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Water quality impacts of young green roofs in a tropical city: a case study from Singapore

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ABSTRACT

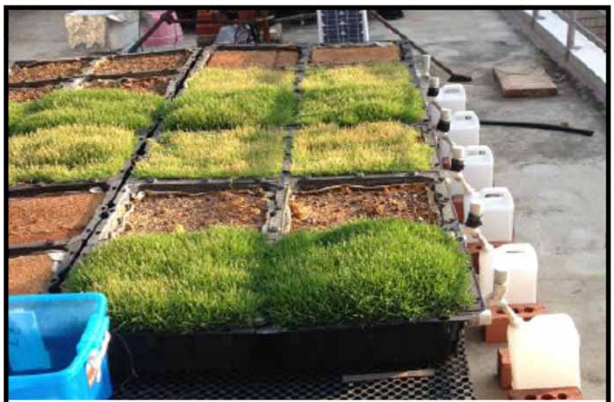
This study examined the effects of two substrates (SOIL and COMMERCIAL) and grass on the green roof runoff quality in Singapore. Ten events were sampled over a 9-month period. Rainfall and green roof runoff from grass and bare experimental configurations were tested for total organic carbon (TOC), nitrogen and phosphorus nutrients (NO_3^--N and PO_4^{3-}-P), cations/anions and trace metals (Fe, Cu, Zn, Cd and Pb). All configuration units neutralised acid rainfall and removed metals except Fe despite their proximity to an industrial area. Concentrations decrease over the monitoring period for most water quality variables. The COMMERCIAL (COM) configurations elevated Cl^- (3.8–10.8 ppm), SO_4^{2-} (1.5–32.4 ppm), NO_3^--N (7.8–75.6 ppm) and NH_4^+-N (22.0–53.1 ppm) concentrations in the runoff. Concentrations of NO_3^--N (4.5–67.7 ppm) and NH_4^+-N (14.7–53.0 ppm) remained high at the end of the monitoring period for the COMgrass configuration, even with dilution from monsoon rainfall, making it suitable as an irrigation water source and a fertiliser substitute. The SOIL substrate retained N-nutrients, TOC and trace metals with concentrations comparable or below rainfall inputs. This substrate is suitable for widespread green roof applications in Singapore and other tropical cities. We recommend substrate testing before their approval for use on green roofs and encourage the long-term monitoring of these systems.

Key words: carbon, eutrophication, green roof water quality, nutrients, trace metals

HIGHLIGHTS

- All configurations removed trace metals and neutralised acid rainfall despite close proximity to an industrial area.
- Substrates low in organic matter content were found to be suitable for widespread implementation in Singapore.
- High nutrient concentrations in green roof runoff make them suitable for irrigating urban greenery.

GRAPHICAL ABSTRACT



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Substrate low in organic matter suitable for widespread implementation in Singapore.

High nutrient concentrations in green roof runoff may be used to irrigate urban greenery.

1. INTRODUCTION

As cities grow, vegetation is replaced by impervious surfaces. This landcover change creates a host of environmental problems that include increased flood risk, poor water quality, biodiversity loss and urban heating that may be partly addressed by green roofs (Berndtsson 2010). Studies have shown that green roofs can retain approximately 50–89% of incoming rainfall, lowering stormwater runoff volumes and peak flows at both the building and catchment scales (Mentens *et al.* 2006). The vegetation/soil complex also removes contaminants found in urban rainfall and atmospheric deposition (trace metals and aerosols). As a result, green roofs have been widely implemented in many regions, since the 1960s, for example, in Europe, the United States, China, Hong Kong and Singapore (Nguyen *et al.* 2019).

A global review of green roof studies shows that they generally neutralise acid rainfall found in urban environments and remove trace metals (Berndtsson *et al.* 2009; Bliss *et al.* 2009; Van Seters *et al.* 2009; Vijayaraghavan *et al.* 2012; refer to Supplementary Material, Appendix A). However, their presence contributes eutrophication-causing nutrients such as nitrogen (N) and/or phosphorus (P) to urban runoff, especially when fertilisers are used (Supplementary Material, Appendix A). Only a few studies have reported the removal of N and P by green roofs (Kohler *et al.* 2002; Beck *et al.* 2011; Speak *et al.* 2014). These results point to the potential negative impact of green roofs on the urban runoff quality from a nutrient perspective.

