Influence of grain size distribution towards improvements of turbidity, colour and suspended particles in a riverbank filtration process - a column study

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Abstract. Riverbank filtration (RBF) system is an efficient and natural treatment technology which, consists of high capacity pumping wells, located adjacent to river. It takes advantage of natural attenuation processes that occur as surface water infiltrate through the riverbed to produce potable water. This research determined the influence of media size distribution, and its hydraulic conductivity and porosity as filter media, of sand and gravel. The efficiency of column model for riverbank filtration system to remove turbidity, colour and suspended solids was also determined. The best condition of column model to remove contaminants with different flowrates and different types filter media used was identified through this research. The column study was conducted with three different types of filter media; C1 (sand), C2 (gravel) and C3 (sand + gravel) and with three different flowrates; 20 mL/min, 25 mL/min and 40 mL/min. Based on the results, C3 (sand + gravel) shows the highest percentage removal for turbidity, colour and suspended solids, which were 28.5%, 59.1%, 71.4% and 29.4%, respectively, although at difference flowrates. The highest percentage of removal of suspended solids (71.4%) occurs at 25 mL/min. The highest percentage of removal of colour (59.1%) occurs at 40 mL/min. Longer contact time might improve the removal of these contaminants.

Keywords: Riverbank filtration, column study, grain size distribution, river water abstraction

1. Introduction
Riverbank filtration (RBF) system is an efficient and natural treatment technology, which consists of high capacity pumping wells that located adjacent to rivers [1, 2] During riverbank filtration, a reduction in the concentration of pollutants is achieved by physical, chemical and biological processes that take place, between the surface water and underground, and with the substrate [3, 4] found that the RBF system is mostly constructed at alluvial aquifers that are located along the riverbanks. There are a variety of aquifers used in RBF system ranging from sand, sand and gravel, large cobbles and boulders. The ideal condition for this system typically includes coarse-grained and low permeability zones (such as clay and silt layers). A riverbank filtration can also occur under natural conditions or be
induced by lowering the groundwater table below the surface water level by abstraction from adjacent boreholes [5]. There are three types of RBF wells that can be designed, which are vertically (as the most common practice especially for the extraction of low water quantities), horizontally (for higher extraction rates) or pit well (for individual residential water supply) [3, 4]. A study in 2013 indicated that RBF system is the traditional drinking water treatment technology with low cost and sustainable alternatives that have the potential to supply water to 120 million people in the United States [6]. A study in 2012 [3] shows that the pollutants (particles, microorganisms, organic, and inorganic compounds) can be removed as the river water flow through the aquifer, which acts as a barrier against concentration peaks. The concept of RBF system is similar to some extent, to slow-sand filtration (SSF) [7]. A study in 2012 mentioned that the RBF systems have been used in Europe to supply drinking water to communities along the Rhine, Elbe, Danube, and Seine Rivers for more than 100 years. 75% of the city of Berlin depends on RBF, as the main drinking water supply [3]. About 50% of potable water was supplied by RBF in Slovak republic, 45% in Hungary, 25% in Switzerland, 16% in Germany and 5% in Netherlands [8, 9]. Nowadays, there are many countries around the world that have started to use RBF system for water treatment including India, South Korea, China and Jordan [7]. Regarding the suitability of grain size for an RBF system, it was found that the quality of water produced was satisfied by filtering with sand sizes larger than 0.2mm up to 0.45mm [10]. However, in other studies, the grain size of sand used by in their column study was between the range of 0.125 mm until 0.250 mm [9, 11].

Malaysia is blessed with rainfall throughout the year and surface water has been the major option of drinking water source. However, water shortages still occur at certain time in the year during the drought season which might be due to uneven rainfall distribution and poor water management due to extensive development of certain areas. RBF can be an option to increase the water abstraction quantity from an existing drinking water treatment plant, however the suitability of its soil as filter media and its abstraction capability must be tested. RBF has been practiced since 2013 in Malaysia [12, 13] however this technology must be tested locally for the suitability of the existing soil for RBF application. In Kota Lama Kiri, Kuala Kangsar the sieve analysis for the soil test found that the soil consisted mostly of medium sand, with fine sand, coarse sand and gravel present. The hydraulic conductivity for Kota Lama Kiri soil sample showed to be in the similar range to other alluvial aquifers in Ohio river (Louisville) and the Great Miami river (Cincinnati) in the USA [13]. This indicate the potential application of Kota Lama Kiri for RBF application. Thus, in this study, the suitability of sand and gravel from a river in Kelantan was studied to determine its suitability and capability for a possible RBF application.

