly laminar or turbulent. Using the typical design values for BSF shown in Table 2, it can be shown that the flow in the BSF unit is predominantly laminar due to the low filtration velocity and the relatively small grains. The second turbulent term on the RHS of Equation (1) can thus be ignored.

The Ergun equation applies to a specific grain diameter, which is taken as the geometric mean diameter of the

largest and smallest grain diameter in the media bed. When dealing with filter media with a wide range of diameters, it is necessary to conceptually separate the media into a number of fractions to limit the range of diameters within each fraction. The Ergun equation is now applied to each of the fractions in turn, by assuming that each fraction has a depth of  $\alpha \cdot L$ . This transforms Equation (1) into:

$$h = \left[ \frac{150 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L \cdot V}{\rho \cdot g \cdot \psi^2 \cdot \varepsilon^3} \right] \cdot \sum_{i=1}^n \frac{\alpha_i}{d_i^2} \quad (2)$$

where:

- $n$  = number of size fractions (-)
- $\alpha$  = fraction of the total media depth (-)
- $d$  = geometric mean of diameter of each fraction (m)

For conventional large-scale applications, the fractionation of the media is done by sieve analysis and Equation (2) can be directly applied using the results of the sieve analysis. For BSF, as shown above, the media specifications are not so stringent and a simplified proposal follows which will require only the effective size and the uniformity coefficient of the media. Making the reasonable assumption that the logarithm of the grain diameters is normally distributed (Cleasby 1990), the standard deviation can be linked to the uniformity coefficient as follows:

$$\ln UC = \ln d_{60} - \ln d_{10} = (1.282 + 0.253) \cdot \sigma = 1.535 \cdot \sigma \quad (3)$$

Knowing the standard deviation, the grain diameter at any percentile value can be expressed in terms of  $d_{10}$  and the UC. For example,  $d_{85}$  would be calculated as follows:

$\ln d_{10}$  is  $1.282 \cdot \sigma$  to the left of the median, while  $\ln d_{85}$  is  $1.036 \cdot \sigma$  to the right of the median. The two values are therefore  $2.318 \cdot \sigma$  apart:

$$\ln d_{85} - \ln d_{10} = 2.318 \cdot \sigma = \frac{2.318}{1.535} \cdot \ln UC$$

From which follows:

$$d_{85} = d_{10} \cdot UC^{2.318/1.535} \quad (4)$$

If the media bed is assumed to be composed of 10 discrete layers of equal depth, then  $\alpha = 0.1$  for all the layers.

For 10 such layers of equal depth, Equation (2) can be rewritten as:

$$h = \left[ \frac{15 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L}{\rho \cdot g \cdot \psi^2 \cdot \varepsilon^3 \cdot d_{10}^2} \right] \cdot f(\text{UC}) \cdot V \quad (5)$$

The function  $f(\text{UC})$  requires tedious calculation and is more conveniently represented in graphical form as shown in Figure 2. To enable the meaningful evaluation of  $f(\text{UC})$ , assumptions had to be made regarding the minimum and maximum grain diameters. The minimum diameter was taken as 70% of  $d_{10}$ , and the maximum as 130% of  $d_{90}$ .

## MATHEMATICAL MODELLING OF BIOSAND FILTRATION

The importance of the initial clean bed filtration rate  $v_{\text{ini}}$  was pointed out earlier. Having developed a mathematical relationship between head loss, media properties and filtration velocity in the previous section, the initial clean bed velocity  $v_{\text{ini}}$  can be incorporated into Equation (5) to give:

$$h = \left[ \frac{15 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L}{\rho \cdot g \cdot \psi^2 \cdot \varepsilon^3 \cdot d_{10}^2} \right] \cdot f(\text{UC}) \cdot v_{\text{ini}} \quad (6)$$