Clearly, differences in green roof designs (intensive versus extensive), substrate and vegetation determine the amount of nutrients present in their outflow water. Both controlled laboratory experiments and field trials have identified the important role substrates play in elevating the levels of eutrophication-causing nutrients in green roof runoff (Vijayaraghavan & Joshi 2014; Chen *et al.* 2018; Qiu *et al.* 2020; Akther *et al.* 2021). Phosphorus concentrations tend to be controlled by the substrate, while nitrogen concentrations are controlled by both the substrate and vegetation (Chen *et al.* 2018).

Furthermore, the temporal variability in green roof runoff quality has important implications for urban water quality. Newly established green roof systems that are less than a year old tend to have the poorest runoff quality (e.g., Vijayaraghavan *et al.* 2012; Harper *et al.* 2015), sometimes with nutrient concentrations comparable to the wastewater or agricultural systems (Kuoppamäki & Lehvävirta 2016; Mitchell *et al.* 2017). The initial flushing (first flush effect) of poor green roof runoff quality, for nutrients and trace metals, was observed for the first rainfall event in a series of events that occurred after a dry period (e.g., Vijayaraghavan & Joshi 2014; Harper *et al.*

2015; Buffam *et al.* 2016). Over time, pollutant concentrations may decline after they are flushed out of the substrate and/or removed by vegetation (Berndtsson *et al.* 2009; Buffam *et al.* 2016).

In Singapore, green roof implementation has increased since 2017 to combat the urban heat island effect, improve the stormwater quality and increase liveability. Under the Landscaping for Urban Spaces and High-Rises programme (LUSH programme, the high-rise greenery is expected to reach 200 ha by 2030 (The Straits Times, November 10, 2017). Currently, there are already 133 ha of high-rise greenery installed. These applications include green roofs, rooftop farms and vertical greenery. Although the standard guidelines exist for green roof systems (https://www.nparks.gov.sg/skyrisegreenery/news-and-resources/guidelines), only limited research has been conducted to understand their water quality dynamics. Green roofs in Singapore have positive hydrological impacts, reducing runoff volumes (~45%), dampening peak flows (80–85%) and sustaining downstream flow during dry periods (Vergroesen & Joshi 2010). The water quality impacts are variable. In an earlier study conducted approximately 0.56 km north of this study, Vijayaraghavan *et al.* (2012) reported that a newly established green roof system (2-month-old) using local garden soil and *Sedum mexicanum* vegetation removed trace metals, but nitrate (0.34–0.86 mg/L), phosphate (19.8–40 mg/L) and sulphate (76.7–109.2 mg/L) concentrations were higher than the rainfall samples. The phosphate concentrations exceeded the US Environmental Protection Agency (USEPA) recommended concentrations for freshwater (0.05 mg/L) and may be an eutrophication risk for downstream waterways.

Apart from the green roof studies in Singapore and Malaysia (Vijayaraghavan *et al.* 2012; Kok *et al.* 2016), there has been limited research on their impacts on urban runoff quality in the Southeast Asian region where green roofs are starting to be implemented widely. It is within this context of effectiveness uncertainty around water quality impacts of green roofs in the tropics that we conduct a study comparing a commercial substrate with a soil substrate recommended for blue-green infrastructure in Singapore and to consider the implications of widespread implementation on urban water quality in the region. The main objective of our study was to investigate the effect of growing medium and vegetation on the green roof outflow quality for a newly established green roof using a commercial green roof setup that is widely used in Singapore. We also examine the changes in the green roof outflow quality over the 9-month monitoring period to characterise the water quality impacts associated with these green infrastructures.

2. METHODS

2.1. Experimental setup

The green roof experimental configuration units were located on the second level of a small roof linking two buildings at the Department of Geography, National University of Singapore (1°17′42.36″, 103°46′15.91″). Singapore experiences uniform temperature (24.9–29.9 °C), high humidity (60–88%) and abundant rainfall (annual rainfall is approximately 2,400 mm) throughout the year due to its location just north of the Equator (Joshi & Balasubramanian 2010). Rainfall variability is associated with the Northeast Monsoon (December–March) and the Southwest Monsoon (June–September). The site is in the western part of Singapore where there are considerable industrial activities, including port facilities, oil-fired power plants and offshore refineries (Jurong Island).

