Effect of particle size distribution on the removal of color and *Escherichia coli* in shallow groundwater

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Abstract:

Shallow riverbank groundwater along permanent rivers represents a good water resource. The particle distribution in a soil determines its hydraulic conductivity, which is a critical criterion in the selection of riverbank sites for filtration. Over time, particle size distributions (PSD) may change because of clogging and the weathering of local soil. In this study, the effect of PSD on the removal of color and *Escherichia coli* (*E. coli*) from groundwater was investigated. A laboratory scale model was constructed to determine the horizontal hydraulic conductivity of local alluvial soil with different PSD. The results were analyzed on the basis of two factors: (a) different alluvium soils and (b) soil uniformity coefficient (*C*). The alluvial soils (Sands A, B, C, and D) showed hydraulic conductivities ranging from 6.87 × 10⁻⁴ m/s to 8.96 × 10⁻⁴ m/s. Results indicated that an increase in *C* can improve the removal of color and *E. coli*. The Sand A, which had a well-graded PSD and the highest *C* value, achieved color and *E. coli* removal rates of up to 70% and 100%, respectively.

KEYWORDS particle size distribution; riverbank filtration; hydraulic conductivity; coefficient of uniformity; alluvium soil; shallow groundwater

INTRODUCTION

In some parts of the world, people’s water for daily use is largely sourced from groundwater. Shallow groundwater is the water present in the saturated zone beneath the water table in riverbanks along permanent rivers and seasonal water courses (Van der Perk, 2006). Alteration of shallow groundwater levels can occur due to climate change (Ibrahimi et al., 2010). As stated by Wang (2002), soil aquifers can remove or retard certain water contaminants after water passes through gravel, sand, clay, and silt particles. These underground passages ensure high-quality drinking water, which requires little or no further treatment or disinfection before supply (Tischendorf et al., 2008).

Riverbank filtration (RBF) is a natural treatment that involves the inflow of river water to the underground aquifer induced by hydraulic gradients, and is especially useful for treatment during groundwater abstraction. RBF systems have been applied in countries such as Germany, Korea, India, Egypt, and Austria (Lee et al., 2009; Shamrukh and Ahmed, 2011). The RBF treatment process could also support other treatment processes by providing a robust barrier for multiple contaminants and reducing the overall cost of water treatment (Ray et al., 2002).

Hiscock and Grischeck (2002) stated that pollutants such as color, turbidity, total coliform, *Escherichia coli* (*E. coli*), Cryptosporidium parvum, dissolved organic matter, and heavy metals could be removed through RBF. For example, an RBF system located near the Yamuna River in India reduces color by around 50% via bed filtration (Singh et al., 2009). The Netherlands has extensive experience with RBF over more than 100 years. There, RBF can yield 0.04 m³/s in soils consisting of 85% gravel. It has been observed that gravel aquifers are very inert with extremely low organic carbon and cation exchange capacity (CEC). The alluvial soil at a RBF site in the United States (US) consists of a mix of brown clay, gravels and fine sand, with estimated yield of 0.23 m³/s of water. However, RBF sites in Jordan display lower yields than in the US at 0.003–0.004 m³/s. There, alluvial soil consists of 90% sand. Nevertheless, together RBF sites in Jordan, US, and Netherlands show *E. coli* removal rates of up to 99% (Saadoun et al., 2010; Weiss et al., 2002; Tufenkji et al., 2002). These studies indicate that most RBF sites have been built on sandy aquifers. Therefore, in this study we focused on sandy soil types.

Grain size determines the hydraulic conductivity of a soil. Unlike fine particles, such as those in clay, large particles create large void ratios in soil media. However, Teng and Zhao (1999) found that compared with particle size, pore structure has a greater influence on the resistance of fluid to transport via porous media because the amount of free space affects the amount of fluid that can flow. If the fluid path is blocked because of poorly sorted sediments, then the amount of fluid that can flow through the sediment is reduced (Belen, 2003). Soil particle distribution determines pollutant elimination rates. However, such distribution in natural filtration systems such as RBFs cannot be controlled in the same way as that in man-made filtration treatment systems, where we can sort particles according to size. Considering these factors, in this study we focused on the capability of local alluvial soil to remove contaminants. The main objective of the study is to determine the effect of changes in particle size distribution (PSD) and soil uniformity coefficient (*C*), on the removal of contaminants (color and *E. coli*) in RBF systems. These parameters are among the most critical in sifting, and determining the suitability of RBF water abstraction sites (Henry, 2002).
MATERIALS AND METHODS

Study area

The study area (Figure 1) is located in Jenderam Hilir, Dengkil, Selangor along Sungai Langat (2°53’28.47” N, 101°42’4.58” E). Water and soil samples were taken to a laboratory in the School of Civil Engineering of Universiti Sains Malaysia for further analysis.