A water dosage volume  $V_D$  will cause the water level in the filter to increase by a height ( $h$ ), which provides the initial head loss. For a BSF with media surface area ( $A$ ),  $V_D$  can be expressed as:

$$V_D = A \cdot h \quad (7)$$

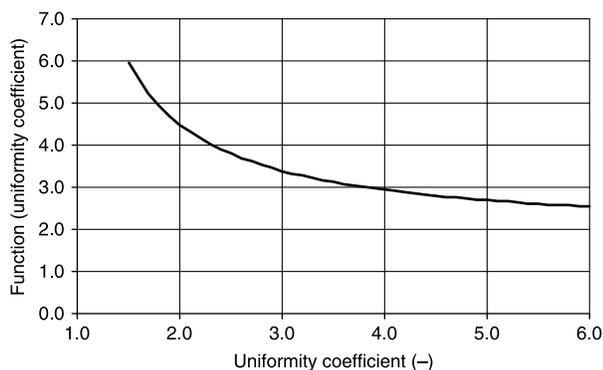


Figure 2 | Graphical representation of function (UC).

Substituting Equation (6) into (7) yields the following expression for the media volume ( $V_{\text{media}} = L \cdot A$ ):

$$V_{\text{media}} = \left[ \frac{\rho \cdot g \cdot \psi^2 \cdot \varepsilon^3 \cdot d_{10}^2}{15 \cdot \mu \cdot (1 - \varepsilon)^2} \right] \cdot \frac{V_D}{f(\text{UC}) \cdot v_{\text{ini}}} \quad (8)$$

Equation (8) shows that, for given media properties and filtration velocity, the volume of the filter media should be directly proportional to the dosage volume. Somewhat surprisingly, both the initial head loss and the media depth had been eliminated. A tall filter with small media surface will yield exactly the same initial clean bed filtration rate as a short filter with large media surface, provided the media volume stays constant. In the first case, the water will rise substantially in the BSF unit, but the filtration rate will be checked by the deeper media bed. In the second, the shallower bed will produce less flow resistance, but the unbalanced head will be smaller.

Equation (8) ensures that the initial clean bed filtration rate will not be exceeded. There is a second concern: namely, to ensure that water does not pass completely through the BSF unit during a single filtration cycle (thus ensuring contact with the media during the ensuing resting period). The pores within the media bed must be adequate to contain at least the full dosage volume:

$$V_{\text{media}} > \frac{V_D}{\varepsilon} \quad (9)$$

Introducing a safety factor (SF) into Equation (9) to account for hydraulic short-circuiting (non-perfect plug flow conditions), Equation (9) can be rewritten:

$$V_{\text{media}} = \text{SF} \cdot \frac{V_D}{\varepsilon} \quad (10)$$

## RELATIONSHIP BETWEEN THE INITIAL AND AVERAGE CLEAN BED FILTRATION RATE

The distinction between the initial and average clean bed filtration rates has already been raised. In this section, a mathematical relationship will link the initial and average clean bed filtration rates. As alluded to above, BSF is not a constant rate process since the filtration rate varies as the

water level in the headspace drops. Therefore the filtration rate ( $V$ ) in the Ergun Equation (Equation (1)) can be expressed as  $dh/dt$ . Substituting for  $V$  in Equation (1) and ignoring the second turbulent term leads to a differential equation:

$$\frac{h}{L} = \left[ \frac{150 \cdot \mu \cdot (1 - \varepsilon)^2}{\rho \cdot g \cdot d^2 \cdot \psi^2 \cdot \varepsilon^3} \right] \cdot \frac{dh}{dt} \quad (11)$$

Integration of Equation (11) for the water level to drop from  $h_0$  to  $h_1$  during the filtration time ( $t_F$ ) gives:

$$\frac{1}{L} \int_0^{t_F} 1 dt = \left[ \frac{150 \cdot \mu \cdot (1 - \varepsilon)^2}{\rho \cdot g \cdot d^2 \cdot \psi^2 \cdot \varepsilon^3} \right] \cdot \int_{h_0}^{h_1} \frac{1}{h} dh \quad (12)$$

Equation (12) gives the following expression for the filtration time:

$$t_F = \frac{150 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L}{\rho \cdot g \cdot d^2 \cdot \psi^2 \cdot \varepsilon^3} \cdot \ln \frac{h_1}{h_0} \quad (13)$$

