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Longitudinal assessment of rainwater quality under tropical climatic conditions in enabling effective rainwater harvesting and reuse schemes

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ABSTRACT

A longitudinal harvested rainwater quality monitoring study was undertaken at 6 sites within Selangor, Malaysia over a period of 8 months. Overall, harvested rainwater is of good quality, falling within the Malaysian recreational water quality Class IIB standards with exceptions for pH (18/92), ammonia (1/92), phosphates (3/92), and total coliforms (8/92). A large number of samples tested positive for *Escherichia coli* (22/92), total coliforms (64/92) and *Chromobacterium violaceum* (7/92), showing that disinfection of harvested rainwater is mandatory prior to reuse. 2/37 harvested rainwater samples exceeded lead limits in Malaysian drinking water standards, showing that consuming rainwater without additional treatment may pose a health risk. Mixing harvested rainwater with groundwater resulted in higher phosphates and total coliforms. Rainwater collected during the wet seasons have higher concentrations of suspended solids, turbidity, and *Escherichia coli* than dry seasons due to the antecedent dry period. Last but not least, both principal component analysis and positive matrix factorisation were conducted on 37 samples to apportion pollutant sources in harvested rainwater. 7 principal components were identified, namely: industrial dust, steel, roadside dust, faeces, organic decay, fertilisers, and plumbing. The results from principal component analysis and positive matrix factorisation were in agreement, although the latter identified mains water top-up as an additional factor responsible for dissolved solids. Both techniques are effective at apportioning pollutant sources in harvested rainwater, and show that a rainwater harvesting system should be designed carefully to reduce contributions from steel, plumbing, organic decay, bird faeces, industrial dust and roadside dust.

1. Introduction

Rainwater harvesting has long supplemented mains water supplies in households for both non-potable and potable activities (Ghisi and Mengotti de Oliveira, 2007). Rainwater has a lower concentration of pollutants than other urban sources of water, such as greywater (Leong et al., 2016), and is thus ideal for urban reuse. In Malaysia, rainwater harvesting systems have garnered renewed attention via the 2012 Uniform Building by-Laws, which mandate the installation of rainwater harvesting systems in all new buildings with roof areas $\geq$100 m^2.

In spite of this new requirement, data on rainwater harvesting systems are limited. Few rainwater quality studies have been conducted in Malaysia (Yaziz et al., 1989), although numerous studies have been conducted in Australia (Huston et al., 2012), Brazil (Lara et al., 2001), Canada (Despins et al., 2009), China (Zhu et al., 2004), France (Vialle et al., 2011), Greece (Gikas and Tsihrintzis, 2012; Sazakli et al., 2007), the Netherlands (Albrechtsen, 2002), New

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Zealand (Simmons et al., 2001), Nigeria (Uba and Aghogho, 2000), Spain (Farreny et al., 2011), South Korea (Lee et al., 2012), UK (Ward et al., 2010), and the USA (Crabtree et al., 1996). Collectively, these studies show how harvested rainwater quantity is dependent on geographical climate and storage tank size (Campisano et al., 2013), whereas harvested rainwater quality is dependent on the spatial and temporal variability of rainfall (Evans et al., 2006), roofing materials (Mendez et al., 2011), and first-flush diverters (Gikas and Tsihrintzis, 2012). Successful implementation of rainwater harvesting systems therefore requires local data inventory on the physical, chemical, and microbiological characteristics of rainwater in order to minimise health risks from rainwater reuse and to design water treatment systems effectively (Chong et al., 2013).

Effective design of rainwater harvesting systems additionally require source apportionment techniques to quantify the contribution of non-point sources to rainwater. Common techniques include principal component analysis (PCA), chemical mass balance (CMB) models, and positive matrix factorisation (PMF). PCA is a multivariate technique which decomposes the initial data set into principal components in order to uncover latent structures, and has been utilised in a number of rainwater quality studies (Vialle et al., 2011; Gikas and Tsihrintzis, 2012; Sazakli et al., 2007; Vázquez et al., 2003). PMF is a relatively new technique (Paatero and Tapper, 1994), and holds two advantages over PCA: samples can be weighed with an uncertainty value, and solutions are constrained to be non-negative (Reff et al., 2007). PCA and PMF are preferred for source apportionment studies because they do not require pre-measured source profiles, unlike CMB.

Thus, the objectives of this study are threefold: first, to monitor physical, chemical, and microbiological rainwater quality harvested from six full-scale rainwater harvesting systems in Selangor state, Malaysia; second, to assess the suitability of rainwater for non-potable urban reuse by comparison with Malaysian Class IIB (recreational waters with body contact) and Class IV (irrigation waters) water quality standards; and third, to apportion pollutant sources using complementary multivariate chemometric techniques, such as PCA and PMF.