Soil analysis

Soil samples were obtained from boreholes in the Sungai Langat riverbanks (approximately 9.5 m from the right bank). Four samples obtained at depths of 16, 18, 19, and 23 m were labeled as A, B, C, and D, respectively. The PSDs of the samples were subsequently analyzed according to the ASTM D 2487-06 standard procedure.

Water analysis

Color was measured with a Hach DR 2800 Spectrophotometer according to Method 8025. E. coli was measured with a Quanti-Tray according to Method 9223B.

Experimental setup

A Perspex laboratory-sized physical model of the riverbank was set up, as shown in Figure 2 (a), (b) and (c). The model was rectangular and measured 0.6 m × 0.2 m × 0.8 m. The sand was mixed well (with 8 kg of sand) before being poured into Section II of the physical model (Figure 2a). The sand was levelled over the whole area of Section II without placing any pressure on the sand. A peristaltic pump with a capacity of 100 mL/min was used to create different heads between Sections I and III. Subsequently, water levels at Sections I and III (Figure 2a) were measured and recorded as the head difference. When the flow was stable (water is saturated in sand), the effluent in Section III was collected for 180 seconds retention time, and color and E. coli (initial concentration 140 NTU and 151.5 MPN, respectively) were analyzed. This method was repeatedly performed with different soil PSDs (constant volume = 5 m³) to investigate their removal capabilities. Darcy’s Law was considered in determining the horizontal hydraulic conductivity, as shown in Eq. (1).

\[ Q = -kAi \]  

where \( k \) is the coefficient of hydraulic conductivity (m/s), \( A \) is the area of the soil column (m²), and \( i \) is the inclination of the water table. A constant head hydraulic conductivity test (horizontal), as described in ASTM D 2434-68, was performed on the sand samples. Given the large pore openings, a high hydraulic conductivity (\( k > 10^{-6} \) m/s) was expected.

RESULTS AND DISCUSSION

Soil analysis

The PSDs of the four sand samples showed different curves (Figure 3). \( C_u \) was determined using the curve below (Figure 3) by setting the value of \( D_{60} \) and \( D_{10} \) on the basis of the curve and then calculating the coefficient using the formula \( D_{60}/D_{10} \). Sieve analysis results revealed that the calculated \( C_u \) ranged from 2.50 to 4.62. The curves for Sands A and D in Figure 3 were nearly vertical, which reflected the uniform grade of the sands.

Figure 1. Location of the study area using GeoEye-1 satellite imagery with an acquisition date of 1 Feb 2012. Location: Jenderam Hilir, Dengkil, Selangor
Hydraulic conductivity and results of coefficient of uniformity

Table I shows that the horizontal soil hydraulic conductivities of the samples ranged from $6.87 \times 10^{-4}$ to $8.96 \times 10^{-4}$ m/s. The $k$ of the soil varied with different sands in the physical laboratory model. Sand B showed the highest horizontal $k$, followed by Sands A, D, and C. This result is most likely attributable to Sand B having a high density.

Removal of pollutants

Sands A and D achieved good color removal rates of 70%–76% (Figure 4) while Sands B and C yielded low color removal rates of 39% and 40%, respectively. In terms of grading, Sands A and D can be considered well-graded sands. The soil structure included small particles that filled the interspaces between the large particles, thereby encouraging clogging. This situation can assist the adsorption process because of the high specific surface area (James and Jerry, 2000). The mechanisms for color removal are adsorption and flocculation. Particles which contact the surface of the medium or with other particles will be held together either by chemical or physical adsorption or both. Flocculation can occur when the larger particles formed by the velocity gradients within the model are removed by straining removal mechanisms. The removal efficiency of these processes depends on grain size, specific surface area, pore size distribution, and density of the media used (Pani, 2013). The color removal rates of Sands A and D were high, 76% and 70% respectively, compared to those of Sands B and C, which were 39% and 40% respectively. This is probably due to the high $C_u$ values in Sands A and D.