Assuming normal distribution of the logarithm of the grain diameters, and that the media is composed of 10 discrete layers as done previously, Equation (13) can be rewritten as:

$$t_F = \frac{15 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L}{\rho \cdot g \cdot d_{10}^2 \cdot \psi^2 \cdot \varepsilon^3} \cdot f(\text{UC}) \cdot \ln \frac{h_1}{h_0} \quad (14)$$

The average clean bed filtration velocity can then be expressed as:

$$v_{\text{ave}} = \frac{\Delta h}{t_F} = \frac{\Delta h \cdot \rho \cdot g \cdot d_{10}^2 \cdot \psi^2 \cdot \varepsilon^3}{15 \cdot \mu \cdot (1 - \varepsilon)^2 \cdot L \cdot f(\text{UC}) \cdot \ln(h_1/h_0)} \quad (15)$$

Comparison of this equation with Equation (8) provides the following ratio:

$$\frac{v_{\text{ini}}}{v_{\text{ave}}} = \frac{V_D}{V_{\text{media}}} \cdot \frac{L}{\Delta h} \ln \frac{h_1}{h_0} \quad (16)$$

The ratio is strongly dependent on the assumed end-point of the filtration cycle. For example, if it is taken as the point where 99% of the dosed volume had been filtered, then  $h_1/h_0 = 0.01$  (this would correspond to the point where 200 ml of water of a 20 litre container remains unfiltered).

## APPLICATION OF THE BIOSAND FILTRATION MODEL

### Water properties

Both the density and viscosity of water vary with the water temperature. The following relationships are commonly used:

$$\rho = \frac{999.8 + 16.96T - 7.987 \times 10^{-3} \times T^2 - 4.617 \times 10^{-5} \times T^3}{1 + 1.688 \times 10^{-2} \times T} \quad (17)$$

$$\mu = 1.787 \times 10^{-3} - 5.857 \times 10^{-5} \times T + 1.195 \times 10^{-6} \times T^2 - 1.115 \times 10^{-8} \times T^3 \quad (18)$$

where  $T$  = water temperature ( $^{\circ}\text{C}$ ).

The water temperature in the rural home varies widely from summer to winter. In winter, the water temperatures will drop close to freezing. In summer, the water temperature in a small container in a rural South African home could rise to  $30^{\circ}\text{C}$ .

### Media properties

Typical values for effective size and uniformity coefficient for the fine media used in BSF are given in Table 2. A minimum media depth of 0.4 m has been suggested (Elliott *et al.* 2008). The porosity of granular silica sand (the media universally used for filtration) ranges from 0.40 to 0.50, with an assumed average of 0.45. The sphericity of the media is a measure of its roundness and ranges from 0.70 (angular grains) to about 0.90 (grains rounded by water or wind), with an assumed average of 0.80.

The gravel support serves to support the sand bed and to permit uniform drainage of the overlying sand. Uniform drainage requires minimal head loss. To achieve both functions, the gravel support must be graded, with finer material at the top and coarser material at the bottom. The top layer of the gravel support should not allow the migration of sand from the sand bed and the gravel of any layer should not migrate to a lower level. Additionally, the bottom layer should not permit entry of gravel to the under-drain orifices (AWWA 1991). Based on the above considerations, the following rules for the design of the

gravel support layers have been proposed (Huisman & Wood 1974):

1.  $d_{90}/d_{10} \leq 1.4$  for each support layer
2.  $d_{10}$  (lower layer)/ $d_{10}$  (upper layer)  $\leq 4$
3.  $d_{10}$  (top layer)/ $d_{15}$  (sand)  $\geq 4$
4.  $d_{10}$  (top layer)/ $d_{85}$  (sand)  $\leq 4$
5.  $d_{10}$  (bottom layer)  $\geq 2 * d$ (drain orifice diameter)

Furthermore, the thickness of each gravel support layer should be greater than three times the diameter of the largest stones (Huisman & Wood 1974). It follows then from rule 5 that the total depth of the gravel support is determined by the size of the orifices in the under-drain (AWWA 1991). Thus small orifices in the under-drain would permit a smaller depth of the gravel support.

