Empirical models of bio-sand filter to calculate the design parameters

Mohamad Ali Fulazzaky, Norshuhaila Mohamed Sunar, Ab Aziz Abd Latiff and Amir Hashim Mohd Kassim

ABSTRACT

The performance of bio-sand filters (BSF) should be monitored periodically to ensure the quality of water produced for the safety of consumers. An engineering design of BSF is proposed to achieve the desired efficacy of the treatment system. Accurate designs to achieve bio-sand filtration are not available in detail for most BSFs since present physical models were not originally able to calculate design's parameters. This paper develops the mathematical models to calculate the depth of sand filter and water velocity in operating the proposed BSF especially to remove organic and suspended matter simultaneously. Parameters in the equations are all physically meaningful, experimental data validation shows the equations remained accurate. The baseline design's parameters are analyzed to contribute to bio-sand filtration process technology. The filtration rates and depths of sand filter proposed in designing of the BSF system are justified.

Key words | bio-sand filter, COD, design parameter, empirical model, rainwater, SS

Mohamad Ali Fulazzaky (corresponding author)
Norshuhaila Mohamed Sunar
Ab Aziz Abd Latiff
Amir Hashim Mohd Kassim
Department of Water Resources and Environmental Engineering,
Faculty of Civil and Environmental Engineering,
Universiti Tun Hussein Onn Malaysia (UTHM),
Parit Raja Batu Pahat 86400, Johor,
Malaysia
E-mail: *fulazzaky@gmail.com*; *alif@uthm.edu.my*

INTRODUCTION

The main characteristic of a treated water supply is that it is safe to drink. This requires removal of all contaminants in raw water that threaten human health or are unpleasant to users. The treatment objectives are to remove the contaminants of suspended and dissolved matters and pathogenic organisms to achieve the permissible threshold values as regulated in the drinking water standards. Safe potable water is a luxury that is generally unavailable to the majority of rural and suburban populations of developing, underdeveloped and often developed countries. Important considerations in the development and maintenance of safe water supplies are the availability and use of efficient, inexpensive and appropriate technology for removing microbial hazards, parasites and toxicants. Slow sand filtration is one filtration techniques mainly used in combination with other water purification methods to achieve these considerations. Slow sand systems have recently been adapted for point-of-use systems especially in developing countries. In this context they are generally known as "bio-sand filter (BSF)". The BSF is a technological adaptation of the centuries-old slow sand filtration process. While implementations exist in many different sizes and varieties, the most common design is intended for use in rural homes where naturally safe or treated water sources are not available. This technology may remove 95 to 99% of organic contaminants, including bacteria, viruses, protozoa, worms, and particles. Safe water produced by the filters is free of discoloration, odor, and unpleasant taste, and can be used for drinking, food preparation, personal hygiene, and sanitation. Most common home-based models can produce between 20 and 60 litres of water per hour. Cleaning the slow sand filter does not consume any media and produces virtually no wastewater. The BSFs can be used with surface, well, or rain water sources.

The ability of the BSF to reduce concentrations of bacteria, coliphages and human enteric viruses and

doi: 10.2166/ws.2009.228

the changes in filter effectiveness with biological ripening and length of operation were studied as ripening time varies. This is probably due to influent water quality. Also reductions of 95–98% *E. coli* and 80–90% viruses in a ripened filter were verified (Stauber *et al.* 2006). An investigation of the performance of the BSF with respect to the pause time between filtration runs showed greater removal of total coliforms when the filter pause period was 12 hr than 30 hr and the total coliforms removal by the BSF decreased with an increase in the sample collection volume (Baumgartner *et al.* 2007). A field study of 107 households was conducted to evaluate the use and performance of the Manz's BSF in the Artibonite valley of Haiti, and the results of the study were reported that the average of BSF efficiency of bacterial removal is 98.5% for long-term users and 76% for new users (Duke *et al.* 2006). Using two different filters and two different water supplies indicated that the intermittent slow sand filter could remove more than 83% of total heterotrophic bacteria populations, 100% of Giardia cysts, 99.98% of Cryptosporidium oocysts, 50–90% of organic and inorganic toxicants when administered in concentrations varying from 10 to 100 times of environmental population levels (Palmateer *et al.* 1999). Natural or synthetic organic matter in water can cause a problem for human health due to organic matter reacting with chlorine during the disinfection process of conventional water treatment technology to form disinfection by-products such as trihalomethanes, haloacetic acids, haloacetonitrile and cyanogen halides, which are classified as carcinogenic substances (Rook 1974; AWWARF 1982; Marhaba & Washington 1998). The increasing of suspended matter in water will increase the amount of organic matter because organic matter can be captured by the particles of solid (Fulazzaky & Abdul Gany 2009). Despite the fact that the risks of organic and suspended matter in water supply affect the environmental and social costs and public health, previous studies have not focused on investigating the ability of BSF to remove organic and suspended matter simultaneously.

Although the earlier studies reported that: i) the BSF is effective in removing 95% of fecal coliform indicators and reducing turbidity levels to below 1 NTU, ii) a mathematical model to describe the diffusion of oxygen transfer into the filter bio-layer was developed and supported by experimental data (Buzunis 1995), and iii) a turbidity decrease from an average of 6.2 NTU in raw water to 0.9 NTU in the filtered water was reported (Duke *et al.* 2006), the mathematical models calculating the design parameters of BSF to remove organic and suspended matter simultaneously are still not fully understood.

The objectives of this study are: (1) to verify the threshold of water velocity to propose in running a BSF system, (2) to analyze the baseline design's parameters that are applicable in designing the bio-sand filtration process, (3) to calculate the design's parameters i.e., the depth of sand filter and water velocity to maintain in operating the BSF system, in accordance with the expected efficacy of the proposed BSF.