The following two types of substrates were tested in this study: a local garden soil (ASM) and a commercially available green roof mix resembling sawdust that was supplied by a local company. We refer to these media as SOIL and COMMERCIAL, respectively, in this paper. The SOIL medium is commonly used in Singapore for roadside greenery and blue-green infrastructure. It is composed of three parts of local soil, two parts of woodchips and one part of sand, resulting in a texture of clay (5–30%), silt (5–60%) and sand (20–75%) (National Parks Board Singapore, cited in Lim & Lu 2016). The COMMERCIAL medium is a proprietary material. We know it contains coconut husk and pumice. The COMMERCIAL substrate has a higher organic content (loss on ignition (LOI) = 98.9%) and higher specific electrical conductivity (SEC) 247.7 μS/cm than the SOIL substrate (Table 1). The vegetation used for the green roof is couch grass (*Cynodon dactylon*), commonly used in water-sensitive urban design infrastructure in Singapore. This grass is suitable as green roof vegetation because it is drought-resistant, fast-growing and requires little maintenance.

The configuration units used in this study are commercially designed small green roof units that can be connected to produce an extensive green roof. Each unit (46 × 46 cm plots) contains an upper layer holding the growing medium (75 mm deep), a geotextile material in the middle layer and a 7-L storage reservoir at the bottom. Each configuration unit is connected by a drainage pipe that discharges the green roof runoff through a single outlet into a sampling bottle (Figure 1).

Table 1 | Properties of substrates tested in this study

Substrate	pH	LOI (%)	Dry bulk density (g/cm³)	SEC (μS/cm)	Comments
Soil (SOIL)	6.54	16.9	2.85	66.7	ASM soil approved for blue-green infrastructure in Singapore
Commercial substrate (COM)	5.45	98.9	0.95	247.7	Commercial substrate. According to the supplier, substrate contains pumice and coconut husk.
Universal garden soil (Vijayaraghavan *et al.* 2012)	5–6	22	0.243	400	White peat, black peat, clay +1.2 kg/m³ of NPK fertiliser
Commercial substrate (DAKU) (Vijayaraghavan *et al.* 2012)	?	?	1.04	?	Natural inorganic volcanic material, compost, organic and inorganic fertilisers

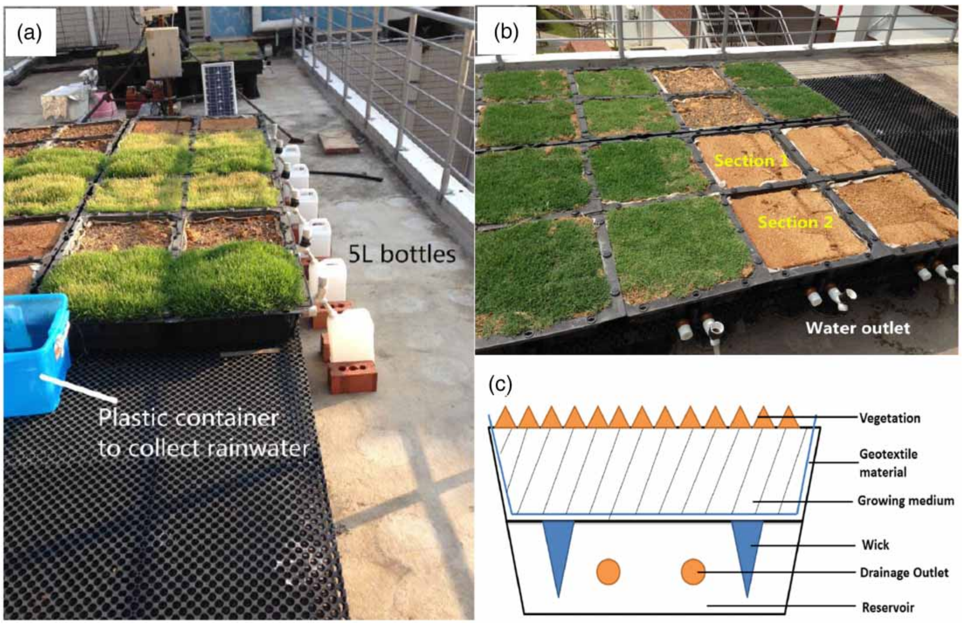

Figure 1 | (a, b) The green roof experimental configuration units and the wet–dry rainfall collector and (c) the cross-section of the green roof configuration unit.