An alternative and simpler method for grading of the media support layers is a time-tried rule dating back to the 1930s (Baylis 1935): namely, that the average grain size ( $d_{50}$ ) of each successive coarser layer must be not more than twice the average grain size of the layer above it. If typical BSF media had a  $d_{10}$  of 0.3 mm and a UC of, say, 3, then the average grain diameter would be 0.75 mm (from Equation (4)). The first support layer then should have an average size of less than 1.5 mm and the second layer an average size of less than 3.0 mm.

### Hydraulic properties

The most important hydraulic parameters are the initial clean bed filtration velocity ( $v_{ini}$ ) and the safety factor (SF), discussed earlier. A safety factor of 1.4 has been mentioned above. Equation (8) can be used to calculate  $v_{ini}$  for given media properties. It may be somewhat surprising that  $v_{ini}$

(Equation (8)) is determined solely by the water temperature, the media properties and the media volume. As there is little one can do about the water temperature (which determines the water density and viscosity), the heart of BSF design thus lies in the careful and appropriate selection of the media and sizing of the media bed.

### Sensitivity analysis

Table 3 lists the variables that determine  $v_{ini}$  according to Equation (8). For each variable, its typical average, minimum and maximum value is presented based on the literature reviewed above. The corresponding value of  $v_{ini}$  is then calculated as each variable is changed over its range to see which variables have the largest influence on  $v_{ini}$ .

It can be concluded from Table 3 that the most critical variables are the effective diameter and porosity with a sensitivity range of 200% and 132%, respectively. These are media properties and therefore media selection is critical for the successful design of BSF.

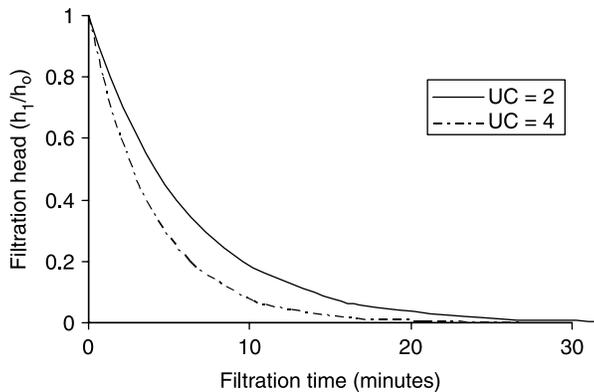
### Quality control on filter media

The mathematical model can also be applied to check the suitability of the filter media. The time it takes to filter away one container of water is a good indication of the grading of the media. If the time is too short, the media is too coarse and the desired initial clean bed filtration velocity will be exceeded.

Figure 3 shows a plot of the clean bed filtration head versus the filtration time for the average conditions given in Table 3, and a media depth of 0.4 m by application of

**Table 3** | Sensitivity analysis of the variables that determine  $v_{ini}$

| Description                              | Value |      | Effect on $v_{ini}$ ( $\text{m h}^{-1}$ ) |      |      | Range (%) |     |
|--|-------|------|---|------|------|-----------|-----|
|  | Min   | Ave  | Max                                       | Min  | Ave  |           | Max |
| Safety factor                            | 1.20  | 1.40 | 1.60                                      | 2.87 | 3.35 | 3.83      | 29  |
| Water temperature ( $^{\circ}\text{C}$ ) | 5.0   | 20.0 | 30.0                                      | 1.74 | 2.64 | 3.28      | 58  |
| Effective diameter (mm)                  | 0.10  | 0.20 | 0.30                                      | 0.66 | 2.64 | 5.93      | 200 |
| Uniformity coefficient                   | 2.00  | 3.00 | 4.00                                      | 1.99 | 2.64 | 3.04      | 40  |
| $f(\text{UC})$                           | 4.49  | 3.39 | 2.94                                      |      |      |           |     |
| Sphericity                               | 0.70  | 0.80 | 0.90                                      | 2.02 | 2.64 | 3.34      | 50  |
| Porosity                                 | 0.40  | 0.45 | 0.50                                      | 1.38 | 2.64 | 4.86      | 132 |



**Figure 3** | Graphical representation of the decrease in filtration head during operation.

Equation (13). It can be observed from the graph that the typical range for the clean bed filtration time is between 28 minutes (for fine media with a small  $UC = 2.0$ ) and 18 minutes (for coarser media with a large  $UC = 4.0$ ). In both cases, 99% of the initial filtration head had been consumed.