METHODOLOGY

The inhabitants of the tropical and temperate regions, particularly for developing countries in which there is abundant rainfall, traditionally use groundwater, surface water or rainwater as the sources of water supply for domestic purposes. The village communities in swamp and tidal areas face the problems of water quality due to the natural surface and groundwater being slightly salty. In contrast, inland communities in mountainous and hilly areas face difficulties in accessing surface and groundwater and public water supply facilities. Hence, rainwater harvesting from the roof catchments is preferably used and stored in vessels for provision of safe drinking water. The main constraints of using rainwater for domestic purposes are related to quality of raw water and costs. The household-scale BSF offers an economic and practical instrument to solve the problems of water quality.

An accuracy of design is critical to ensure the effectiveness of operational BSF system. The important design parameters in BSF performance are the depth of sand filter and water velocity. These parameters really influence from one to other to achieve the efficacy of treatment. The application of parameters creates limits to support the optimal condition of BSF system. This paper develops the empirical models to conceptualize the calculation of an appropriate design of BSF. Figure 1 shows the flow chart of research methodology to develop the models to calculate the design parameters.

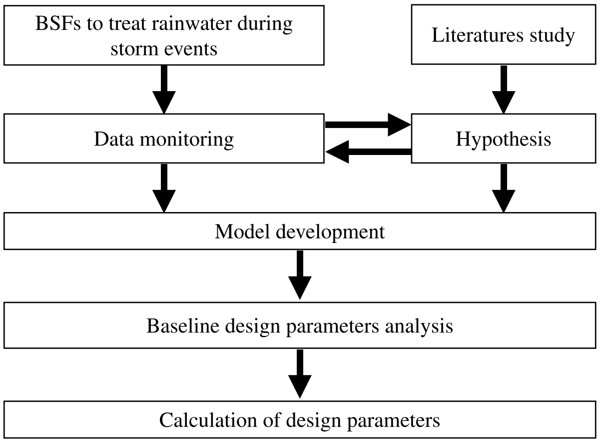

Figure 1 | Flow chart of research methodology.

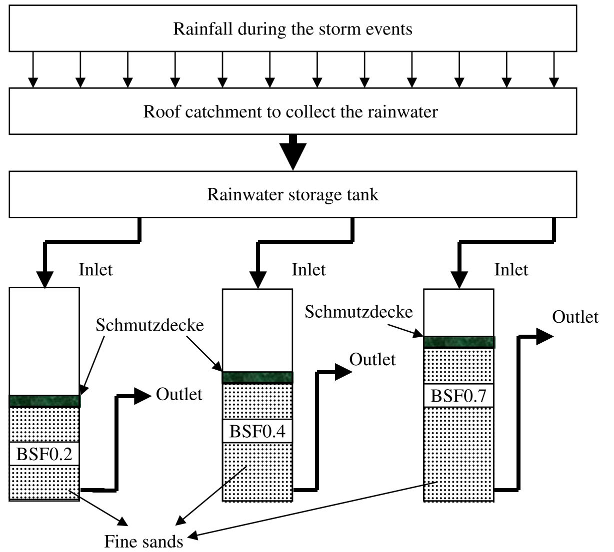

Figure 2 | Diagram of experimental procedure.

Data monitoring

Although the parameters of oxidizable organic matter consisting of dissolved oxygen (DO); percentage of saturated oxygen (%O_2); dissolved organic carbon (DOC); permanganate value (PV); biochemical oxygen demands (BOD); chemical oxygen demands (COD); nitrogen Kjeldahl (NKj); and ammonium (NH_4^+) as well as the parameters of suspended matter consisting of suspended solids (SS); turbidity; and transparency, have been classified (Oudin *et al.* 1999), this study selected COD to represent organic matter and SS to represent suspended matter to develop the models. These parameters were selected due to the rainwater collecting from the location of research in a mixed-zone of housing and industry contaminated by smoke or particulate matter mainly generated from fiberboard industry. Because solid particles can capture organic matter (Fulazzaky & Abdul Gany 2009), COD was selected as the total organic matter surrogate parameter in the rainwater. Also the unit of SS expressing in mg/L is similar to the COD unit (in mg/L) comparing the unit of turbidity in NTU and transparency in metres of water depth.

The data used to develop the models were collected from 10 storm events during 3 months of monitoring from February to April, 2005 within the area of Universiti Tun Hussein Onn Malaysia campus Batu Pahat, Johor, Malaysia (Sunar 2005). Figure 2 shows the diagram of experimental procedure to equip this research study. Three different BSFs were installed to conduct the research, i.e., i) bio-sand filter 0.2 m (BSF0.2) with 0.2 m in depth and 0.09 m^2 of cross-sectional area (0.3 × 0.3 m); ii) bio-sand filter 0.4 m (BSF0.4) with 0.4 m in depth and 0.09 m^2 of cross-sectional area; and iii) bio-sand filter 0.7 m (BSF0.7) with 0.7 m in depth and 0.09 m^2 of cross-sectional area (Sunar 2005). The sampling points to monitor the effectiveness of BSFs were selected at the inlet and outlets of the system (see Figure 2). Since the collected rainwater in the storage tank was limited, the BSFs were operated during wet weather when rainwater in the tank was available. So, the sampling periods were irregular depending on the storm events of wet season in 2005. To shelter the biologically active layer of each BSF, a water level of 5 cm above the top of the sand was maintained. The mode of operation depending on the weather has generated the heterogenous data to assure the accuracy of models due to the different rainfall intensities and frequencies giving the different quality of rainwater for the location of research.