2. Methodology

2.1. Site location

In this column study, river sand from Kampung Semuba, Pasir Mas, Kelantan and gravel was used as a filter media. The water sample was taken from the site on Kerian River at coordinates 5°7’38.79” N, 100°35’44” E, Lubuk Bunta, Kedah, located near to a palm oil and pineapple plantation.

2.2. Particle size distribution (PSD)

Sieve analysis was conducted for particle size distribution for particle sizes larger than 63 μm in diameter. The opening sieve sizes used was according to British Standard (BS), and were set in the order of 14 mm, 10 mm, 6.30 mm, 5.00 mm, 3.35 mm, 2.00 mm, 1.18 mm, 0.600 mm, 0.425 mm, 0.300 mm, 0.212 mm, 0.150 mm, 0.063 mm and pan. The percentage of passing for each sieve was calculated and particle size curve was plotted. By examining particle size curve, the soil type can be determined by referring soil mass fraction percentages that have been developed by the U.S. Department of Agriculture (USDA). This experiment was conducted to classify the soil sample, either it is well or poorly graded soil.
2.3. Hydraulic conductivity
In order to determine the hydraulic conductivity of the filter media used, constant head permeability test was conducted. Permeability is a measure of the capacity of soil to allow the flow of water through the pore spaces between solid particles [14]. The degree of permeability is determined by applying a hydraulic pressure gradient in a sample of saturated soil and measuring rate of flow. The constant head test method is used when the soils are said to be permeable soils (k > 10^{-4} cm/s). The sample must be dried before placing in the permeameter cell and the test was run according to the standard procedure. The principle behind this test is Darcy’s law for laminar flow. Thus, to calculate permeability, the Darcy’s law was used. The general equation of Darcy’s law is in Equation (1) is used to find the flow, Q. The calculation of coefficient of permeability, k value using constant head test was measured using Equation (2).

\[ Q = k \cdot A \cdot i \]  

\[ k_T = \frac{VL}{Ah} \]  

Where,

- \( k \) = Darcy’s coefficient of permeability
- \( i \) = Hydraulic gradient = h/L
- \( k_T \) = Coefficient of permeability at temperature T (cm/s)
- \( V \) = Volume of collected water (cm³)
- \( L \) = Length of specimen (cm)
- \( t \) = Time of discharge (s)
- \( A \) = Cross-sectional area of permeameter (cm²)
- \( h \) = Hydraulic head difference, \( h_1 - h_2 \) (cm)

2.4. Porosity
Two 1000 mL beakers were prepared (beaker 1 for soil sample and beaker 2 for water). Soil sample and water were added until 500 ml into each beaker. Water from beaker 2 was added into beaker 1 until the level is the same as the soil sample. The remaining volume of water was recorded. The total pore volume in the soil sample was calculated by subtracting the initial volume of water with the remaining volume of water. Lastly, the porosity of the soil sample was calculated by dividing the total pore volume by the total volume (Equation 3).

\[ \text{Porosity} (\%) = \frac{\text{Total pore volume}}{\text{Total volume}} \times 100 \]  

2.5. Column experiment
The column properties in this study are presented in Table 1.

| Table 1. Column properties. |
|----------------------------|
| Parameter                  | Column 1 (sand) | Column 2 (gravel) | Column 3 (sand + gravel) |
| Diameter of the column (mm) | 76             | 76               | 76                        |
| Length of the column (mm)   | 180            | 300              | 300                       |
| Depth of sand in the column (mm) | 160            | 0                | 140                       |
| Depth of gravel in the column (mm) | 0              | 210              | 70                        |
| Porosity (%)                | 32             | 41               | 32 & 41                   |
| Grading of soil             | Poorly graded  | Poorly graded    | Poorly graded             |
| Flowrate, mL/min            | 20, 25, 40     | 20, 25, 40       | 20, 25, 40                |
A schematic representation of the setup of the column experiment is as shown in Figure 1. The column was completed with two sampling ports (SP), which are SP 0 for the inlet and SP 1 for the outlet. The grain size of the river sand used in this experiment was 0.15 mm to 0.6 mm, while the grain size of the gravel used was between 3.35 mm to 6.3 mm. Three sets of column experiment were conducted; Column 1 (sand), Column 2 (gravel) and Column 3 (sand + gravel). These experiments were conducted to evaluate the performance of the three types of filter media to remove contaminants. First, media were washed with tap water and distilled water to remove the dirt off the media. Then, the washed media were dried in the oven for ±24 hours. Each set of columns were packed with the media. River water from Kerian River, Lubuk Buntar was used as feed water as this is the nearest source of river water to the lab. It was pumped from the bottom to the top of the column by using the peristaltic pump at 20, 25 and 40 mL/min flowrate. The experiment was conducted continuously for 3 hours and filtered water was taken at 15, 30, 60, 120 and 180 minutes and the filtered water were tested for the selected water quality parameters.