### Verification of a reported case study

In this section, a successful BSF case study reported by Elliott *et al.* (2008) is analysed with the design equations developed above. Based on the design parameters used by Elliott *et al.* (2008), our mathematical expressions suggest a clean bed filtration time of 25 minutes, an initial clean bed filtration rate of  $3.26 \text{ m h}^{-1}$  and an average clean bed filtration rate of  $0.96 \text{ m h}^{-1}$  (Table 4).

## PROPOSED DESIGN PROCEDURE

The second author, since 2006, has been involved in the technical assessment of numerous small, rural water supply systems in Venda, a region in the far north of South Africa and bordering on Zimbabwe. A number of research projects are ongoing in this region, covering all the impacts from improved rural water supply—health, social, economic and environmental. The projects have now progressed to the point where point-of-use systems are piloted to improve the quality of the water consumed in the homes. Although BSF has not been used yet, the example below targets a typical BSF system in a Venda home, an option which may be pursued in future.

The **first step** is to determine the required water production rate. Demographic surveys showed an average of just over five inhabitants in a typical Venda household. Water use in the home had been measured at 20 litres per capita per day. Allowing for laundry and personal hygiene, it is estimated that 10 litres per capita per day is used for drinking and the preparation of food. The average daily demand is thus assumed to be 50 litres per household per day.

The containers used in rural villages are now exclusively plastic containers. Many of these containers had been measured during field surveys and they typically have a capacity of between 20 and 25 litres (the height of the containers varies between 330 mm and 460 mm with a median of 410 mm. This has a bearing on the positioning of the BSF unit in the home, as the containers have to fit below the outlet of the BSF unit). To satisfy the daily demand of a household, two containers per day are therefore required. Assume that one container of 25 litres is filtered in the morning and another in the evening, giving a dosing volume of 25 litres and a total cycle time of 12 hours.

The **second step** is to determine the media and water properties. Normal silica sand can be assumed to have porosity and sphericity values of 0.45 and 0.8, respectively. Assume that the locally available sand has an effective diameter of 0.20 mm and a uniformity coefficient of 3.2. From Figure 2,  $f(UC) = 3.27$ . The filtration rate will be the fastest, hence most undesirable, when the water has its maximum temperature. Venda reaches extreme temperatures in summer, and a maximum water temperature of  $32^\circ\text{C}$  is assumed. At this temperature, by applying Equations (17) and (18), the water density and viscosity are  $995 \text{ kg m}^{-3}$  and  $0.00080 \text{ kg m}^{-1} \text{ s}^{-1}$ , respectively.

The **third step** is to determine a suitable media volume. First, calculate the media volume required to limit the initial clean bed filtration rate to a chosen value of say  $3.5 \text{ m h}^{-1}$ . By applying the media and water properties established in the previous step and a water dosage volume of 25 litres into Equation (8) the required media volume is  $0.051 \text{ m}^3$ .

Next determine the media volume required to ensure that the media pores will retain one container of water. Applying a safety factor of 1.4 and previously determined values for dosage volume and porosity into Equation (10) the required media volume is  $0.078 \text{ m}^3$ . The larger of the

