The role of the "urban karst" and mineralogy of surrounding soils in the fate of infiltrated pollutants

Le rôle du « karst urbain » et de la minéralogie sur la migration des polluants dans le sol

Amir Behroozi*, Meenakshi Arora*, Tim D Fletcher**, Andrew Western*

*Department of Infrastructure Engineering, University of Melbourne, Victoria 3010, Australia (abehroozi@student.unimelb.edu.au)
**Department of Ecosystem and Forest Sciences, University of Melbourne, Victoria 3121, Australia

RÉSUMÉ

La conception et l'emplacement des ouvrages d'infiltration nécessitent une compréhension du devenir des eaux infiltrées et des polluants transportés. Le défi porte sur la complexité des zones urbaines, dû à la perturbation liée à la modification du sol pour la construction des infrastructures souterraines. Ces modifications peuvent induire des chemins préférentiels, permettant le transfert rapide des eaux infiltrées et des polluants vers les milieux récepteurs : phénomène dit de « karst urbain ». Les recherches ont identifié le risque de transfert des polluants des bassins d'infiltration vers la nappe phréatique, mais peu ou pas de travaux ont porté sur le risque de migration des polluants vers le cours d'eau. La présente étude réalisée en laboratoire a pour but de quantifier l'effet du karst urbain et de la minéralogie du sol sur le transfert des polluants solubles. Les résultats montrent le rôle important de la minéralogie dans la rétention des polluants, mais mettent surtout en évidence la capacité des tranchées (d'enfouissement des réseaux) à permettre une migration des polluants. Ce dernier pose un fort risque de dégradation du milieu récepteur. Ces facteurs devraient être pris en compte dans la conception des bassins d'infiltration.

ABSTRACT

Stormwater infiltration basin design and siting in the landscape requires an understanding of where and how quickly the infiltrated stormwater and its associated pollutants move. Urban environments pose a particular challenge due to the complex network of gravel trenches associated with subsurface infrastructure that likely creates strong preferential flow pathways, potentially short-circuiting the soil and rapidly transmitting water and pollutants to streams; undermining the objectives of infiltration systems. Many papers to date have undertaken studies into the transfer of soluble pollutants from stormwater infiltration basins into groundwater; but the subsequent transfer from urban soils into receiving waters has received less attention. Hence, the transport of pollutants from infiltration basin to the stream and the effect of urban karst on the mobilisation of these pollutants are investigated through laboratory experiments. The experimental results indicate that the clay mineralogy has a significant impact on the movement of the pollutants. Moreover, the existence of karst-like aquifer accelerates the transport of pollutants through the subsurface, potentially degrading urban stream ecosystems. These two factors should therefore be carefully examined before implementing stormwater infiltration systems.

KEYWORDS

Clay mineralogy, pollutant fate, permeable trenches, stormwater infiltration basins, urban streams

1 BACKGROUND AND AIMS OF THE WORK

Urbanisation introduces significant impervious areas, reducing soil water and groundwater recharge and increasing stormwater runoff (Pitt, Clark, & Field, 1999). This is a primary cause of the degradation of receiving waters (Walsh et al., 2005), depriving urban communities of the ecosystem services provided by healthy urban streams. The degradation occurs both due to changes to flow regimes (Poff et al., 1997) and water quality (Roy, Dybas, Fritz, & Lubbers, 2009). Mitigation measures have been widely implemented to reduce the degradation, using technologies such as stormwater wetlands, rain gardens and infiltration basins. Infiltration basins are widely applied, in part for their assumed ability to recharge groundwater; restoring clean, filtered baseflows to urban streams (Hamel, Daly, & Fletcher, 2013).

Increasing evidence exists (e.g. Fischer, Charles, & Baehr, 2003), however, of unintended consequences of such basins, including the potential to introduce a variety of pollutants into the soil and groundwater and subsequent transport to receiving waters. It is plausible that infiltration basins may fail to restore stream baseflow regime and water quality (Kirchner, 2003), due to the gross disturbance of subsurface flow paths caused by urban karst (Soulsby, Birkel, & Tetzlaff, 2014). The urban karst is the gravel trenches associated with water, energy, communications and other infrastructure, which potentially short-circuits the hillslope by rapidly transmitting water and pollutants to streams.

This research aims to conduct a series of laboratory experiments to better understand the movement of pollutants in urban landscapes as one part of an effort to better locate and design stormwater infiltration basins to improve urban stream health.