Even though the parameters of pH, DO, turbidity, COD, SS, total coliforms and metals were monitored 15 times at the inlet and outlets of BSFs system, this study intentionally used COD and SS to develop the models. Experimental analysis was conducted according to *Standard Methods* (AWWA 1998). Hence, COD was analyzed using HACH/DR 4000 Spectrophotometer after digestion in the COD reactor. Three different filtration rates of BSF were maintained in running the BSFs, i.e., i) BSF0.2 with filtration rate (V) of 0.30 m/hr; ii) BSF0.4 with V of

0.60 m/hr; and iii) BSF0.7 with V of 0.91 m/hr (Sunar 2005). The average value of COD in the raw rainwater was reported about 43 mg/L with the range of COD values varies from 6 to 129 mg/L and the average value of SS was reported about 65 mg/L with the range of SS values varies from 18 to 145 mg/L. The performance of BSFs to remove COD was reported about 51% for BSF0.2; 65% for BSF0.4; and 84% for BSF0.7 and to remove SS was about 66% for BSF0.2; 79% for BSF0.4; and 89% for BSF0.7 (Sunar 2005).

Hypothesis

A slow sand filter contains biological activity and is therefore often referred to as a BSF. As micro-organisms such as bacteria, viruses and parasites travel through the sand, they collide with and adsorb onto sand particles (Huisman & Wood 1974; Haarhoff & Cleasby 1991). Most commonly, a BSF takes the form of a container a little less than a metre tall and perhaps 30 cm in width and depth, filled with sand. The biologically active layer, which takes a week or two to fully develop, is maintained by keeping the water level above the top of the sand, as with slow sand filters, this bioactive layer helps to filter, adsorb, destroy, or inactivate pathogens.

The organisms and particles collect in the greatest density in the top layers of the sand, gradually forming a biological zone. The biological zone is not really a distinct and cohesive layer, but rather a dense population that gradually develops within the top layer of the sand. The population of micro-organisms is part of an active food chain that consumes pathogens (disease-causing organisms) as they are trapped in and on the sand surface. The uppermost 1 to 3 cm of this biological zone is sometimes referred to as '*schmutzdecke*' or 'filter cake' which is defined as a layer of particles deposited on top of the filter bed or biological growth on top of the filter bed (Huisman & Wood 1974; Haarhoff & Cleasby 1991). A porous plate is usually located above the sand to prevent disturbance to the bioactive layer when water is added. Users simply pour water into the top of the apparatus, and collect treated water from the outlet. Slow sand filters are usually cleaned by scraping of the bio-film and/or the top sand layer (Huisman & Wood 1974; Haarhoff & Cleasby 1991).

Development of the mathematical models in this study based on the data collected via the physical models is required. The parameters in the equations are important for describing the biological and physical phenomena during filtration process. This requires understanding of the physical meaning of each parameter. The basic approach to develop the models is based on the hypothesis that (i) biological phenomena which involve removing organic matter affect the substrate depletion rate and to remove suspended matter affects the rate of solid particles reduction, (ii) physical phenomena which involve collision and adsorption of organic and suspended matter as well as biomass onto the sand depends on the depth of sand filter and water velocity used, and (iii) active layers of different depths of sand filter biologically contribute no significant difference to filtration process.

MODELS DEVELOPMENT

A plot of SS removal versus COD removal at the BSF0.2; SS removal versus COD removal at the BSF0.4; and SS removal versus COD removal at the BSF0.7 takes the shapes intercept at zero and gives the mathematical expression (see Figure 3) that,

$$\mathrm{COD_{mov}} = a \cdot \mathrm{SS_{mov}}. \tag{1}$$

where,

SS_{mov} is SS removal at BSF as the horizontal line (in mg/L)

COD_{mov} is COD removal at BSF as the vertical line (in mg/L)

α is coefficient to correlate the values of COD to SS (dimensionless)

Figure 3 shows that the values of α in Equation (1) to each depth of BSF are verified as a good correlation with $R^2 > 0.978$. While COD parameter is chemically different to SS, the amounts of matter adsorbed onto the sand particles as either organic or suspended matter are referred in the same unit i.e., mg per litre (mg/L). If we recognize that the sum of organic and suspended matter removed is,

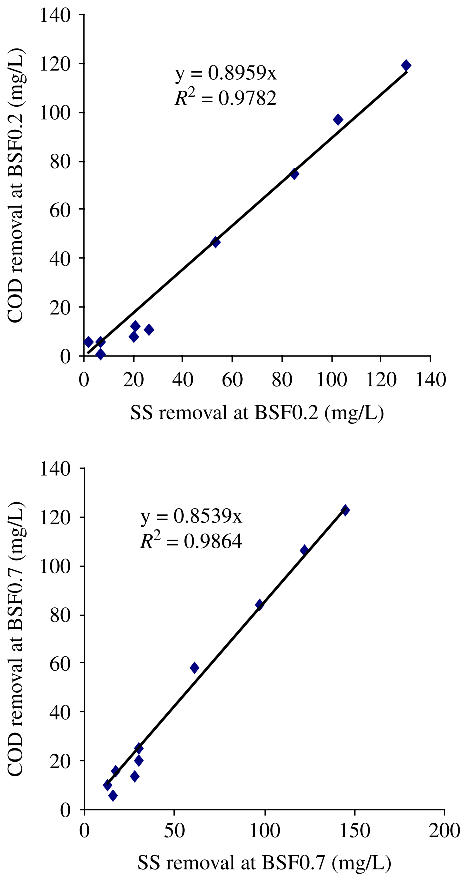

Figure 3 | SS removal versus COD removal.

$$R = COD_{mov} + SS_{mov}. \quad (2)$$

substituting Equation (1) into Equation (2) yields,

$$R = COD_{mov} + \frac{COD_{mov}}{\alpha}, \quad (3)$$

where R is organic and suspended matter (COD and SS) removal at BSF (in mg/L).