**Table 4** | Verification of a reported case study

| Parameter  | Value                        |                      |  |
|--|------------------------------|----------------------|--|
|  | Elliott <i>et al.</i> (2008) | Assumed <sup>*</sup> | Calculated <sup>†</sup>                    |
| <i>Water properties</i>                                    |                              |                      |  |
| Temperature (°C)   |                              | 20                   |  |
| Density (kg m <sup>-3</sup> )                              |                              |                      | 998.38                                     |
| Viscosity (kg m <sup>-1</sup> s <sup>-1</sup> )            |                              |                      | 0.0010                                     |
| <i>Media properties</i>                                    |                              |                      |  |
| Porosity (-)   |                              | 0.45                 |  |
| Effective dia. (mm)  | 0.21                         |                      |  |
| Sphericity (-)   |                              | 0.8                  |  |
| Uniformity coeff. (-)                                      |                              | 3.75                 |  |
| Function (UC)  |                              |                      | 3.00                                       |
| Media depth (m)  | 0.4                          |                      |  |
| <i>Other parameters</i>                                    |                              |                      |  |
| Gravity (m s <sup>-2</sup> )                               |                              | 9.81                 |  |
| Water dose volume (l)                                      | 20                           |                      |  |
| Volume of pores (l)  | 18.3                         |                      |  |
| Volume of media (m <sup>3</sup> )                          |                              |                      | 0.04 ( = pore volume/porosity)             |
| Safety factor (-) <sup>‡</sup>                             |                              |                      | 0.92                                       |
| Resting time (h)   | 18                           |                      |  |
| Terminal head (as % of initial head)                       |                              | 0.1                  |  |
| <i>Design parameters</i>                                   |                              |                      |  |
| Filtration time (min)                                      |                              |                      | 25   |
| Initial clean bed filtration velocity (m h <sup>-1</sup> ) |                              |                      | 3.26                                       |
| Average clean bed velocity (m h <sup>-1</sup> )            |                              |                      | 0.96                                       |
| Maximum filtration velocity <sup>§</sup>                   | 0.95                         |                      |  |
| Cycle time (h)   |                              |                      | 18.42 (sum of resting and filtration time) |

<sup>\*</sup>This refers to values that were not reported by Elliott *et al.* (2008) and reasonable assumptions have been made.

<sup>†</sup>These are values that have been calculated from the data given by Elliott *et al.* (2008) using the mathematical expressions developed in this paper.

<sup>‡</sup>The safety factor is less than 1 because available pore volume is less than the dosage volume used.

<sup>§</sup>This refers to the maximum filtration rate, which is the flow rate just after the introduction of a charge.

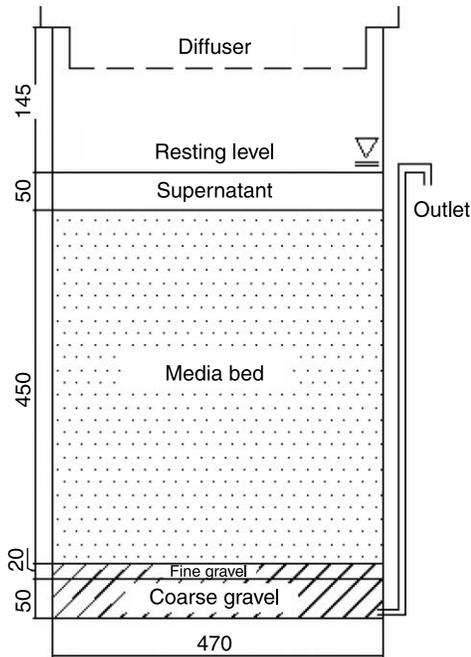
two volumes satisfies both criteria. The required media volume is thus 0.078 m<sup>3</sup>.

The **fourth step** is to proportion the BSF media bed. From Table 2, a depth of 0.45 m for the media can be adopted. Considering that the media volume has been established to be 0.078 m<sup>3</sup> from the previous step, the surface area of the bed will therefore be 0.17 m<sup>2</sup> ( = 0.078/0.45). If a circular configuration is to be adopted then the media bed will have a diameter of 0.47 m otherwise values for the length and width can be chosen to achieve a surface area of 0.17 m<sup>2</sup>. For a water dosage volume of 25 litres and a

media surface area of 0.17 m<sup>2</sup>, the water level will rise by 145 mm according to Equation (7).

In the **fifth step**, the filtration time is determined according to Equation (14) for the water level to drop by 99%. This gives a filtration time of 17.3 minutes. For a cycle time of 12 hours adopted earlier, this gives a resting time of 11.7 hours which is within the typical range of 6 to 24 hours shown in Table 2.