This study had 10 configuration units and considered the effect of two growing media and the presence or absence of vegetation (bare versus grass). This resulted in four configurations that are summarised below:

1. Bare SOIL (SOILbare, $n = 2$ units)
2. Vegetated SOIL (SOILgrass, $n = 2$)
3. Bare COMMERCIAL (COMbare, $n = 3$)
4. Vegetated COMMERCIAL (COMgrass, $n = 3$)

There were only two units for the SOIL configurations as one unit from each of the bare and grass configurations was used to monitor the green roof runoff depth and hence could not be sampled for water quality analysis. We placed the 10 green roof configuration units randomly across the site on which they were located to minimise any effect of spatial variation in rainfall on the experimental setup (Figure 1).

The green roofs were installed at the end of February 2014. The grass mats were grown in a local nursery and placed on the substrate during installation. The grass mats were watered with tap water for a month to ensure that it was established on the green roof substrate before the monitoring started in April 2014. None of the 10 configuration units were fertilised or irrigated during the monitoring period. Bulk deposition (including both dry deposition and wet deposition when rainfall occurs) was collected using a plastic container (0.33×0.46 m) placed next to the configuration units as a comparison to the runoff collected from the green roof configuration units (Figure 1). Bulk deposition is termed as the RAINFALL in this paper.

A controlled batch leaching study in the laboratory was conducted to examine the leachate quality of both substrates and to compare this to the green roof runoff quality. A 20:1 liquid:solid ratio was used for the batch study. Samples were placed in Erlenmeyer flasks filled with deionised water acidified to a pH value of 4.2 to simulate the mean acidity of Singapore's rainfall (Balasubramanian *et al.* 2001; Hu *et al.* 2003). Triplicates of each substrate were tested. The flasks were agitated continuously for 24 h before samples were filtered and preserved for analysis. We chose 24 h because it was the hypothesised mean residence time of water in the green roof system.

2.2. Sample collection and geochemical analysis

Ten rainfall events were sampled between April and December 2014 (Table 2, Figure 2). Field monitoring started in April which corresponds to the inter-monsoon season that is generally the drier period in the year. Coincidentally, drought conditions prevailed during the first 3 months of 2014, exacerbating the already dry conditions experienced during the inter-monsoon season.

We divided the experimental period into three periods (Figure 2). Period 1 corresponds to the first half of the year, which was relatively dry. Only 31% of the total annual rainfall had fallen when the third event was sampled in end-June 2014. Period 2 corresponds to the period just as the wet season was starting, representing wetting up conditions for the green roofs. The events sampled in Period 3 represented wet season conditions during the Northeast Monsoon season (Figure 2, Table 2). The rainfall properties of Periods 2 and 3 are quite similar. The greatest distinction in rainfall properties between the three periods is seen in the event rainfall amount, which is highest for Period 3 (Table 2).

The total volume of green roof runoff and RAINFALL samples were collected immediately after each rainfall event. An aliquot was taken from the green roof runoff sample for water quality analysis and represents the event mean concentration for the storm event. Both the green roof runoff and RAINFALL samples were stored in acid-washed containers. Samples were tested for pH, SEC, total organic carbon (TOC), anions (Cl^-, SO_4^{2-}, NO_3^--N and PO_4^{3-}-P) and cations (Ca^{2+}, Mg^{2+}, K^+, Na^+ and NH_4^+-N). Metals (Fe, Cu, Zn, Cd and Pb) were determined for the final seven events when the scope of the initial study expanded to include more variables. Water quality parameters such as pH, SEC and TOC were tested on unfiltered samples. A 0.45-μm Millipore PTFE syringe filter

Table 2 | Properties of rainfall events sampled and summary of rainfall characteristics of the three periods sampled during the study