A plot of R for BSF0.2 versus R for BSF0.4; R for BSF0.4 versus R for BSF0.7; and R for BSF0.2 versus R for BSF0.7 takes the shapes shown in Figure 4 and gives the mathematical expression that,

$$R_v = \beta \cdot R_h + C, \quad (4)$$

where,

R_h is COD and SS removal at first BSF as the horizontal line (in mg/L)

R_v is COD and SS removal at second BSF as the vertical line (in mg/L)

β is bio-film coefficient related to the performance of BSF to biologically remove COD and SS (dimensionless)

C is biophysical adsorption constant related to the depth of sand filter and biochemical fixation onto the sand particles during filtration process (in mg/L).

The shapes show very good correlation with $R^2 > 0.994$ and the value of β is close to one (see Figure 4). We suggest that the performance of BSF to biologically remove COD and SS is approximately similar for each BSF. If we recognize that the value of β is equal to one ($\beta = 1$), re-arranging Equation (4) yields,

$$R_v = R_h + C. \quad (5)$$

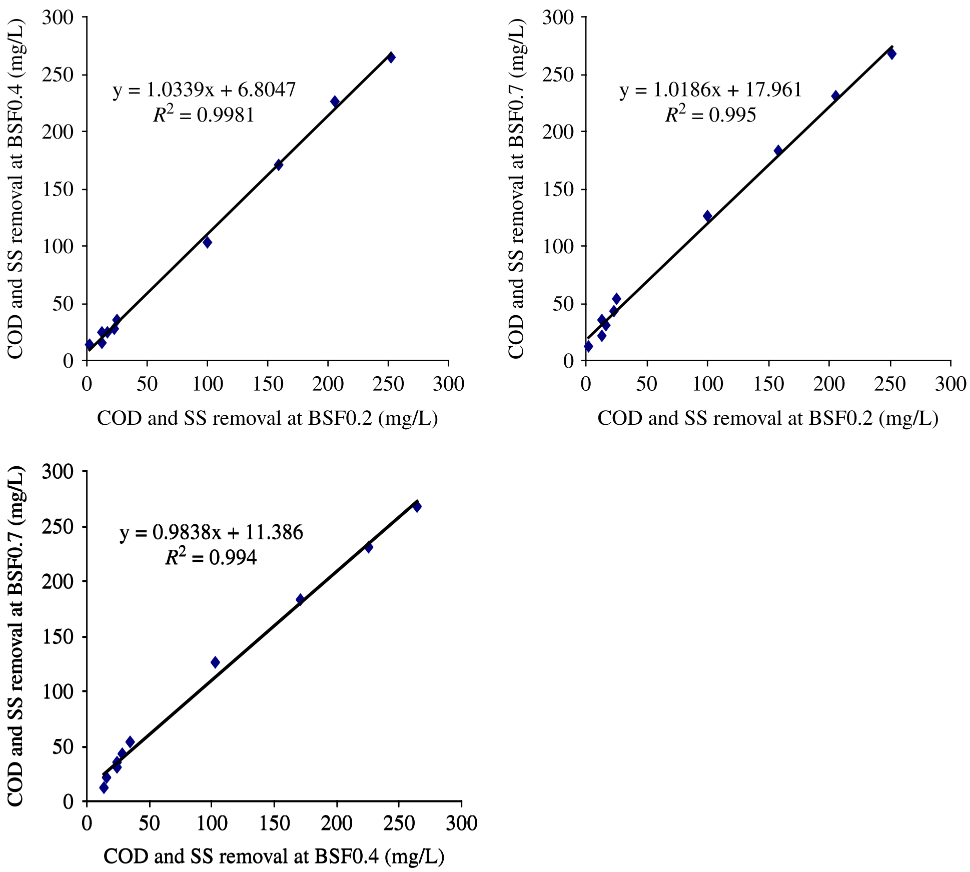

Figure 4 | Correlation of SS and COD removal at two different depths of BSF.

The main removal mechanisms found in the BSF are metabolic breakdown, bacteriovary, death of influent bacteria, adsorption of pollutants and biomass onto sand and mechanical straining (Jellison *et al.* 2000; Adin 2003). All these mechanisms may be summarized as biological and physical phenomena that lead to collision with and adsorption of the suspended matter and biomass as well as other organic and inorganic matters onto the sand particles during filtration process. Figure 4 shows that the values of C will increase with increasing of the difference of depth between two BSFs (ΔH). A plot of ΔH versus C gives the linear equation intercept at zero as shown in Figure 5 that,

$$C = \lambda \cdot \Delta H, \qquad (6)$$

where,

C is biophysical adsorption constant (in mg/L);
ΔH is difference of depth between two BSFs (in m);
λ is biochemical fixation coefficient that relies the biological and chemical fixations onto the sand during filtration process (in mg/L.m).

The physical parameters such as water velocity and depth of sand filter are important in order to investigate the physical adsorption phenomenon of bio-sand filtration process. Flow rate in the sand column is proportional to the cross-sectional area of the sand and the pressure head (hydraulic loading) of water on top of the sand. Flow rate is also affected by the length of the sand column, as well as by the properties of the fluid (viscosity, density and raw water quality) and the sand characteristics. Traditionally, flow rates also known as water velocities or filtration rates in slow sand filters should be around 0.1 m/hr. Flow rates can be increased up to 0.4 m/hr (Huisman & Wood 1974). Note that this is a compaction of $m^3/m^2/hr$ and sometimes the unit is in days and not hours. Using Equation (6) permits us