2 METHODS

Experiments used both batch and column designs. The mineralogical composition of the natural soil used, which had a median particle size of 36 µm, was determined by X-ray diffraction (Warren, 1990) as quartz (76%), kaolinite (13%) and muscovite (11%). A synthetic soil was also made by mixing 76% quartz and 24% kaolinite, based on the natural soil characteristics.

2.1 Equilibrium batch tests

Batch sorption tests evaluated the impact of initial Zn^{2+} concentration on Zn^{2+} sorption in the natural and synthetic soils. These were performed at room temperature (22 ±2 °C) in 100 mL Pyrex flasks stirred at 250 rpm using a digital orbital shaker. The solutions were filtered after the equilibrium time and residual Zn^{2+} concentrations in the liquid were determined using an inductively coupled plasma-optical emission spectrometer ICP-OES (Optima 4400, Perkin Elmer, USA). The equilibrium mass of sorbed Zn^{2+} per unit soil mass, q_e, (mg g^{-1}), was calculated using:

$$q_e = \frac{(C_0 - C_e)V}{m} \quad (1)$$

in which C_0 and C_e (mg L^{-1}) are aqueous Zn^{2+} concentrations at the initial and equilibrium time, respectively, V is the volume of the aqueous solution (L) and m is the mass of soil material (g). Sorption equilibrium is usually described using an isotherm equation such as the two chosen here; the Langmuir and Freundlich models (Freundlich, 1907; Langmuir, 1918). These are:

(a) Langmuir model: $\frac{C_e}{q_e} = \frac{1}{bq_m} + \frac{C_e}{q_m}$ (2)

(b) Freundlich model: $q_e = K_f {C_e}^n$ (3)

where C_e is the concentration of the adsorbate at equilibrium in the liquid phase and q_e is the corresponding concentration in the solid phase. K_f and n are Freundlich coefficients related to adsorption capacity and intensity of the adsorbent. The Langmuir coefficients, b and q_m, are the equilibrium constant and the monolayer capacity of the adsorbent. Models were fitted based on the regression correlation coefficient (R^2) and fit between the computed and experimental q_e values.

2.2 Column experiments

To better mimic Zn^{2+} movement through the natural soil, column experiments were performed using 10 cm high, 1.2 cm internal diameter columns. The columns were packed to achieve the field soil bulk density of 1.55 g cm^{-3}. Both ends of the columns were packed with 2 cm of glass wool to ensure proper water drainage. A peristaltic pump (Precision Pump Co., Baoding, China) drove an upflow (50 µL min^{-1}) of distilled water, and zinc solutions. Influent Zn^{2+} concentrations were 10, 20, 40, 60, 80, and 100 mg L^{-1}. The experiments ended when the effluent zinc concentration reached that of the influent.

To simulate the impact of urban karst on the movement of Zn^{2+} a 50 cm high, 5 cm internal diameter flow cell (Soil Measurement Systems Co., Arizona, USA) was used. A highly permeable ($2.8 < d_p < 4.75$ mm) 1.5 cm diameter was gravel core filled in the middle core of the column, surrounded by the natural soil. Influent Zn^{2+} concentration was fixed to 100 mg L^{-1}. A flow rate of 1 mL min^{-1} was used.

3 RESULTS AND DISCUSSION

3.1 Equilibrium batch tests

Batch tests (Figure 1) showed very high correlation coefficients for the sorption of Zn^{2+} on both the natural and synthetic soils (R^2: 0.98-0.99). Both the Langmuir and Freundlich models fitted the experimental data well, with Freundlich having a higher correlation for the natural soil and Langmuir for the synthetic soil. This suggests sorption of Zn^{2+} onto heterogeneous clay surfaces in the natural soil and uniform monolayer sorption process onto homogenous clay minerals surfaces in the synthetic soil. The Langmuir q_m showed that the natural soil adsorbed 6.5 times more Zn^{2+} than the synthetic soil, presumably due to the muscovite present in the natural soil.