	Event rainfall (mm)	Rainfall intensity (mm/h)	Duration (days)	Time between events (days)	7-day antecedent rainfall ADP7[a] (mm)	Cumulative rainfall by the time event occurred (as a proportion of annual rainfall[b]) (%)
Period 1 (April–June)	10.7 ± 7.7 (0.3–90.9)	2.3 ± 2.0 (0.3–56.6)	0.1 ± 0.1 (0.0001–2.6)	1.8 ± 0.9 (0.5–6.6)	26.3 ± 13.5 (1.0–156.9)	
14/4/2014	24.9	15.8	0.1	2.3	9.4	9.6
19/5/2014	55.0	12.1			146.4	20.5
30/6/2014	83.8	31.7	0.3	0.71	17.3	30.6
Period 2 (November)	12.0 ± 11.4 (0.26–62.5)	1.7 ± 1.4 (0.26–31.5)	0.24 ± 0.15 (0.03–0.81)	0.93 ± 0.26 (0.11–4.86)	88.8 ± 51.2 (2.3–174.3)	
5/11/2014	32.5	10.3	0.24	4.9	2.3	57.7
6/11/2014	10.2	12.3	0.03	0.7	33.8	58.1
7/11/2014	15.1	8.7	0.32	0.9	44.0	59.8
17/11/2014	7.7	5.3	0.12	0.8	41.2	64.8
Period 3 (December)	36.9 ± 28.9 (0.3–67.1)	2.05 ± 1.8 (0.3–57.9)	0.22 ± 0.15 (0.1–0.6)	1.9 ± 1.0 (0.5–0.9)	84.2 ± 32.5 (24.1–151.3)	
4/12/2014	40.7	7.6	0.22	2.9	24.1	75.8
17/12/2014	65.8	16.0	0.62	0.5	51.7	83.8
19/12/2014	36.9	4.8	0.28	1.6	112.6	85.2

Values are median value and median absolute deviation. Values in brackets refer to the minimum and maximum values.
[a]Antecedent rainfall occurring 7 days prior to the event of interest occurring.
[b]Cumulative rainfall, including event of interest, presented as a percentage of the total annual rainfall for 2014 (2,669.8 mm).

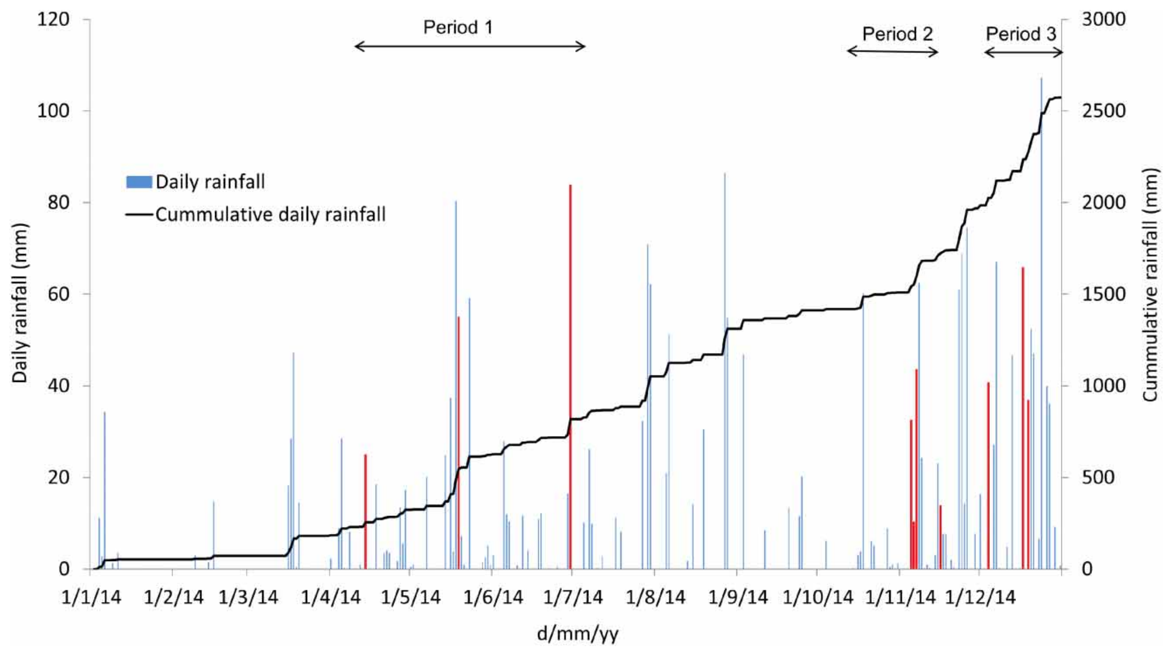

Figure 2 | Daily and cumulative rainfall for the 10 sampled events (red columns).

was used to filter the samples. TOC was determined using an Elementar Vario TOC cube using catalytic high temperature combustion. Cations and anions were tested using the Dionex Ion Chromatography ICS 5000 System with a capillary column each for cations and anions, respectively. Trace metal extraction was conducted using the USEPA3051A method, and concentrations were determined using an ICP-MS (Agilent Technologies, 7700 Series). Five calibration standards were used for the analysis together with two certified reference materials (Environment Canada Certified Reference Material TMDA 64.2 and TM23.4).

