Point-of-use upflow sand filter for rural water treatment using natural local sand: Understanding and predicting pressure drop

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Abstract. A simple, small scale upflow sand filter was fabricated using a locally obtained sands at three different rivers in Sabah, Malaysia: Liwagu River (SL), Tamparuli River (ST), and Kaingaran River (SK). The grain size, porosity, bulk density, particle density and sphericity of the sands were characterized to associate with the corresponding pressure drop across the sand bed. The highest pressure drop per unit length for SK, PT, and SL are 15.85 kPa m⁻¹ at 0.747 m s⁻¹, 10.18 kPa m⁻¹ at 0.352 m s⁻¹, and 9.24 kPa m⁻¹ at 0.747 m s⁻¹, respectively. The pressure drop per unit length at different filter bed depth were plotted, and compared against three theoretical models of Ergun, Kozeny-Carman, and Fair and Hatch. By analyzing the experimental-theoretical comparison using RMSE and Chi-Test, prediction of pressure drop in an upflow sand filter is able to be predicted using the Kozeny-Carman equation preceding filter bed fluidization and subsequently Fair and Hatch’s equation after bed is fluidized.

1. Introduction
To this day, provision of clean water in isolated areas is still an issue in most developing countries. Without treating water for consumption, these communities are highly susceptible to waterborne diseases such as dysentery, typhoid, polio, cholera and diarrhea [1]. In Sabah, Malaysia alone, absence of treated water in rural areas has caused numbers of severe cases of cholera and diarrhea [2]. To provide clean water in rural areas that is outside of a main water supply network, point-of-use treatment system is usually preferred. For such purpose, sand filters constructed using local sands have been widely used due to its sustainability, low cost and high efficiency in removing pollutants. However, a conventional sand filter with downflow configuration is often associated with fouling, owing to the presence of Schmutzdecke layer, formed at the top most of the sand bed. This layer is a collection of alluvial mud, microorganism, organic waste and algae sediments during settlement and straining [3].

In view of a simple treatment method for isolated areas, an upflow configured sand filter has been viewed to be advantageous [4], especially as a point-of-use water treatment. Upflow sand filter has been applied in numerous water purification processes, such as in the removal of bacteria, algae, phosphorus, nitrogen, heavy metals, turbidity, total suspended solids (TSS), and chemical oxygen demand (COD) [5]. The absence of the Schmutzdecke layer indicates that filter clogging is less likely to occur and filter cleaning will be less frequent. Backwash can be conducted rapidly, require a shorter time, and filter downtime is thus minimized [6]. Similar to the conventional down-flow sand filter, the upflow sand filter separation mechanism operates based on screening, filtration, sorption, and ion exchange [7]. As
opposed to the down-flow sand filter, removal mechanism of its upflow counterparts, mainly occurs at depth where particles are attached to the sand grain or to previously retained particles. Such filtration mechanism is commonly associated with rapid filtration as the pressure driven filter causes contaminants to be removed deep in the filter bed.

Pressure drop is one of the most important aspects in designing a sand filter. It is resulted from the obstruction and drag produced by the sand media and the internal auxiliary of sand filters, such as the diffuser plate and nozzle underdrain [8]. Excessive pressure drop significantly reduces the water flux, requiring higher pumping power on sand filters, which reduces its overall efficiency. Conventionally, pressure drop monitoring can be conducted through manual observation of operating pressure at the start and the end of a filter bed. On the other hand, prediction using modelling is equally possible. Ergun and Kozeny-carman equations are often used to predict the pressure drop in a packed bed (equation 1 and 2), where $\frac{\Delta P}{\Delta L} = \text{pressure loss per unit length (Pa/m)}, \mu = \text{viscosity of water (Pa s)}, d_{eq} = \text{particle equivalent diameter (m)}, \psi = \text{sphericity (dimensionless)}, \rho = \text{fluid density (kg/m}^3), \varepsilon = \text{media porosity}, v_f = \text{filtration rate (m/s)}. However, in order to accurately estimate the pressure drop throughout the filter bed, physical parameters of the sand media such as the porosity, sphericity, and equivalent diameter must be determined [9].