2.6. Analytical experiments
In the analytical experiment, the parameters of water quality measured were turbidity, colour and suspended solids. Turbidity was measured by using a HACH 2100N portable turbidimeter. For true colour (455nm), the filtered water was filtered through 0.45 μm cellulose nitrate filter by using a vacuum pressure pump then was measured by using HACH DR 2800 Spectrophotometer. For suspended solids, HACH DR 2800 Spectrophotometer was used to measure the concentration of suspended solids in raw and treated river water.

3. Results and discussions

3.1. Particle size distribution (PSD)
Figure 2 shows the particle size distribution curve of soil sample from Kampung Semuba, Pasir Mas, Kelantan. D_{10} represents 10% of the particles finer and 90% of the particles coarser than that particular size of D_{10}. D_{30} represents 30% of particles are finer and 70% of the particles are coarser than that particular size of D_{30}. D_{60} represents 60% of particles are finer and 40% of the particles are coarser than that particular size of D_{60}. 

![Figure 1. Schematic representation of the setup of the column experiment.](image-url)
The results of $C_u$ for sand and gravel are 5.00 and 1.31 respectively. For a gravel to be classified as well graded, $C_u$ and $C_c$ should range between $C_u \geq 4$ and $1 \leq C_c \leq 3$. For a sand to be classified as well graded, $C_u$ and $C_c$ should range between $C_u \geq 6$ and $1 \leq C_c \leq 3$. In cases where both characteristics are not met, the soil is classified as poorly graded soil. Therefore, both sand and gravel media in this study were classified as poorly graded as sand has the value of $C_u$ less than 6 and gravel has the value of $C_u$ less than 3. The range of size of the particles that were obtained from the sieve analysis of the sand was 0.063 mm to 14.00 mm while the range of size of particles for the gravel was 3.35 mm to 6.3 mm.

3.2. Hydraulic conductivity
According to Das (2010), permeability or hydraulic conductivity, $k$, is a measure of the capacity of soil to allow the flow of water through the pore spaces between solid particles. The hydraulic conductivity, $k$ value, for sand and gravel were 0.06 cm/s and 3.07 cm/s, respectively. The hydraulic conductivity of the gravel was greater than the hydraulic conductivity of the sand, with a difference of 3.01 cm/s. Hydraulic conductivity for sand at Pasir Mas showed to be similar to the sand in Kota Lama Kiri [13] that ranges between 0.10 and 0.91 cm/s. A large hydraulic conductivity value indicates high permeability and filtration [6]. Finer sediments exhibit low conductivity because water cannot filter as well through the pore spaces. The range of permeability indicates its high permeability and filtration. Study of filtration media is important to determine the suitability to establish a riverbank filtration system of a location [15] in their research also verify that this site (Pasir Mas, Kelantan) is suitable for riverbank filtration due to the presence of sand and gravels that come from granite and quartz [16].

3.3. Porosity
Porosity is normally calculated from measurements of bulk density. This varies with water content in soils that reflect the performance of filtration process. Based on the results obtained, it was found that the porosity for the river sand and gravel was 32% and 41%, respectively. It influences the velocity at which water moves through an aquifer under a given hydraulic gradient [17]. The porosity of the river sand is lower than gravel because of the size of the river sand was smaller compared to the gravel. As the size of the river sand was small, the void ratio obtained was also small. Thus, river sand which has low porosity compared with gravel will has less void within, to hold the flocs and solids removed from the water.
3.4. Column experiments

Column study was conducted regarding the effect of different filter media and flowrate used during column experiment. Flowrate used in this experiment was set at 20, 25 and 40 mL/min for all three column conditions. Here, three types of filter media were used, sand (C1), gravel (C2) and combination of sand and gravel (C3). The type of filter media used affected the performance of water quality during column experiment due to porosity, hydraulic conductivity and particle size distribution of the filter media. The lower the porosity, the lower the void space between particles, which allows it to better filter the particles present in the water. However, this might also affect its outflow rate, due to less porosity. Flowrate is also one of the factors that affect the percentage of removal in the continuous flow of column experiment. This flowrate for this research has been set at 20, 25 and 40 mL/min. A study indicated that the lower the flowrate used, the more effective the diffusion process was and the higher the residence time is, thus resulted in high sorption capacity [18].