2.3. Data analysis

Statistical analyses were conducted using the SPSS Statistics 22 software. The data were screened for normality using the Shapiro–Wilk test. Levene's test of homogeneous variances was performed on the data. The paired sample *t*-test was conducted to test for statistically significant differences between the outflow water quality from the four green roof configurations. The Spearman correlation coefficient was used to test for correlation between the RAINFALL and green roof outflow water quality and environmental variables such as event rainfall amount and antecedent rainfall amount. The 95% significance level ($\alpha = 0.05$) was used to test for the significance.

The enrichment factor and removal efficiency (RE) quantify the substrate performance by comparing green roof runoff concentrations versus RAINFALL concentrations:

$$\text{Enrichment factor} = \frac{C_s}{C_r} \tag{1}$$

$$\text{Removal efficiency (\%)} = \frac{(C_r - C_s)}{C_r} \times 100\% \tag{2}$$

where C_r is the concentration of a water quality parameter in the RAINFALL (ppm), and C_s is the concentration of the same parameter in the green roof runoff (ppm). The enrichment ratio identifies the magnitude of green runoff water quality relative to the RAINFALL with enrichment occurring when the green roof runoff concentrations are higher than those in rainfall. The RE index measures the green roof performance. Positive values indicate that the green roof runoff concentrations are lower than those in bulk deposition, RAINFALL, which in turn means that the green roofs remove pollutants.

To evaluate the change in green roof runoff quality over time, a ratio of concentrations between two periods was calculated by the following equation:

$$\text{Period ratio} = \frac{Cy}{Cx} \tag{3}$$

where C is the RAINFALL or green roof runoff concentration for the reference period, x, and the comparison period, y. The reference period and comparison periods in this study are Period 1 and Period 3, respectively, allowing a comparison of the magnitude of change in water quality between the start and the end of the monitoring period. For trace metals, only Periods 2 and 3 were used to calculate the period ratio because trace metal concentration data were only available for these two periods. Ratio values >1 indicated a higher concentration in Period 3 relative to Period 1 and may reflect additions from external sources. The reverse is true for values <1, which generally reflect a flushing effect over time. Values close to 1 indicated a minimal difference between the two periods.

3. RESULTS AND DISCUSSION

3.1. Laboratory leaching results

The leaching experiments provide insights into the substrate characteristics and leachability of the various water quality parameters examined in this study. Leachate concentrations from the COMMERCIAL substrate had higher concentrations of SEC, TOC (239.7 ± 7.3 ppm), NH_4^+-N (42.6 ± 0.41 ppm), Cl^- (113.8 ± 1.21 ppm) and Zn (39.1 ± 5.3 ppm) (Table 3). This may be related to its higher organic content (LOI = 98.9%) and SEC (247.7 μS/cm) than the SOIL substrate, highlighting the greater risk of poor water quality when this substrate is used for green roof installations (Table 1).

3.2. Green roof runoff quality

3.2.1. Acid-neutralising effect

All the sampled rain events were acidic (4.1 ± 0.18) and were comparable to the previous studies in Singapore (rainfall pH 3.8, Vijayaraghavan *et al.* 2012; Table 4). The configurations neutralised the acidic rainfall, such that the runoff pH was close to neutral (6.7–6.9), very similar to an earlier study conducted nearby (pH 7–7.5, Vijayaraghavan *et al.* 2012) and with the other studies elsewhere (e.g., Teemusk & Mander 2011; Whittinghill *et al.* 2016; Wang *et al.* 2017a). The least neutralising effect was observed for the COMgrass configuration (pH 5.8 ± 1.0).

Table 3 | Leachate concentration for the SOIL and COMMERCIAL substrates

	SOIL leachate	COMMERCIAL leachate
TOC	6.65 ± 0.32	239.7 ± 7.3
pH	6.4 ± 0.02	5.97 ± 0.04
SEC (μS/cm)	54.7 ± 2.0	522 ± 8
Ca^{2+} (0.3)	7.91 ± 0.13	2.30 ± 0.20
Mg^{2+} (0.4)	1.18 ± 0.038	1.02 ± 0.10
Na^+ (0.4)	2.92 ± 0.22	4.9 ± 0.062
K^+ (0.4)	24.6 ± 0.87	36.5 ± 0.31
NH_4^+-N (0.06)	Not detectable	42.6 ± 0.41
NO_3^--N (0.002)	Not detectable	Not detectable
PO_4^{3-}-P (0.02)	0.018 ± 0.00	0.046 ± 0.041
Cl^- (0.003)	12.6 ± 0.56	113.8 ± 1.21
SO_4^{2-} (0.015)	32.5 ± 0.79	5.16 ± 0.48
Fe (0.12)	2.64 ± 0.40	0.77 ± 0.04
Cu (0.048)	0.121 ± 0.12	1.57 ± 0.01
Zn (0.21)	1.5 ± 0.08	39.1 ± 5.3
Cd (0.002)	0.002 ± 0.00	0.04 ± 0.00
Pb (0.093)	0.01 ± 0.00	0.02 ± 0.00