\begin{equation}
\frac{\Delta P}{\Delta L} = 150 \frac{\mu v_f}{d_{eq}^2 \psi^2} \left(\frac{1-\varepsilon}{\varepsilon^3}\right) + 1.75 \frac{\rho v_f^2}{d_{eq} \psi} \left(\frac{1-\varepsilon}{\varepsilon^3}\right) \tag{1}
\end{equation}

\begin{equation}
\frac{\Delta P}{\Delta L} = 180 \frac{\mu v_f}{d_{eq}^2 \psi^2} \left(\frac{1-\varepsilon}{\varepsilon^3}\right) \tag{2}
\end{equation}

Previous literatures had designed the upflow sand filter in a towering vessel with a height of more than 30 feet [6], which is not practical for a small-scale application in a rural setting. To scale down the sand filter, Li and Pashley [10] constructed a miniaturized upflow sand filter using glass particles, industrial-produced quartz particles and activated charcoal. However, to enable the construction of simple, efficient sand filters in rural regions, local sands are preferred. In this study, locally obtained sands are used to fabricate small scale upflow sand filters. The pressure drop across the sand bed caused by varying grain size and filter bed depth is closely monitored, where the obtained pressure drop data is compared against the theoretical models. The findings of this study will be used for future design of an upflow sand filtration unit that is able to be self-assembled and operated in rural areas.

2. Material and Methods

2.1. Sand media

Sand sampling was conducted at three different rivers located in rural areas in Sabah, Malaysia: Liwagu River (SL), Tamparuli River (ST), and Kaingaran River (SK). All three locations were upstream from any residential areas and ensured to be less frequented by human or animals. Sand selection was carried out based on a few simple guides, i.e.: (i) Coarseness of the sand should be felt, (ii) the individual particle of sand can be observed, (iii) while squeezing the sand and letting go, the sand particles should smoothly pour out of the hand. Washing of the sand was done by swirling the sand and water in a container, before decanting the dirty water from the container. The process was repeated multiple times.

2.2. Physical characteristics

The bulk density, particle density, porosity, sphericity, and equivalent diameter were determined for each sand sample. The sand sphericity, $\psi$ was assessed visually under the microscope with $20\times$ magnification and compared to the Krumbein Roundness Sphericity Chart [11]. Sphericity is described as the ratio of the surface area of an equivalent volume sphere to the surface area of the sand grain. Sphericity increases with the roundness of the particle. $\psi = 1$ defines perfectly the spherical grains and
φ < 1 defines the angular particles [12]. The equivalent diameter, $d_{eq}$, was determined based on the method presented by Bové et al. [8]. $d_{eq}$ of sand grain is the diameter of a sphere with a volume equal to the average volume of the media grains [9].

2.3. Laboratory scale upflow sand filter

The experiment was carried out with a laboratory scaled sand filter fabricated from a clear acrylic tube with 0.154 m inner diameter and 1.5 m height. A 4 mm thick inner plate was affixed 150 mm from the bottom of the filter as support for sand media, and 2-mm holes of 6 mm apart were drilled across the plate to act as support as well as a diffuser. A variation of sand media was placed ranging from 0.4 to 0.8 m above the plate supported by two gravel layers to ensure no sand media travel to the lower layer of the filter. Manometer outlet was placed across the sand filter at intervals of 100 mm.

![Figure 1. Upflow sand filter configuration](image_url)

At the beginning of each trial set, the sand filter was operated at filtration velocity $10 \times 10^{-4}$ m.s$^{-1}$ for 10 minutes, allowing the sand bed to expand and ensuring a standardized initial compaction of the sand media. This step would ensure the experimental replicability and reduce the effect of different initial porosities for each trial set. After performing this initial procedure, the sand filter was allowed to reach a steady-state condition and data acquisition for pressure variables was initiated. Tap water was used throughout the experiment at a velocity ranging from $1.34 \times 10^{-4}$ to $12.99 \times 10^{-4}$ m.s$^{-1}$. The pressure head was recorded when the water flow and manometer reading stabilized.