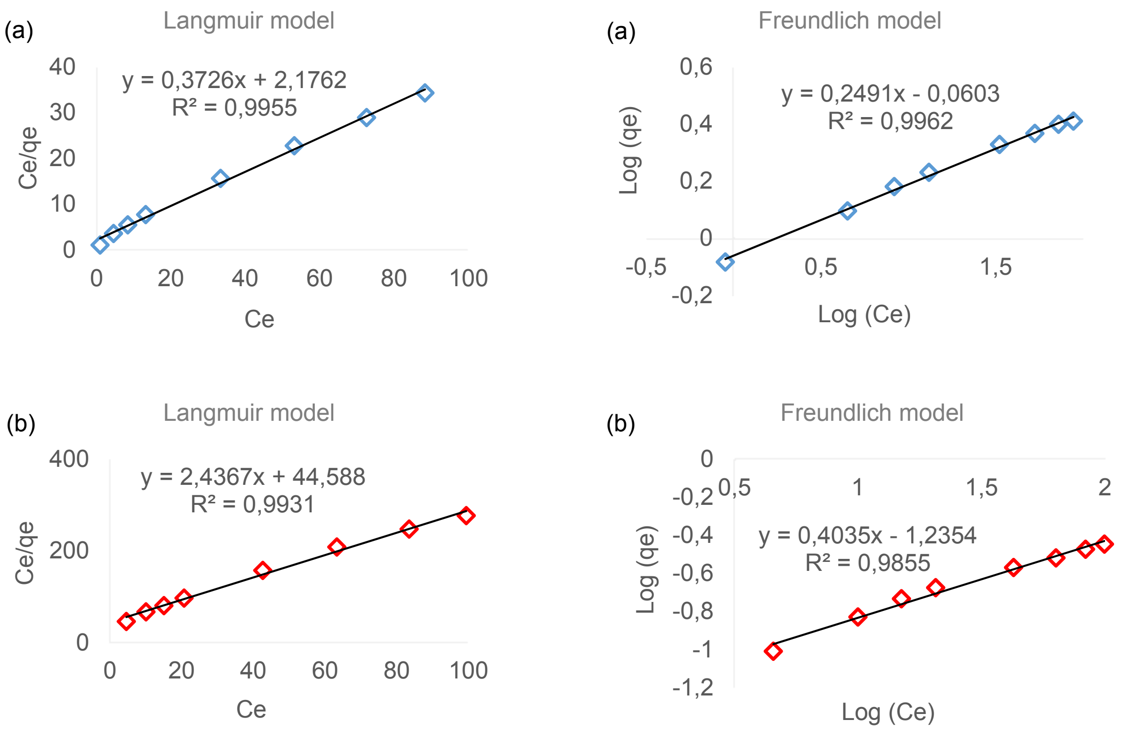
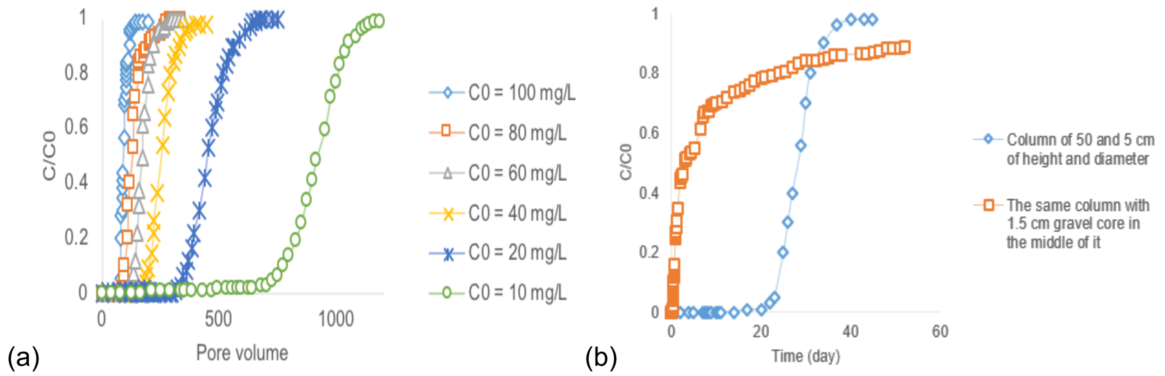


Fig.1. Langmuir and Freundlich models for sorption of Zn^{2+} onto (a) the natural soil and (b) the synthetic soil.

3.2 Column experiments

Figure 2 (a) shows the Zn^{2+} breakthrough curves (BTC). The relative timing indicates that Zn^{2+} sorption is proportional to the influent concentration (Jellali et al., 2010). This is because the binding sites became more slowly saturated for lower influent concentrations (Chowdhury, Zain, Rashid, Rafique, & Khalid, 2012). Indeed, 400 pore volumes were sufficient to reach breakthrough ($C/C_0 = 0.05$) for C_0 = 20 mg L^{-1}, while almost double this (800 pore volumes) is needed for C_0 = 10 mg L^{-1}.