Table 2 shows the summary of results of the percentage of removal of contaminants for the column experiment. From this study, the percentage of removal was relatively low. Here, three types of filter media were used; C1 (sand), C2 (gravel) and C3 (sand + gravel). In general, C1 has better removal of the pollutants and C3 also shows a comparable result. Results show that at the lowest flowrate (20 mL/min), percentage removal of turbidity was the highest for C1, C2 and C3 (28.5%, 22.2% and 28.5%) followed by 25 mL/min and 40 mL/min. For colour removal, it was the highest when high flowrate (40 mL/min) was applied for C1, C2 and C3 (50.0%, 50.0% and 59.1%) followed by 20 mL/min and 25 mL/min. At medium flowrate (25 mL/min), percentage removal of suspended solids is the highest for C1, C2 and C3 (67.4%, 65.3% and 71.4%) followed by 20 mL/min and 40 mL/min.

Sand media has been frequently used due to their advantages and its efficiency to remove pollutants [19]. Gravel is commonly used to support the filter media. Gravel role is not just to avoid filter media from flowing out of the filter in filtration process but also to distribute clean water flowing into the filter in backwashing process. Based on the results, it is not suitable to only use gravel as a filter media to remove contaminants. For the removal of turbidity, the percentage removal is higher when the flowrate is 20 mL/min. For the removal of colour, the percentage removal is higher when the flowrate is 40 mL/min. For the percentage removal of suspended solids, the percentage removal is higher when the flowrate is 25 mL/min. Thus, different flowrates used in this column experiment does not significantly affect the efficiency to remove these selected water contaminants. This might also be affected with the short column run time, only 3 hours. A longer period of experiment might be needed to reach the stability and better performance of the filtration system. This is supported by the finding in Egypt [20], where it took 2 to 8 months to stabilise the RBF for hydrochemical parameters monitoring, with a continuous operation of the RBF. The time for column study to stabilise might be lesser than on-site study as the scale is smaller as well. However, it still requires continuous flow of water to ‘ripen’ the column condition. In a column study of sand filtration and schmutzdeckes layer function on E.coli removal by Unger (2006), between 4 hours and 2 weeks of ‘ripening’ time was applied to understand the effects of the layer on bacteria removal in water [21]. With a longer continuous run time, the development of schmutzdeckes layer will be faster. It was shown that over time, particles clogging, and the layer development slows the water seepage in the media and thus improved the discharged water quality. Overall, different types of filter media used affect the efficiency to remove water contaminants in which C1 (sand) and C3 (sand + gravel) show a better performance compared with C2 (gravel), but the flowrates did not affect the contaminants removal performance.
Table 2: Summary of percentage removal of contaminants for column experiment

| Flowrate (mL/min) | Percentage removal (%) |
|-------------------|------------------------|
|                   | 20                     | 25                     | 40                     |
| Filter media      | C1 C2 C3               | C1 C2 C3               | C1 C2 C3               |
| Turbidity (NTU)   | 28.5 22.2 28.5         | 20.2 19.9 23.7         | 17.2 16.6 22.2         |
| Colour (TCU)      | 47.1 11.8 29.4         | 6.7 13.3 20.0          | 50.0 50.0 59.1         |
| Suspended solids (mg/L) | 50.0 42.0 48.0 | 67.4 65.3 71.4 | 35.6 30.1 35.6 |

4. Conclusions

Sand and gravel media used in this study were classified as poorly graded as sand has the value of Cu less than 6 and gravel has the value of Cu less than 3. The sand sample has a low hydraulic conductivity and porosity compared to gravel. Based in the column study, the percentage removal was relatively low, the maximum removal in all condition was only 71.4% of suspended solids in the gravel only column, that might be due to the duration of time to conduct this experiment for each different flowrate is only 3 hours. Basically, a longer duration of time is required in order to achieve higher percentage removal of contaminants. Types of filter media used is one of the factors that affects the percentage removal of water quality. Here, three types of filter media were used; C1 (sand), C2 (gravel) C3 (sand + gravel). From these three types of filter media, C1 and C3 have a better potential to remove contaminants compared with C2. For the removal of turbidity, the percentage removal is higher when the flowrate is 20 mL/min. For the removal of colour, the percentage removal is higher when the flowrate is 40 mL/min. For the percentage removal of suspended solids, the percentage removal is higher when the flowrate is 25 mL/min. Thus, different flowrates used in this column experiment does not significantly affect the efficiency to remove water contaminants.