3. Results and discussion

3.1. Physical characterization of filtration granules

The particle density of each sand sample was relatively in the same range, considering the equivalent diameter varied from 1.5 to 2.5 mm (Table 1). In general, smaller grain size will have greater porosity, however, the shape and angularity of the grain will have similar to greater effect on porosity. The angularity of the grain, which also determined by its sphericity affected the porosity of sand as pointed out by Rutledge and Gagnon [13]: porosity increases with more angularity of the sand. Bové et al. [8] have reported the same finding. Overall, the analysis shows that the acquired sands are suitable to be utilized as a media for upflow filtration as 0.4 porosity has been reported to provide deep filtration for removal of bacteria and viruses [14].
### Table 1. Sand and gravel support physical parameters

| Sample | $d_{eq}$ (mm) | Porosity | $\rho_b$ (kg/m$^3$) | $\rho_r$ (kg/m$^3$) | $\phi$ |
|--------|---------------|----------|---------------------|---------------------|--------|
| SL     | $2.5 \pm 0.0002$ | $0.42 \pm 0.013$ | $1477 \pm 19.76$ | $2536 \pm 31.93$ | $0.8$ |
| PT     | $1.7 \pm 0.0001$ | $0.40 \pm 0.016$ | $1507 \pm 34.27$ | $2512 \pm 17.55$ | $0.8$ |
| SK     | $1.5 \pm 0.0010$ | $0.43 \pm 0.025$ | $1461 \pm 62.17$ | $2575 \pm 28.99$ | $0.7$ |

#### 3.2. Pressure drop across bed

An increase in $v_s$ results in an increase of pressure drop. The highest pressure drop per unit length for each grain size was recorded as the following: SK (15.85 kPa m$^{-1}$ at 0.747 m s$^{-1}$ $v_s$) > PT (10.18 kPa m$^{-1}$ at 0.352 m s$^{-1}$ $v_s$) > SL (9.24 kPa m$^{-1}$ at 0.747 m s$^{-1}$ $v_s$). The result indicated that the smaller grain size resulted in a greater pressure drop. According to Ergun equation (equation 1), the pressure drop is also influenced by the collective effect of the sphericity and porosity of the grains. The highest pressure drop per unit length was observed for sand sample SK at 15.8 kPa m$^{-1}$ before the pressure drop stabilized during fluidization. Other researchers have observed a similar trend while applying different types of granular media [8, 15]. This study reveals that, although selection of smaller grain size may potentially have greater pollutant removal rate, it is not necessarily desirable in order to avoid a greater pressure drop in the filter bed.

It was interesting to witness that after a linear increase of pressure drop, at one point the pressure drop decreased before stabilizing with a further increase in $v_s$. The decline in pressure drop occurred after the fluidization of the filter bed. For each sand sample, this phenomenon occurred at a different velocity: SL at 0.747 m s$^{-1}$ $v_s$, SK at 0.747 m s$^{-1}$ $v_s$, and PT at 0.352 m s$^{-1}$ $v_s$. All experiments showed that the pressure drop remained relatively constant after the filter bed was fluidized. Increases in the $v_s$ expanded the filter bed, yet pressure drop remained comparatively steady. The fluidized pressure drop was recorded at 7.79 kPa m$^{-1}$, 8.48 kPa m$^{-1}$, and 14.1 kPa m$^{-1}$ for SL, PT, and SK, respectively (figure 3). This pressure drop should remain constant until 90% porosity is achieved [16]. The pressure drop during fluidization can be calculated by the equation developed by Fair and Hatch (1933) [17], which relates the pressure drop across a fully fluidized bed to the bed height and the porosity of the sand media. Same pressure drop behavioral tendencies have been explained by previous researchers [16, 18, 19]. It is also important to note that the equation is independent of the size of granular media.

$$\rho h \Delta h = g(\rho_p - \rho)(1 - \epsilon)l$$  \hspace{1cm} (3)
The result indicates that higher pressure drop is developed by deeper filter bed (figure 4). The maximum pressure drop occurred at a similar $\nu_s$ (0.835 m$^3$s$^{-1}$) except for 40 cm at 0.747 m$^3$s$^{-1}$ and 80 cm at 0.878 m$^3$s$^{-1}$. The respective maximum recorded pressure drops in each setup were: 30 cm at 7.96 kPa m$^{-1}$, 40 cm at 13.86 kPa m$^{-1}$, 50 cm at 18.03 kPa m$^{-1}$, 60 cm at 22.94 kPa m$^{-1}$, 70 cm at 28.68 kPa m$^{-1}$, and 80 cm at 32.54 kPa m$^{-1}$. Succeeding the maximum pressure drop, the filter bed was fluidized and the pressure drop stabilized. Previous studies have also recorded that deeper filter beds significantly increases the operating pressure drop [20]. This is primarily caused by the higher energy required for the water getting through the barriers provided by the depth of the media. Hence, demanding a higher energy consumption for a certain water yield. Additionally, gravity may play a small role as the current configuration is in upflow direction. For that reason, a higher filter bed may not be necessarily beneficial for removal of pollutants as similar removal efficiency can be achieved through a shallow bed depth [21].