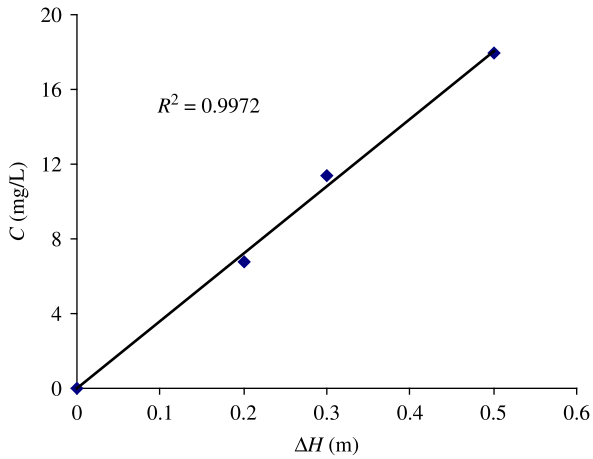

Figure 5 | ΔH versus C.

to calculate the value of C at any value of ΔH. The value of C increases proportional to the value of ΔH. A plot of water velocity (V) versus C gives the linear equation (see Figure 6) that,

$$C = -\varphi \cdot V + \chi, \quad (7)$$

where,

C	is biophysical adsorption constant (in mg/L);
V	is water velocity or filtration rate (in m/hr);
φ	is velocity coefficient (in mg hr/L m);
χ	is physical adsorption constant related to the water velocity and depth of sand filter (in mg/L).

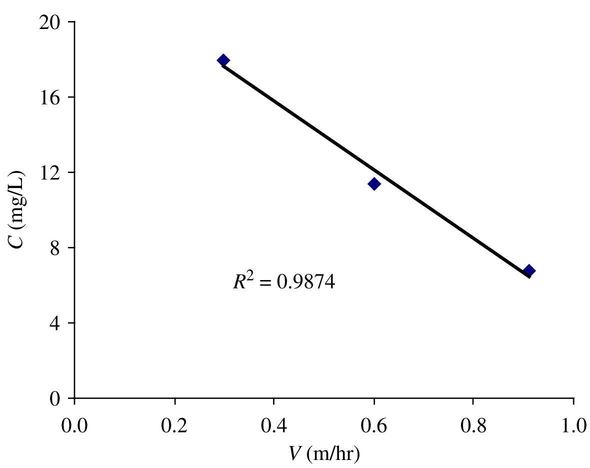

Figure 6 | V versus C.

Within a range, however, water velocities do not seem to affect bacteriological effluent quality. This was reported in a previous study on the use of higher filtration rates in the Netherlands i.e., 0.25 and 0.45 m/hr without any marked difference in effluent quality (Huisman & Wood 1974). Also the research done in India for continually operated sand filters found no significant difference in fecal coliform reductions with flow rates of 0.1, 0.2 and 0.3 m/hr (NEERI 1982). However, it is possible to increase the filtration rate considerably if effective pretreatment is given and if an effective disinfection stage follows the filtration (Ellis 1987). Although the bacteriological quality of filtrate water does not deteriorate significantly with the filtration rates higher than the conventional figure, turbidity and colour removal efficiency decline considerably with higher filtration rates, even though the filtrate quality remains reasonably good. Filtration rates higher than the conventional one can therefore be adapted in slow sand filters if using a good quality of raw water (Muhammad *et al.* 1996). We verify that to simultaneously remove organic and suspended matter contaminated the rainwater at location of research in Malaysia that the physical models of BSF used confirm to accommodate the values of C range from 0 to 23.07 mg/L and the values of V range from 0 to 1.26 m/hr in performing of the BSF. Referring to Equation (7) the capability of BSF to adsorb COD and SS onto the sand particles increases with decreasing the value of V due to the increasing of C will yield.

BASELINE DESIGN PARAMETERS ANALYSIS

The bio-sand pitcher filter relies on natural biological, chemical and physical processes to purify raw water. A 5 cm layer of standing water supports a microbial community at the surface of the sand layer; this diverse ecosystem consists of algae, bacteria, protozoa, and small invertebrates, which are both free and attached to bio-film communities that form on the surface (sand layer) and sand grains (Huisman & Wood 1974). The bio-film is derived initially from the biology in the raw water and is subsequently sustained by the organic matter in the raw water (Ritenour 1998). This study proposes to distinguish the biophysical adsorption onto the sand particles from biological process in the filter cake to remove organic and suspended matter influential on the efficiency of BSF. A plot of C versus the efficiency of BSF (θ) gives the linear equation as shown in Figure 7 that,

$$\theta = \pi \cdot C + \eta, \quad (8)$$

where,

- C is biophysical adsorption constant (in mg/L);
- θ is efficiency of BSF (in %);
- π is biophysical efficiency coefficient that relies to biophysical adsorption (in %.L/mg);
- η is biological performance constant (in %).

Equation (8) shows that the value of θ increases proportional to the value of C. If $C = 0$ mg/L, the efficiency of BSF is verified to extrapolate at 36.4% (see Figure 7). The physical meaning of this percentage solely refers to biological process in the filter cake to remove COD and SS simultaneously. This is due to a part of COD and SS being removed biologically in the top of the filter bed before adsorption onto the sand particles.

BSFs have been shown to remove more than 90% of fecal coliform, 100% of protozoa and helminths, 95 to 99% of zinc, copper, cadmium and lead, and all suspended sediments. BSFs have also been shown to remove 76 to 91% of arsenic, reducing it to acceptable concentrations (Duke *et al.* 2006). These filters do not sufficiently remove dissolved compounds such as salt and fluoride or organic chemicals such as pesticides and fertilizers. The biological layer's effectiveness is influenced by temperature. Additionally, because the BSFs are not able to handle high turbidity, they may become clogged and ineffective during monsoon or rainy seasons (Duke *et al.* 2006). This study monitoring 10 storm events to examine the efficiency of BSFs is also addressed to verify the physical parameters affecting the performance of BSFs. A plot of V versus θ gives the linear equation as shown in Figure 8 that,

$$\theta = -\mu \cdot V + \zeta, \quad (9)$$

where,

- V is filtration rate or water velocity (in m/hr);
- θ is efficiency of BSF (in %);
- μ is physical efficiency coefficient that relies to filtration rate (in %.hr/m);
- ζ is physical performance constant (in %).