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References

[1] Massmann G, Nogeitzig A, Taute T and Pekdeger A 2008 Seasonal and Spatial Distribution of Redox Zones during Lake Bank Filtration in Berlin, Germany Environmental Geology 54 p 53-65

[2] Ulrich C, Hubbard S S, Florsheim J, Rosenberry D, Borglin S, Trota M, and Seymour D 2015. Riverbed Clogging Associated with a California Riverbank Filtration System: An Assessment of Mechanisms and Monitoring Approaches Journal of Hydrology 529 p 1740-53

[3] Jaramillo M 2012 Riverbank Filtration: An Efficient and Economical Drinking-Water Treatment Technology Dyna 79(171) p 148-157

[4] Hunt H 2002 American Experience in Installing Horizontal Collector Wells. Riverbank Filtration Springer Netherlands. p 29-34

[5] Hiscock K M and Grischek T 2002 Attenuation of Groundwater Pollution by Bank Filtration Journal of Hydrology 266 p 139-144

[6] Vozza G M 2013 Riverbed Filtration Clogging at Wohler on the Russian River, Sonoma County, California p 1-25.

[7] Shamrukh M and Abdel-Wahab A 2008 Riverbank Filtration for Sustainable Water Supply: Application to a Large-Scale Facility on the Nile River Clean Technology Environment Policy 10 p 351-358.
[8] Dash R R, Prakash E B, Kumar P, Mehrotra I, Sandhu C and Grischek T 2010 River Bank Filtration in Haridwar, India: Removal of Turbidity, Organics and Bacteria. *Hydrogeology Journal* **18** p 973-983

[9] Diem S, Von Rohr M R, Hering J G, Kohler H P E, Schirmer M and Von Gunten U 2013 NOM Degradation during River Infiltration: Effects of the Climate Variables Temperature and Discharge *Water Research* **47** p 6585-95

[10] Muhammad N, Ellis K, Parr J and Smith M D 1996 Optimization of Slow Sand Filtration. WEDC, Loughborough University, Leicestershire Le 11 3 TU(UK) p 283-285

[11] Von Rohr M R, Hering J G, Kohler H P E and Von Gunten U 2014 Column Studies to assess the Effects of Climate Variables on Redox Processes during riverbank filtration *Water Research* **61** p 263-275

[12] Rashid, N. A., Abustan, I., and Adlan, M. N. 2016. River Bank Filtration Artificial Barrier to Remove Escherichia Coli. *International Journal of Scientific Research in Knowledge,(IJSRK)*, 4, pp. 45-54.

[13] Adlan M N, Mohd Ariff Zainol M R R, Ghazali M F, Selamat M R and Othman S Z 2016. A study on the soil characteristic and properties of riverbank soil samples from Sungai Perak, Kota Lama Kiri, Kuala Kangsar, Malaysia *IOP Conference Series: Materials Science and Engineering, 133(1)* p 012003

[14] Das B M 2010 Principles of Geotechnical Engineering. 7th Edition. p 1-666.

[15] Sharma B, Uniyal D P, Dobhal R, Kimothi P C and Grischek T 2014. A Sustainable Solution for Safe Drinking Water through Bank Filtration Technology in Uttarakhand, India. *Current Science* **107** p 1118-24

[16] Adlan M N, Nawawi M, Murshed M F, Palaniandy P, Abustan I, Abdul Aziz H and Mohd Ariff Zainol, M R R 2015 Preparedness on Water Abstraction and Treatment on Flood Prone Areas in Kelantan River Basin *Jurnal Teknologi* p 1-8.

[17] Caldwell T G 2006 Presentation of Data for Factors Significant to Yield From Several Riverbank Filtration Systems in the U.S. and Europe *Springer Netherlands*. p 299-344.

[18] Bharathi K S and Ramesh S P T 2013 Fixed-Bed Column Studies on Biosorption of Crystal Violet from Aqueous Solution by Citrullus Lanatus Rind and Cyperus Rotundus *Applied Water Science* **3** p 673-687.

[19] Segismundo E Q, Kim L H, Jeong S M and Lee B S 2017 A Laboratory Study on the Filtration and Clogging of the Sand-Bottom Ash Mixture for Stormwater Infiltration Filter Media. *Water* **9** p 32.

[20] Wahaab R A, Salah A, Grischek T 2019 Water Quality Changes during the Initial Operating Phase of Riverbank Filtration Sites in Upper Egypt. *Water* **11(6)** 1258.

[21] Unger, M C 2006 The Role of the Schmutzdecke in Escherichia Coli Removal in Slow Sand and Riverbank Filtration. Master's Theses and Capstones. 251. [https://scholars.unh.edu/thesis/251](https://scholars.unh.edu/thesis/251)