3.3. Pressure Drop Prediction Model

Evaluation of significant difference between the experimental and empirical results were performed using Chi-test and Root Mean Square Error (RMSE). Experimental results (figure 3 and figure 4) showed two stages of pressure drop behavior, namely before and after fluidization occurred and therefore the analytical comparison was conducted based on these two stages (figure 5). Before fluidization, Chi-test showed no significant difference (p-value>0.05) between the experimental result and the empirical value predicted by Kozeny-Carman and Ergun equation in varied filter bed height. RMSE shows the Kozeny-Carman equation yielded to have the lowest value, indicating higher prediction performance. After fluidization, the condition was reversed, as Fair and Hatch’s values showed no significant difference, while Kozeny-Carman and Ergun equations showed p-values smaller or equal to 0.05. RMSE value further concurred with the analysis as Fair and Hatch’s equation displayed the smaller values, revealing a better fit to the experimental values in all experimental variations.

This analysis shows that prediction of pressure drop in an upflow sand filter is possible with consideration of its minimum fluidization velocity. The pressure drop behavior can be predicted using Kozeny-Carman equation up until fluidization is about to take place and Fair and Hatch’s equation, subsequent to fluidization. Prediction models are an imperative tool for variable modification, especially sand filter flowrate. Reduction in straining efficiency during filtration due to a fluidized bed can be avoided by pre-determination and working under the minimum fluidization velocity. Although, the
precision of prediction is highly reliant on the accuracy of the values of parameters, such as sphericity, sand media porosity, and sand equivalent diameter. Nevertheless, the obtained outcomes give a comprehensive insight on the filtering process of upflow filters with local sands, which gives promising potential to the realization to construct simple, low-cost sand filters in various rural regions.

Figure 5. Experimental Result Analysis against Empirical Model Value with Bed Height Variation