According to Equation (9) the value of θ proportionally decreases with increasing of V in running the BSF system. An extrapolation or interpolation of straight line in Equation (9) may calculate the water velocity at any desired efficiency of BSF. For example, when the efficacy of BSF is 36.4%, this confirms $V = 1.26$ m/hr (see Figure 8). We suggest that these values are appealing as the baseline data in designing of the BSF system. The BSF does not become more effective to remove COD and SS biologically when the filtration rate is greater than 1.26 m/hr. To extrapolate the straight line of Equation (9) at $\theta = 0\%$ verifies $V = 2.04$ m/hr. This embodies the physical meaning that the BSF system is not worthwhile to biologically treat raw water when the filtration rate of greater than 2.04 m/hr is

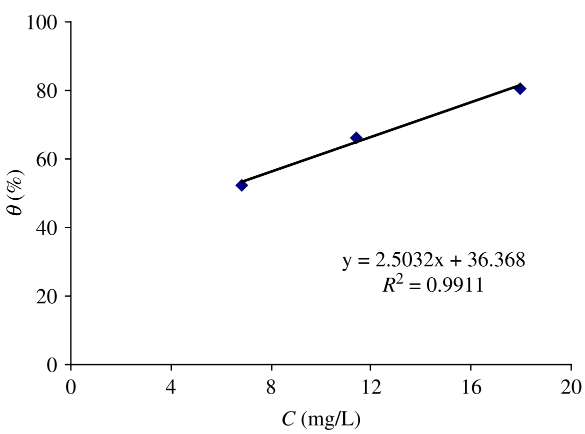

Figure 7 | Correlation between C and θ.

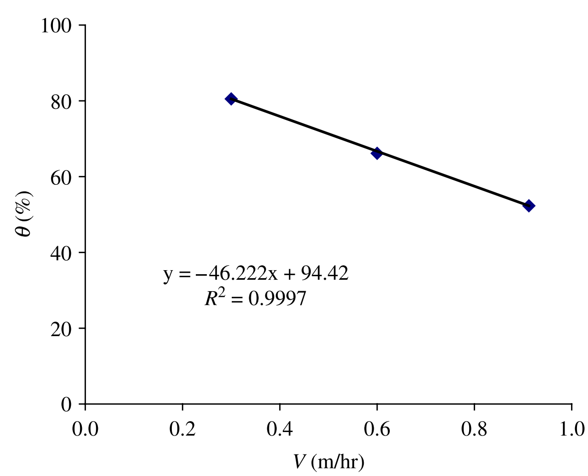

Figure 8 | Correlation between V and θ.

used. The filtration rate of 2.04 m/hr may indicate the limit between the intermediate and rapid sand filter and is suggested to associate with the last threshold which includes an intermediate sand filter system in the process for treating raw water. This study proposes to distinguish the sand filtration categories of slow sand filter, intermediate sand filter and rapid sand filter. Hence, the values of V for intermediate sand filter can range from greater than 1.26 to 2.04 m/hr.

In the earlier study sand layer depth was found to be inconsequential except for the increased head-loss and reduction of flow provided by a deeper sand bed (Buzunis 1995). The reduced flow path length is not expected to result in smaller microbial removal efficiencies as long as the 5 cm supernatant depth is maintained. The depth of the filter's biological layer, i.e., biological removal region, is mainly a function of the depth of water over the sand bed since this controls the rate at which oxygen can be drawn down to the biologically active zone and the depth into the sand oxygen can be supplied. While the intensely tested BSF had a biologically active zone less than 10 cm in depth, in filters with a more shallow standing water depth the biologically active layer is expected to be deeper. This would result in a longer contact time with the filter biology and improved filter efficiency (Buzunis 1995). We were concerned in this study to investigate the possibility of using the filtration rate in accordance with the depth of sand filter (H). A plot of V versus H gives the linear equation intercept at zero (see Figure 9) that,

$$H = \psi \cdot V, \qquad (10)$$

where,

V is filtration rate or water velocity (in m/hr);
H is depth of sand filter (in m);
ψ is time coefficient that depends on filtration rate and depth of sand filter (in hr).

To maintain the contact-time (see hydraulic retention time) is 0.7331 hour to the BSF system. Equations (6) and (7) can be used to sequentially calculate the respective values of C and V. With this value of V Equation (10) permits to calculate the depths of sand filter (H) which range from 0 to 0.92 m to accommodate the baseline

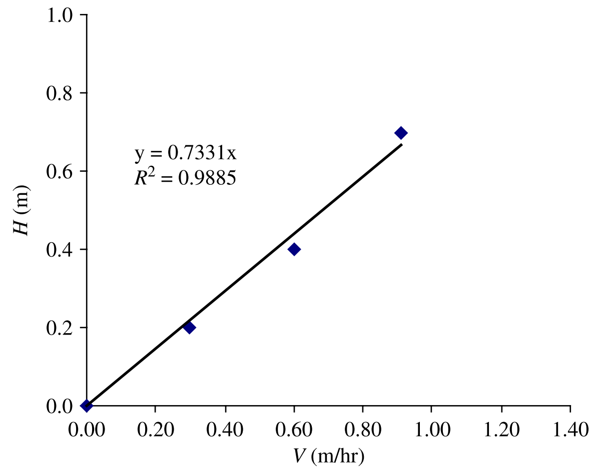

Figure 9 | Correlation between V and H.

filtration rates of BSF system ranged from 0 to 1.26 m/hr. This sets the thresholds of sand filter depth and filtration rate in designing of the BSF system.