2. Materials and methods

2.1. Rainwater sample collection

Malaysia is a tropical country with an annual rainfall of 2500 mm and temperatures ranging between 27 and 35 °C. The wet monsoon season is from September to April. Six full-scale rainwater harvesting systems were randomly selected for monitoring in the state of Selangor, Malaysia. Fig. 1 shows the spatial distribution of the sites, whereas site characteristics are given in Table 1. All sites contained metal flashing on their roofs, and none have de-sludged their tanks prior to sampling. Most of the rainwater harvesting systems were installed for non-potable use, and thus Sites 1, 3, and 4 contained a mains water top-up system which leaves the tank with a minimum level of water to prevent tanks from running dry. Site 2 utilised an underground porous tank where rainwater was free to mix with groundwater at the sampling point.

Sampling of harvested rainwater was carried out once every two weeks from November 2014 to June 2015 (8 months), although heavy metals were only analysed from April–June 2015. A sampling period of 12 months was not possible due to financial constraints. Grab samples of raw harvested rainwater were collected with 1 L Duran glass bottles from each site's rainwater tank. Prior to sampling, all Duran glass bottles were washed with distilled water and disinfected by autoclaving at 120 °C for 15 min. Samples were transported to the laboratory within 6 h, and stored at 4 °C until analysis within 48 h. A total of 92 samples were collected and analysed. On average, 16 samples were collected from each site, with the exception of Site 6. Site 6 had fewer harvested rainwater samples ($N = 12$) due to several months where the rainwater tank was empty due to high water usage.

2.2. Analytical methods

2.2.1. Physicochemical and microbiological analysis

pH, biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), colour, total suspended solids (TSS) and total dissolved solids (TDS) were measured according to the Standard Methods for Examination of Water and Wastewater (American Public Health Association (APHA), 2005). Turbidity was measured using a HACH Portable Turbidimeter 2100Q. Ammonia-nitrogen (NH_3-N) and total phosphates (PO_4-P) were measured according to HACH methods 10023 and 8190, respectively. 7 heavy metals (Co, Cu, Fe, Mn, Ni, Pb, Zn) were measured using a Perkin Elmer Optima 8000 Inductively Coupled Plasma – Optical Emission Spectroscopy (ICP-OES).

Total coliforms and *E. coli* were enumerated in triplicates using the spread-plate method 9215C (American Public Health Association (APHA), 2005) on chromogenic Brilliance™ *E. coli*/coliform Selective Agar (CM1046) and incubated at 37 °C for 24 h. Purple colonies were counted as *Escherichia coli (E. coli)*, whereas red/pink colonies were counted as other coliforms. Total coliforms were counted as the sum of both *E. coli* and other coliforms (purple + pink). Glossy black colonies were isolated and sent to an external laboratory for qualitative PCR analysis, and were revealed to be *Chromobacterium violaceum (C. violaceum)*.

2.2.2. Statistical analysis

All descriptive statistical analysis was carried out in XLSTAT, a commercial software in Microsoft Excel® with significance level set at $\alpha = 0.05$. Harvested rainwater quality data did not follow a normal distribution according to the Shapiro-Wilk normality test, and hence the two-tailed Kruskal-Wallis test or the non-parametric equivalent of analysis of variance (ANOVA), was utilised to determine significant differences in pollutant concentrations between the six rainwater harvesting systems. If the null hypothesis in the Kruskal-Wallis test was rejected, the post hoc two-tailed Dunn-Bonferroni test was to ascertain significant differences between paired sites.

PCA was used to apportion sources of pollutants in harvested rainwater and was carried out in XLSTAT. Only components with eigenvalues ≥1 were retained according to Kaiser's criterion (Kaiser, 1960), and absolute loadings > 0.4 were considered major contributors.

PMF was complementary to PCA, and carried out using PMF 5.0 (US EPA, 2014). The objective of PMF was to minimise the objective function Q, given by:

$$Q = \sum_{i=1}^{n}\sum_{j=1}^{m}\left[\left(\frac{1}{u_{ij}}\right)\left(c_{ij} - \sum_{k=1}^{p} g_{ik} f_{kj}\right)\right]^2 \quad (1)$$

where c_{ij} and u_{ij} are the measured concentration and estimated uncertainty of species j in sample i, g_{ik} is the factor score (source contribution) of factor k to sample i, f_{kj} is factor loading (source profile), and n, m, and p represent the number of samples, species, and sources respectively. More details can be found from in the user manual by US EPA (2014).

Two input files with both the measured concentration of each species in a sample and estimated uncertainties in each sample were prepared for each chemical species. Uncertainties were estimated with method detection limits (MDL) and an assumed error of

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