Concentration values are presented as median and median absolute deviation. Units are in ppm (ppb for trace metals) unless otherwise stated. Values in brackets refer to the respective detection limit.

Table 4 | RAINFALL and green roof runoff concentrations presented as median and median absolute deviation values

		SOIL configurations		COMMERCIAL configurations		Comparison study in Singapore (Vijayaraghavan *et al.* 2012)
	RAINFALL	SOILbare	SOILgrass	COMbare	COMgrass	
pH	4.1 ± 0.18	6.8 ± 0.27*	6.7 ± 0.38*	6.9 ± 0.24*	5.8 ± 1.0*	7.0–7.5
SEC (μS/cm)	53.5 ± 21.0	110.5 ± 67.0	111.0 ± 54.0*	238.5 ± 101.5*	650 ± 312.0*	317.1–387.2
TOC	2.2 ± 1.8	4.6 ± 1.4*	6.1 ± 2.5*	50.4 ± 24.1*	37.7 ± 21.5*	–
Ca^{2+} (0.3)	0.64 ± 0.34	13.1 ± 6.5*	12.7 ± 5.5*	3.8 ± 1.7*	17.8 ± 6.0*	30.4–34.6
Mg^{2+} (0.4)	0.22 ± 0.22	0.94 ± 0.72*	0.96 ± 0.63	0.32 ± 0.20	2.5 ± 0.88	10.0–12.9
Na^{+} (0.4)	0.34 ± 0.13	1.3 ± 1.3*	1.4 ± 0.63*	1.3 ± 0.33*	3.4 ± 1.8*	16.3–21.2
K^{+} (0.4)	0.38 ± 0.07	9.3 ± 8.2*	7.8 ± 5.7*	2.1 ± 1.6	8.0 ± 6.8*	36.1–39.9
NH_4^+-N (0.06)	0.30 ± 0.12	0.01 ± 0.006	0.006 ± 0.006	22.0 ± 8.62*	53.1 ± 31.5*	–
NO_3^--N[a] (0.002)	1.0 ± 0.51	0.30 ± 0.29*	0.59 ± 0.48*	7.8 ± 4.4*	75.6 ± 53.9*	0.077–0.19
PO_4^{3-}-P[a] (0.02)	0.022 ± 0.08	0.094 ± 0.00	0.028 ± 0.015	0.092 ± 0.023	0.048 ± 0.028	6.46–13.0
Cl^- (0.003)	0.5 ± 0.2	6.5 ± 6.0*	5.9 ± 4.8*	3.8 ± 2.7*	10.8 ± 7.9*	10.4–15.6
SO_4^{2-} (0.015)	6.2 ± 1.8	27.2 ± 24.6*	32.4 ± 15.0*	11.6 ± 7.6*	1.5 ± 1.5*	76.7–109.2
Fe[b] (0.12)	2.2 ± 1.3	8.8 ± 8.6	13.7 ± 10.8	3.0 ± 1.4	1.7 ± 0.73	43–113
Cu[b] (0.048)	3.5 ± 1.2	1.3 ± 0.35	2.0 ± 0.42*	2.18 ± 0.63	2.3 ± 1.2	37–56
Zn[b] (0.21)	24.9 ± 9.6	2.1 ± 1.6*	2.5 ± 1.3*	7.8 ± 2.9*	23.8 ± 8.4	–
Cd[b] (0.002)	0.03 ± 0.02	0.003 ± 0.001*	0.005 ± 0.002*	0.047 ± 0.026	0.21 ± 0.059*	–
Pb[b] (0.093)	0.94 ± 0.92	0.2 ± 0.07*	1.2 ± 0.57	13.1 ± 6.9*	9.1 ± 6.9*	–