The highest $E. coli$ removal was observed in Sand A, the removal rate for which ranged from 9.6 MPN/100 mL to 0 MPN/100 mL (100% removal). Sands B and D also showed good $E. coli$ removal, given their removal rates exceeding 80%. Sand C showed the lowest $E. coli$ removal rate of less than 80%. As reported by Ping and Yajun (2010), sandy soil with lowest hydraulic conductivity coefficients and highest apparent density is less likely to remove pollutants by adsorption. Since this experiment used a constant volume of sand ($5 \text{ m}^3$), the hydraulic conductivity for each samples was not very different with $R^2$ of 0.2967 ($C_u$ range 2–5). This value is close to that in similar research by Önar (2014) with $R^2$ of 0.3298. Therefore, the effect of hydraulic conductivity in this experiment is not likely to be significant. The dry density of Sand D was the highest at 1659 kg/m$^3$ ($C_u = 4.00$) compared to Sand C with 1512 kg/m$^3$ ($C_u = 2.50$), but the former can remove color and $E. coli$ up to 80%. Based on this result, $C_u$ is more significant in affecting color and $E. coli$ removal. Microorganisms are primarily removed from water during soil passage via straining, inactivation, and attachment to aquifer grain (adsorption) (Schijven et al., 2002). Changes in PSD do interfere with the efficiency of removing color in groundwater. Sands A and D showed beneficial characteristics, including high color removal rates of 60% to 80%. By contrast, Sands B and C demonstrated poor color removal. As shown in Figure 4, the sand samples with low $C_u$ values (Sands B and C) were not efficient in removing color.
POLLUTANTS REMOVAL IN SHALLOW GROUNDWATER

In summary, based on the limited sources for the sample taken from the constructed borehole near the riverbank, the results show that the sand samples with high $C_u$ values (Sands A and D) performed better than those with low $C_u$ values in the removal of color and E. coli. It can be inferred that pollutant removal by alluvial sandy soil at the water abstraction borehole near the riverbank is influenced by $C_u$ (for $C_u$ range 2–5). Although Sand B can yield the highest abstraction water, which is a good condition for RBF, pressure is applied in real RBF conditions to increase the volume of water yield. Hence, graded sand with $C_u$ higher than 4 is suitable for RBF sites since it can give consistent performance for pollutant reduction. Sands from most natural resources are widely graded, and their grain sizes greatly vary. These characteristics lead to high $C_u$. Widely graded layers are important in preventing fine particles from moving together with flowing water in RBF applications.

As this study showed, the removal of color and E. coli has a direct relationship with PSD and $C_u$. Figure 5 indicates that by increasing $C_u$, the removal of contaminants ($R^2$ for E. coli = 0.9775 and color = 0.6576) increases linearly. In this study, the removal of color and E. coli was prominent and showed a consistent removal with high $C_u$. Therefore, it is suggested that sites selected for RBF abstraction will need to show high coefficient of uniformity of alluvial soil in order to support dynamic performance of the RBF system. A dynamic RBF system has dynamic soil properties that can provide consistently high removal of pollutants over a long period.

CONCLUSIONS

The efficiency of different alluvious soils (within a constant volume) in removing color and E. coli depends most significantly on PSD and $C_u$. The effect of hydraulic conductivity can be ignored. The study of four different sand PSDs showed that Sand A, which had the highest $C_u$ (4.62), achieved the best removal rate. As indicated by the relationship between $C_u$ and removal efficiency, a high $C_u$ equates to good removal efficiency. Alluvial soil with $C_u$ greater than 4 can effectively remove color and E. coli, as evidenced by the respective maximum removal rates of 76% and 100% of Sands A and D, the $C_u$ values for which were 4.62 and 4.00, respectively. The different PSDs of alluvial sands equates to different contaminant removal efficiencies. Consistency in contaminant removal is important in RBF applications, as it ensures sustainability. Dynamic soil properties such as high $C_u$ could aid in achieving such consistency in RBF. Dynamic soil properties are those soil properties which give a consistent RBF performance in removing pollutants over time.

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REFERENCES

Belen LSRB. 2003. Dynamics of gravel and mixed, sand and gravel, beaches. Doctoral Thesis, Imperial College, University of London, London, UK.

Henry CH. 2002. Construction and maintenance of wells for riverbank filtration. Proceedings of Riverbank Filtration the Future is Now September 16–19, 2003 Hilton Ohio, USA; 17–22.

Hiscock KM, Grischeck T. 2002. Attenuation of groundwater pollution by bank filtration. Journal of Hydrology 266: 139–144. DOI: 10.1016/S0022-1694(02)00158-0.