CALCULATION OF DESIGN PARAMETERS

An evaluation of BSFs to determine the long-term filtration efficiency and the rate of sustained use was conducted in Posoltega, Nicaragua. Although in this earlier study was reported that the average filtration efficiency was found to be 98% for total coliforms, 96% for *E. coli* and 88% for turbidity (Vanderzwaag 2008), the mathematical models to calculate the design's parameters are still not fully understood. Important considerations in the development of models are the availability and use of equations to calculate the depth of sand filter and water velocity.

Combining Equation (7) and Equation (6) yields an equation valid to verify the depth of sand filter needed to modify in designing of the proposed BSF, in accordance with the desired water velocity to operate the BSF system that is,

$$\Delta H = \frac{-\varphi . V + \chi}{\lambda}. \qquad (11)$$

If we recognize that $\gamma = \varphi/\lambda$ and $\delta = \chi/\lambda$, re-arranging Equation (11) yields,

$$\Delta H = -\gamma V + \delta, \quad (12)$$

where,

- V is filtration rate or water velocity (in m/hr);
- ΔH is difference of depth between two BSFs (in m);
- γ is time coefficient that depends on V and biochemical fixation (in hr);
- δ is distance constant that depends on physical adsorption and biochemical fixation (in m).

Table 1 shows that the depths of sand filter (see Column 4) to modify are calculated using Equation (12) to accommodate the variations of V (see Column 3). The value of ΔH will decrease with increasing the value of V. By substituting Equation (6) into Equation (5) and re-defining R_h to R_{pil} and R_v to R_{prop}, this may be summarized in Equation (13) to calculate the performance of the proposed BSF that is,

$$R_{prop} = R_{pil} + \lambda \cdot \Delta H, \quad (13)$$

where,

- R_{prop} is COD and SS removal at the proposed BSF (in mg/L);
- R_{pil} is COD and SS removal at the pilot BSF (in mg/L);
- λ is biochemical fixation coefficient that relies to biological and chemical fixations onto the sand during filtration process (in mg/L m);

Table 1 | Calculation of ΔH to accommodate the desired value of V

γ (hr) (1)	δ (m) (2)	V (m/hr) (3)	ΔH (m) (4)
0.5	0.6373	0.1	0.59
0.5	0.6373	0.2	0.54
0.5	0.6373	0.3	0.49
0.5	0.6373	0.4	0.44
0.5	0.6373	0.5	0.39
0.5	0.6373	0.6	0.34
0.5	0.6373	0.7	0.29
0.5	0.6373	0.8	0.24
0.5	0.6373	0.9	0.19
0.5	0.6373	1.0	0.14
0.5	0.6373	1.1	0.09

- ΔH is depth of sand filter that needs to modify for the proposed BSF (in m).

Using Equation (13) permits us to calculate the depth of sand filter that is needed for a desired efficacy in designing of the proposed BSF, if the efficiency of the pilot BSF is known. Equation (13) validates to apply for simultaneously removing of COD and SS. The depth of sand filter proposed in designing of the BSF system can comply with the expected performance such as 80%, 90% or 100%. If we recognize that the performance of proposed BSF is,

$$\theta = \frac{R_{prop}}{OS_{in}} \times 100\%. \quad (14)$$

Substituting Equation (14) into Equation (13) yields Equation (15) that,

$$\Delta H = \frac{\theta \cdot OS_{in} - R_{pil}}{\lambda}, \quad (15)$$

where

- ΔH is depth of sand filter that needs to modify for the proposed BSF (in m);
- θ is expected performance of the proposed BSF (in %);
- OS_{in} is COD and SS in raw water or initial COD and SS (in mg/L);
- R_{pil} is COD and SS removal at the pilot BSF (in mg/L);
- λ is biochemical fixation coefficient that relies to biological and chemical fixations onto the sand during filtration process (in mg/L.m).

Using Equation (15) permits to calculate ΔH to modify for design of a proposed BSF in accordance with the expected performance of proposed BSF (see Table 2

Table 2 | Calculation of ΔH in accordance with expected value of θ

$(COD + SS)_{in}$ (mg/L) (1)	R_{pil} (mg/L) (2)	λ (mg/L.m) (3)	θ (%) (4)	ΔH (m) (5)
107	71	36.2	0.80	0.40
107	71	36.2	0.85	0.55
107	71	36.2	0.90	0.70
107	71	36.2	0.94	0.82

Table 3 | Calculation of V in accordance with the expected value of θ

$(COD + SS)_{in}$ (mg/L) (1)	R_{exi} (mg/L) (2)	θ (%) (3)	φ (mg.hr/L.m) (4)	χ (mg/L) (5)	V (m/hr) (6)
107	86	80	18.27	23.073	1.28
107	86	85	18.27	23.073	0.99
107	86	90	18.27	23.073	0.70
107	86	95	18.27	23.073	0.41
107	86	100	18.27	23.073	0.11

Columns 4 and 5), if the performance of pilot BSF and initial concentrations of COD and SS in the raw water were verified. The value of ΔH will increase with increasing of the expected performance of proposed BSF. Since the evolution of COD and SS in raw water varies over time, the effectiveness of pilot BSF to remove organic and suspended matter in rainwater really changes by the seasons. To secure the safe drinking water production considers the highest values of initial COD and SS in raw water so the depth of sand filter to modify to maintain the expected performance of BSF, for example at 100%, may be calculated.