Figure 2 (b) shows the column representing urban karst. Noted that the breakthrough curve for the homogenous column is predicted based on the smaller columns due to time constraints. Breakthrough in the urban karst is rapid and the shape is very different. The decline in slope after C/C0 =0.5 (approx. 3 days) is a new behavioural feature, likely indicating interaction between the soil and gravel. C/C0 =0.5 is reached an order of magnitude faster for the urban karst case.



Fg. 2 (a) Zinc relative concentration versus pore volume for different influent concentrations for the natural soil (flow rate: 50 µL min^{-1}). (b) breakthrough curve for urban karst together with a simulation based on column experiments (influent Zn concentration: 100 mg L^{-1}, flow rate: 1 mL min^{-1}).

4 CONCLUSIONS

Laboratory batch and column experiments were conducted to study Zn^{2+} transport in clay loam soil collected from a peri-urban catchment in the eastern suburbs of Melbourne, Australia. Batch tests indicated that muscovite, a 2:1 clay mineral in the natural soil, plays a pivotal role in adsorbing Zn^{2+}. Thus, clay mineralogy has a substantial impact on Zn^{2+} transport and should be considered when implementing any stormwater infiltration systems. The column experiments showed that the zinc BTC onto the natural soil was highly retarded for a wide range of concentrations used. The extent of attenuation, however, is highly dependent on the clay mineralogy. The presence of a highly-permeable gravel core highly accelerated the transport of Zn^{2+} through the system and led to new breakthrough behaviour. The breakthrough time also reduced to hours compared with 10s of days. This is further evidence that the urban karst could have a major role in pollutant-transport via preferential flow pathways, and should be taken into account in the design and layout of the infiltration basins.

LIST OF REFERENCES

Chowdhury, Z., Zain, S., Rashid, A., Rafique, R., & Khalid, K. (2012). Breakthrough curve analysis for column dynamics sorption of Mn (II) ions from wastewater by using Mangostana garcinia peel-based granular-activated carbon. *Journal of Chemistry, 2013*.

Fischer, D., Charles, E. G., & Baehr, A. L. (2003). Effects of stormwater infiltration on quality of groundwater beneath retention and detention basins. *Journal of Environmental Engineering, 129*(5), 464-471.

Freundlich, H. (1907). Über die adsorption in lösungen. *Zeitschrift für physikalische Chemie, 57*(1), 385-470.

Hamel, P., Daly, E., & Fletcher, T. D. (2013). Source-control stormwater management for mitigating the impacts of urbanisation on baseflow: A review. *Journal of Hydrology, 485*, 201-211.

Jellali, S., Diamantopoulos, E., Kallali, H., Bennaceur, S., Anane, M., & Jedidi, N. (2010). Dynamic sorption of ammonium by sandy soil in fixed bed columns: evaluation of equilibrium and non-equilibrium transport processes. *Journal of environmental management, 91*(4), 897-905.

Kirchner, J. W. (2003). A double paradox in catchment hydrology and geochemistry. *Hydrological processes, 17*(4), 871-874.

Langmuir, I. (1918). The adsorption of gases on plane surfaces of glass, mica and platinum. *Journal of the American Chemical society, 40*(9), 1361-1403.

Pitt, R., Clark, S., & Field, R. (1999). Groundwater contamination potential from stormwater infiltration practices. *Urban Water, 1*(3), 217-236.

Poff, N. L., Allan, J. D., Bain, M. B., Karr, J. R., Prestegaard, K. L., Richter, B. D., . . . Stromberg, J. C. (1997). The natural flow regime. *BioScience, 47*(11), 769-784.

Roy, A. H., Dybas, A. L., Fritz, K. M., & Lubbers, H. R. (2009). Urbanization affects the extent and hydrologic permanence of headwater streams in a midwestern US metropolitan area. *Journal of the North American Benthological Society, 28*(4), 911-928.

Soulsby, C., Birkel, C., & Tetzlaff, D. (2014). Assessing urbanization impacts on catchment transit times. *Geophysical Research Letters, 41*(2), 442-448.

Walsh, C. J., Roy, A. H., Feminella, J. W., Peter, D. C., Groffman, P. M., & Morgan, R. P. (2005). The Urban Stream Syndrome: Current Knowledge and the Search for a Cure*,* 706.

Warren, B. E. (1990). *X-ray Diffraction*: Courier Corporation.