Ibrahim MK, Miyazaki T, Nishimura T. 2010. A high measurement frequency based assessment of shallow groundwater fluctuation in Metouia Oasis, South Tunisia. Hydrological Research Letters 4: 75–79. DOI: 10.3178/HRL.4.75.

James CC, Jerry TE. 2000. Wisconsin mound soil absorption systems: Sitting, design and construction manual. Small scale waste management project. University-Madison, Madison, U.S.A; 9.

Lee JH, Hamm SY, Cheong JY, Kim HS, Ko EJ, Lee KS, Lee SI. 2009. Characterizing riverbank-filtered water and river water qualities at a site in the lower Nakdong River basin, Republic of Korea. Water Air Soil Pollution 203: 215–225. DOI: 10.1007/s11270-009-0333-9.
of Korea. *Journal of Hydrology* **376**: 209–220. DOI: 10.1016/j.jhydrol.2009.07.030.

Onur EM. 2014. Predicting the permeability of sandy soils from grain size distribution. Master of Science Thesis, Kent State University, Ohio, U.S.A.

Pani S. 2013. *Enhancement of Natural Water Systems and Treatment Methods for Safe and Sustainable Water Supply in India*. UNESCO, Netherlands; 5.

Ping X, Yajun Z. 2010. Media selection of artificial soil filtration system for stormwater runoff treatment in Beijing. *Proceeding of Management and Service Science (MASS) August 24–26, 2010 Wuhan, China*; 1–4. DOI: 10.1109/ICMSS.2010.5577097.

Ray C, Grischek T, Schubert J, Wang JZ, Speth TF. 2002. A perspective of riverbank filtration. *Journal of American Water Works Association* **94**: 149–160.

Saadoun I, Boving T, Schijven J, Shawaqfah M, Al-Ghazawi Z, Al-Rashdan J, Blandford W, Ababneh Q, Berg HVD. 2010. Removal of fecal indicator coliforms and bacteriophages by riverbank filtration (RBF) in Jordan. *Proceedings of the International Conference on Construction and Building Technology (ICCBT) June 16–20, 2008 Kuala Lumpur, Malaysia*; 191–198.

Schijven JF, Berger P, Miettinen I. 2002. Removal of pathogens, surrogates, indicators, and toxins using Riverbank Filtration. In *Riverbank Filtration Improving Source-Water Quality*, Ray C, Melin G, Linsky RB (eds). Kluwer Academic: Netherlands; 73–116.

Shamrukh M, Ahmed AW. 2011. Water pollution and riverbank filtration for water supply along river Nile, Egypt. *Journal of Riverbank Filtration for Water Security in Desert Countries* **233**: 1824. DOI: 10.1007/978-94-007-0026-0_2.

Singh P, Kumar P, Mehrotta I, Grischek T. 2009. Impact of riverbank filtration on treatment of polluted river water. *Journal of Environmental Management* **91**: 1055–1062. DOI: 10.1016/j.jenvman.2009.11.013.

Teng H, Zhao TS. 1999. An extension of Darcy’s law to non-Stokes flow in porous media. *Journal of Chemical Engineering Science* **55**: 2727–2735. DOI: 10.1016/S0009-2509(99)00546-1.

Tschendorf W, Kupfersberger H, Schiling C, Gabriel O. 2008. Investigating artificial groundwater recharge to ensure the water supply to the city of Graz. *Water Practice and Technology* **3**: 1–9. DOI: 10.2166/wpt.2008.063.

Tufenkji N, Ryan JN, Elimelech M. 2002. The promise of bank filtration. *Environment and Science and Technology* **36**: 422A–428A. DOI: 10.1021/es022441j.

Van der Perk M. 2006. Chapter 3: Environmental compartments. In *Soil and Water Contamination: From Molecular to Catchment Scale*, Van Der Perk M (ed). Taylor and Francis: London; 59.

Wang J. 2002. Riverbank filtration case study at Louisville, Kentucky. In *Riverbank Filtration*, Ray C, Melin G, Linsky RB (eds). Kluwer Academic: Netherland; 117–145.

Weiss WJ, Bouwer EJ, Ball WP, O’Melia CR, Arora H, Speth TF. 2002. Reduction in disinfection byproduct precursors and pathogens during riverbank filtration at three Midwestern United States drinking-water utilities. In *Riverbank Filtration Improving Source-Water Quality*, Ray C, Melin G, Linsky RB (eds). Kluwer Academic: Netherlands; 147–173.