Combining Equation (15) and Equation (11) yields the equation valid to calculate the water velocity that is,

$$V = \frac{R_{pil} + \chi - \theta \cdot OS_{in}}{\varphi}. \tag{16}$$

The water velocity can be calculated using Equation (16) to propose to run the BSF system in accordance with the expected performance. Table 3 shows that the value of V decreases when the performance of BSF increases (see Columns 3 and 6). To grasp the application of models to the real treatment process for other works is to define firstly the desired performance of the proposed BSF, if the initial COD and SS in raw water and the efficacy of pilot BSF were verified, and then to calculate the water velocity using Equation (16) when the depth of sand filter calculated using Equation (12) is urged to modify or to calculate the depth of sand filter to modify using Equation (15) when the water velocity calculated using Equation (12) is also decided to modify.

CONCLUSION

We verify that the mathematical models developed to calculate the design's parameters i.e., depth of sand filter and filtration rate in accordance with the expected performance of proposed BSF are relatively accurate. The values of C deriving from the model range from 0 mg/L to 23.07 mg/L valid to accommodate the variations of filtration rate ranged from 0 to 1.26 m/hr.

Functional filtration equations accounting for bio-film, biophysical adsorption, biochemical fixation, water velocity, physical adsorption were presented. Parameters in the equations are all physically meaningful and experimental validation showed that the equations remained accurate. Insight into baseline parameters has been offered in this study to contribute knowledge in the water treatment process related to bio-filtration technology. The bio-sand filtration processes may be classified into the respective categories of slow sand filter or BSF, intermediate sand filter and rapid sand filter characterized with the water velocities ranged from 0 to 1.26 m/hr, from greater than 1.26 to 2.04 m/hr, and greater than 2.04 m/hr respectively.

Filtration rate required to achieve the expected efficacy of a proposed BSF is different for different depth of sand filter. The models to calculate the depth of sand filter to propose in designing the BSF were presented. The accurate water velocity was justified to remove COD and SS in the rainwater simultaneously in accordance with the desired performance of BSF (see Table 3). The application of models in real water treatment process enable us to calculate either the depth of sand filter solely or the depth of sand filter and water velocity together.

REFERENCES

Adin, A. 2003 Slow granular filtration for water reuse. *Water Sci. Technol. Water Supply* **3**(4), 123–130.

AWWA 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edition. AWWA, APHA and WEF Publishing, Washington, DC.

AWWARF 1982 *Treatment Techniques for Controlling Trihalomethanes in Drinking Water*. AWWARF Publishing, Denver, CO.

Baumgartner, J., Murcott, S. & Ezzati, M. 2007 *Effects of Operating Conditions on the Bacterial Removal of Two Household Drinking-Water Filters*. IOP Publishing, Tokyo, Beijing, Environmental Research Letters 2(2007).

Buzunis, B. J. 1995 Intermittently operated slow sand filtration–a new tater treatment process, Master Thesis, University of Calgary, Canada.

Duke, W. E., Nordin, R. N., Baker, D. & Mazumder, E. 2006 The use and performance of bio-sand filters in the Artibonite Valley of Haiti–a field study of 107 households. *Rural Remote Health* **6**, 570.

Ellis, K. V. 1987 Slow Sand Filtration. *WEDC J. Dev. World Water* **2**, 196–198.

Fulazzaky, M. A. & Abdul Gany, A. H. 2009 Challenges of soil erosion and sludge management for sustainable development in Indonesia. *J. Environ. Manage. (ScienceDirect)*. doi: 10.1016/j.jenvman.2009.02.17.

Haarhoff, J. & Cleasby, J. L. 1991 Biological and physical mechanisms in slow sand filtration. In: Logsdon, G. S. (ed.) *Slow Sand Filtration*. ASCE Publishing, New York, pp. 19–68.

Huisman, L. & Wood, W. E. 1974 *Slow Sand Filtration*. WHO Publishing, Geneva.

Jellison, K. L., Dick, R. I. & Weber-Shirk, M. L. 2000 Enhanced ripening of slow sand filter. *J. Environ. Eng.* **126**(12), 1153–1157.

Marhaba, T. F. & Washington, M. B. 1998 Drinking water disinfection and by-products: history and current practice. *Adv. Environ. Resour.* **21**(1), 103–115.

Muhammad, N., Ellis, K., Parr, J. & Smith, M. D. 1996 Optimization of slow sand filtration. Reaching the unreached: Challenges for the 21st Century. 22nd WEDC Conference. New Delhi, India, pp. 283–285.

National Environmental Engineering Research Institute (NEERI) 1982 *Slow Sand Filtration*. NEERI, Nagpur, India, Final Project Report.

Oudin, L. C., Meybeck, M. & Roussel, P. 1999 Système d'evaluation de la qualité de l'eau des cours d'eau. Rapport de présentation SEQ-Eau (Version 1). Agence de l'eau Loire-Bretagne, France.

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

Ritenour, R. 1998 *Biosand Household Water Filter: A Transfer of Slow Sand Filtration Technology to Developing Countries*, 3rd edition. Samaritan's Purse, Canada.

Rook, J. J. 1974 Formation of haloforms during chlorination of natural water. *Water Treat. Exam.* **23**, 234.

Stauber, C. E., Elliott, M., Koksal, F., Ortiz, G. M., Liang, K., DiGiano, F. A. & Sobsey, M. D. 2006 Characterization of the BSF for microbial reductions–lab and field conditions. *Water Sci. Technol.* **54**(3), 1–7.

Sunar, M. N. S. 2005 Kajian kualiti air terhadap system pengumpulan air hujan menggunakan penapis bio-pasir. Master's Thesis, UTHM, Batu Pahat, Johor, Malaysia.

Vanderzwaag, J. C. 2008 Use and performance of bio-sand filters in Posoltega, Nicaragua. Master of Applied Science Thesis, The University of British Columbia, Vancouver, Canada.