The **sixth step** is to determine the depth of the support layers according to Huisman & Wood (1974). For a  $d_{10}$  of 0.20 mm, the  $d_{15}$  and  $d_{85}$  values are 0.24 mm and 1.16 mm,



**Figure 4** | Schematic diagram of the BSF unit dimensioned from the design example above; dimensions are in mm.

respectively, according to Equation (4). Rules 3 and 4 set  $d_{10}$  of support layer 1 to less than 4.63 mm and greater than 0.96 mm, respectively. We adopt a  $d_{10}$  of 2.0 mm for layer 1. From rule 1 the  $d_{90}$  of layer 1 should be less than 2.80 mm. The depth of layer 1 should be greater than three times this  $d_{90}$  value (i.e. greater than 8.40 mm). We adopt a depth of 20 mm.

From rule 2 the  $d_{10}$  of layer 2 should be less than 8 mm. We adopt a  $d_{10}$  of 6.50 mm for layer 2. The  $d_{90}$  of support layer 2 should be less than 11.20 mm from rule 1. The depth of layer 2 should be greater than three times this  $d_{90}$  value (i.e. greater than 33.60 mm). We adopt a depth of 50 mm for layer 2.

The **seventh step** is to determine the orifice diameter of the drainage openings. For the two support layers used in this design example, rule 5 recommends an orifice diameter of less than 3.25 mm. We adopt an orifice diameter of 2.5 mm.

The **eighth step** is to determine the total height of the BSF unit. The total height is the sum of the heights of support layers, media, supernatant and the allowance for the increase in water level after water dosing. From Table 2, we adopt a depth of 50 mm for the supernatant. All other heights have been determined in the preceding steps. This

**Table 5** | Summarised design of the BSF unit

| Parameter  | Value  |
|--|--------|
| <i>Medium properties</i>                                 |        |
| Porosity ( - )   | 0.45   |
| Effective dia. (mm)                                      | 0.2    |
| Sphericity ( - )   | 0.8    |
| Uniformity coeff. ( - )                                  | 3.2    |
| Function (UC)  | 3.27   |
| Media depth (m)  | 0.45   |
| <i>Water properties</i>                                  |        |
| Temperature (°C)   | 32     |
| Density ( $\text{kg m}^{-3}$ )                           | 995    |
| Viscosity ( $\text{kg m}^{-1}\text{s}^{-1}$ )            | 0.0008 |
| <i>Operational and design parameters</i>                 |        |
| Safety factor ( - )                                      | 1.4    |
| Required water production rate (l/day)                   | 50     |
| Water dose volume (l)                                    | 25     |
| Cycle time (h)   | 12     |
| Resting time (h)   | 11.7   |
| Filtration time (min)                                    | 17.3   |
| Maximum initial clean bed velocity ( $\text{m h}^{-1}$ ) | 3.5    |
| <i>Under-drain system</i>                                |        |
| $d_{10}$ of support layer 1 (mm)                         | 2      |
| Depth of support layer 1 (mm)                            | 20     |
| $d_{10}$ of support layer 2 (mm)                         | 6.5    |
| Depth of support layer 2 (mm)                            | 50     |
| Diameter of drainage openings (mm)                       | 2.5    |
| <i>BSF configuration (summary)</i>                       |        |
| Surface area ( $\text{m}^2$ )                            | 0.17   |
| Diameter (if circular configuration is used) (m)         | 0.47   |
| Volume of media ( $\text{m}^3$ )                         | 0.078  |
| Depth of support layer 2 (mm)                            | 50     |
| Depth of support layer 1 (mm)                            | 20     |
| Media depth (mm)   | 450    |
| Supernatant (mm)   | 50     |
| Allowance for dosing (mm)                                | 145    |
| Total height (mm)  | 715    |

gives a total height of 715 mm for the BSF unit. Typical plastic containers with heights ranging from 330 to 460 mm will thus be able to fit below the outlet of the BSF unit without having to raise the BSF unit above the floor of the home.

The resultant BSF configuration arising from this design procedure is shown in Figure 4 and the specifications are summarised in Table 5.