4. Conclusion
A small scale upflow sand filter was constructed using natural sands obtained from three local rivers around Sabah, Malaysia. Physical characterization was conducted to determine the grain size, porosity, bulk density, particle density and sphericity of the sand, where the grain size were SL (2.5 mm) > PT (1.7 mm) > SK (1.5 mm). The sand porosities (0.4 to 0.43) are suitable for removal of pollutants, especially bacteria in a deep filtration process. Pressure drop analysis showed that a smaller grain size contributes to a higher pressure drop. Maximum pressure drop recorded were: SK (15.85 kPa m$^{-1}$ at 0.747 m s$^{-1}$ $v_s$) > PT (10.18 kPa m$^{-1}$ at 0.352 m s$^{-1}$ $v_s$) > SL (9.24 kPa m$^{-1}$ at 0.747 m s$^{-1}$ $v_s$). The effect of the sphericity of the sand on the pressure drop was not observed since the variance of sphericity index was not obvious. Smaller sand grain, although could increase the removal efficiency, it also increases the pressure drop and pumping energy requirement. The pressure drop per unit length in the upflow filter bed was greatly affected by the depth of the filter bed. A deeper filter bed showed a higher pressure drop across the filter: 30 cm at 7.96 kPa m$^{-1}$, 40 cm at 13.86 kPa m$^{-1}$, 50 cm at 18.03 kPa m$^{-1}$, 60 cm at 22.94 kPa m$^{-1}$, 70 cm at 28.68 kPa m$^{-1}$, and 80 cm at 32.54 kPa m$^{-1}$. Although, the maximum pressure drop occurred at around similar $v_s$ (0.747 – 0.878 m s$^{-1}$ $v_s$). A deeper filter bed may not be ideal for optimum operation of the filter in terms of energy consumption as smaller depth could present better or equivalent efficiency in pollutant removal. Therefore, the optimization of filter bed height can only be done with the additional knowledge of pollutant removal efficiency with respect to filter height. Comparison of experimental results against prediction model showed that the pressure drop in the upflow sand filter could be predicted using the Kozeny-Carman equation preceding filter bed fluidization. After fluidization occurs, pressure drop lowers and then stabilizes. The fluidized filter bed pressure drop can then be predicted using the Fair and Hatch’s equation. The obtained knowledge of prediction models provides a preliminary understanding on upflow sand filters with locally obtained sands. This shows that further development of small scaled, point-of-use upflow sand filter that can be assembled locally are highly promising in order to deliver solutions for rural areas water provision.
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6. Reference
[1] World Health Organization WEDC 2013 Emergency treatment of drinking-water at the point of use Tech. notes Drink. water. Sanit. Hyg. emergencies 3–6
[2] Zin T, SabaiAung T, Saupin S, Myint T, KhinSN D, Soe Aung M 2015 Influencing Factors for Cholera and Diarrhoea: Water Sanitation and Hygiene in Impoverished Rural Villages of Beluran District, Sabah Malaysia. Malaysian J. Public Heal. Med. 15 30–40
[3] Barret, JM, Bryck J, Collins MR, Janonis BA, Logsdon GS 1991 Manual of Design for Slow Sand Filtration. AWWA Res. Found. AWWA 288
[4] Sarbatly R, Lahin FA, Ken CC 2020 The outlook of rural water supply in developing country: Review on Sabah, Malaysia J Borneo Sci. 41 19–43
[5] Heikal G, Wagdy, R, Eldidamony G 2017 Bacteriophage Removal Using Upflow Biosand filter: A Laboratory Study. Am. Sci. Res. J. Eng. Technol. Sci. 118–125
[6] Smith CK 1979 Tangentially fed upflow sand filter method and apparatus. 845341
[7] Pratap MR 2005 Upflow Filter for Rapid and Effective Treatment of Stormwater at Critical Source Areas. Pennsylvania State University
[8] Bové J, Arbat G, Duran-Ros M, Pujol T, Velayos J, Ramírez de Cartagena F, Puig-Bargués J 2015 Pressure drop across sand and recycled glass media used in micro irrigation filters. Biosyst. Eng. 137 55–63
[9] Soyer E, Akgiray O 2009 A new simple equation for the prediction of filter expansion during backwashing J. Water Supply Res. Technol. - AQUA 58 336–345
[10] Li X, Pashley RM 2016 A study on the characteristics of upflow matrix filter materials for the treatment of domestic sewage water J. Water Process Eng. 9 179–187
[11] Krumbein WC 1941 Measurement and geological significance of shape and roundness of sedimentary particles J. Sediment. Petrol. 11 64–72
[12] McCabe WL, Schmith JC, Harriot P 2001 Unit operations of chemical engineering (New York: McGraw-Hill) p 133
[13] Rutledge SO, Gagnon GA 2002 Comparing crushed recycled glass to silica sand for dual media filtration J. Environ. Eng. Sci. 1 349–358
[14] Aronino R, Dlugy C, Arkhangeskly E, Shandalov S, Oron G, Brenner A, Gitis, V 2009 Removal of viruses from surface water and secondary effluents by sand filtration Water Res. 43 87–96
[15] Mesquita M, Testezlaf R, Ramirez JCS 2012 The effect of media bed characteristics and internal auxiliary elements on sand filter head loss Agric. Water Manag. 115 178–185
[16] Summerfelt ST 2006 Design and management of conventional fluidized-sand biofilters Aquac. Eng. 34 275–302
[17] Fair GM, Hatch LP 1933 Fundamental factors governing the streamline flow of water through sand Am. Water. Assoc. 25 1551–1565
[18] Brouckaert BM 2004 Hydrodynamic detachment of deposited particles in fluidized bed filter backwashing (Georgia Institute of Technology)
[19] Cocco R, Karri SBR, Knowlton T 2014 Introduction to fluidization Chem. Eng. Prog. 110 21–29
[20] Escudero D, Heindel TJ, 2011 Bed height and material density effects on fluidized bed hydrodynamics Chem. Eng. Sci. 66 3648–3655
[21] Solé-Torres C, Puig-Bargués J, Duran-Ros M, Arbat G, Pujol J, Ramírez de Cartagena F 2019 Effect of underdrain design, media height and filtration velocity on the performance of micro irrigation sand filters using reclaimed effluents Biosyst. Eng. 187 292–304