## REFERENCES

- AWWA 1991 *Manual of Design for Slow Sand Filtration*. AWWA Research Foundation, Denver, Colorado.
- Baker, D. L. & Duke, W. F. 2006 Intermittent slow sand filters for household use—a field study in Haiti. In: Gimbel, R., Graham, N. J. D. & Collins, R. (eds) *Recent Progress in Slow Sand and Alternative Biofiltration Processes*. IWA Publishing, London, pp. 278–282.
- 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.
- Baylis, J. R. 1935 A study of filtering materials for rapid sand filters. *Water Works Sewerage* **40**, 20–25.
- Biosand 2006 *Biosand Water Filtration Systems*. Available at: [www.biosandfilter.org](http://www.biosandfilter.org) (accessed 19 October 2006).
- Buzunis, B. J. 1995 *Intermittently Operated Slow Sand Filtration: A New Water Treatment Process*, MSc Thesis, University of Calgary, Calgary, Alberta, Canada.
- Campos, L. C., Su, M. F. J., Graham, N. J. D. & Smith, S. R. 2002 Biomass development in slow sand filters. *Water Res.* **36**, 4543–4551.
- CAWST 2007 *BioSand Concrete Filter*. Center for Affordable Water and Sanitation Technology. Available at: <http://www.ca-wst.org/index.php?id=128>, (accessed 7 July 2008).
- Clasen, T. F. 2008 *Developing a National Strategy for Scaling Up Household Water Treatment and Safe Storage in Lao PDR*. Available at: <http://www.wpro.who.int/> (accessed 1 July 2009).
- Cleasby, J. L. 1990 Filtration. In: Pontius, F. W. (ed.) *Water Quality And Treatment: A Handbook of Community Water Supplies*. McGraw-Hill, New York.
- Duke, W. D., 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 and Remote Health* **6**(570) (online).
- Earwaker, P. 2006 *Evaluation of Household BioSand Filters in Ethiopia*. MSc Thesis, Center for Water Science, Cranfield University, UK.
- Elliott, M. A., Stauber, C. E., Koksals, 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.
- Fewster, E., Mol, A. & Wiesent-Brandsma, C. 2004 The Long-term Sustainability of Household Biosand Filtration. *30th WEDC International Conference*, Vientiane, Lao PDR, October 25–29 2004.
- Fox, K. R., Graham, N. J. D. & Collins, M. R. 1994 Slow sand filtration today: an introductory review. In: Collins, M. R. & Graham, N. J. D. (eds) *Slow Sand Filtration*. American Water Works Association, Denver, CO, pp. 1–8.
- Hillman, A. 2007 *Adapting the BioSand Filter to Remove Fluoride: An Investigation into Alternative Filter Media.*, MSc Thesis, Cranfield University, UK.
- Huisman, L. & Wood, W. E. 1974 *Slow Sand Filtration*. WHO, Geneva.
- Liang, K., Sobsey, M., Sorya, P. & Sampson, M. 2007 *Independent Assessment of Biosand Filters: Cambodia*. Available at <http://www.purefilteredwater.com/docs/append8.pdf>, (accessed 31 July 2008).
- Lukacs, H. 2002 *From design to implementation: Innovative slow sand filtration for use in developing countries*, MEng Thesis, Civil and Environmental Engineering Department, Massachusetts Institute of Technology.
- Manz, D. H., Buzunis, B. & Morales, C. 1993 *Nicaragua Household Water Supply and Testing Project*. Accessed 17 September 2008 from <http://www.manzwaterinfo.ca/documents/>
- Mintz, E., Bartram, J., Lochery, P. & Wegelin, M. 2001 Not just a drop in the bucket: expanding access to point-of-use water treatment systems. *Am. J. Public Health* **91**(10), 1565–1570.
- Palmateer, G., Manz, D. & Jurkovic, A. 1999 Toxicant and parasite challenge of Manz intermittent slow sand filter. *Environ. Toxicol.* **14**, 217–255.
- Sobsey, M. D. 2002 *Managing Water in the Home: Accelerated Health Gains from Improved Water Supply*. WHO/SDE/WSH/02.07, World Health Organisation, Geneva.
- Stauber, C. E., Elliott, M. A., Koksals, F., Ortiz, 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., Ortiz, G., Loomis, D. & Sobsey, M. 2009 A randomised 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.
- Vanderzwaag, J. 2007 *Use and Performance of BioSand Filters in Posoltega, Nicaragua*. University of British Columbia, Vancouver.

First received 17 February 2009; accepted in revised form 10 October 2009