Units are in ppm (ppb for trace metals) unless otherwise stated. The USEPA drinking water guidelines (2009) for the following trace metals: Fe (300 ppb), Cu (1,300 ppb), Zn (5 ppb), Cd (5 ppb) and Pb (15 ppb). The USEPA national recommended guidelines for aquatic life: Fe (1,000 ppb), Cu (no value given), Zn (120 ppb), Cd (1.8 ppb) and Pb (82 ppb). Singapore's guideline values for discharge into controlled watercourse: Fe (1,000 ppb), Cu (100 ppb), Zn (500 ppb), Cd (3 ppb) and Pb (100 ppb). *Source*: https://www.nea.gov.sg/our-services/pollution-control/water-quality/allowable-limits-for-trade-effluent-discharge-to-watercourse-or-controlled-watercourse, https://www.epa.gov/wqc/national-recommended-water-quality-criteria-aquatic-life-criteria-table#table.

[a]Singapore's guideline values for discharge into controlled watercourse: NO_3^--N (4.4 mg/L) and PO_4^{3-}-P (0.65 mg/L).

[b]Trace metal concentrations from other studies (Alsup *et al.* 2011; Seidl *et al.* 2013): Cu (6–45 ppb), Zn (6.9–1,053.6 ppb), Pb (13.8–135.4 ppb), Fe (5.0–831.6 ppb) and Cd (0–20.3 ppb).

*Statistically significant difference between rainfall and green roof design configuration runoff outflow ($\alpha = 0.05$). Values in brackets are the detection limits.

3.2.2. Nitrogen and phosphorus

The RAINFALL samples contained NH_4^+-N (0.30 ± 0.12 ppm) and NO_3^--N (1.0 ± 0.52 ppm), but PO_4^{3-}-P was not detectable (Table 4). Concentrations were similar to an earlier study conducted in Singapore (He *et al.* 2011). The green roof configurations added PO_4^{3-}-P with runoff concentrations higher than the RAINFALL samples with enrichment ratios quite similar for both the substrates (SOIL: 1.3–4.4, COM: 2.2–4.2, Table 5). However, phosphorus pollution is not an issue with the green roof configurations in this study. The PO_4^{3-}-P concentrations were lower than the Singapore's guidelines for the trade effluent into a controlled waterway and a study conducted at a nearby location (6.46–13.0 ppm, Vijayaraghavan *et al.* 2012), other green roofs (0.05–0.72 ppm, Razzaghmanesh *et al.* 2014) and a rooftop farm (1.38 mg/L, Whittinghill *et al.* 2016) (Table 4).

For nitrogen, the SOIL configuration units were a sink for NO_3^--N. This positive nitrate performance is reflected in the high RE for NO_3^--N (RE = 70.7%, SOILbare) and NH_4^+-N (approximately 97% for both SOIL configurations). The COMMERCIAL configurations were a source of N-nutrients, with NO_3^--N and NH_4^+-N concentrations that were 76 and 177 times higher than the RAINFALL (Table 4), close to or above the USEPA (2009) standards for drinking water (10 ppm NO_3^--N) and Singapore's guidelines for the trade effluent into a controlled waterway (Table 4). In particular, the NO_3^--N concentrations (75.6 ± 53.9 ppm) from the COMgrass configuration were above the limit for surface freshwater eutrophication (11.3 mg/L NO_3^--N, Speak *et al.* 2014), at least an order of magnitude higher than the other published studies (0.29–8.9 ppm, Aitkenhead-Peterson

Table 5 | Values of the enrichment ratio that compares the green roof runoff outflow to RAINFALL concentrations for the four green roof configurations

	SOILbare	SOILgrass	COMbare	COMgrass
TOC	2.1	2.7	22.4	16.8
SEC	2.1	2.1	4.5	12.1
Ca^{2+}	20.5	19.8	5.9	27.8
Mg^{2+}	4.3	4.4	1.5	11.6
Na^{+}	3.8	3.9	3.7	9.8
K^{+}	24.4	20.4	5.5	21.0
NH_4^+-N	0.03	0.02	74.1	179.1
NO_3^--N	0.29	0.58	7.8	75.3
PO_4^{3-}-P	4.4	1.3	4.2	2.2
Cl^-	12.9	11.7	7.5	21.5
SO_4^{2-}	4.3	5.2	1.9	0.24
Fe	4.1	6.3	1.4	0.79
Cu	0.38	0.57	0.63	0.66
Zn	0.08	0.10	0.31	1.0
Cd	0.11	0.17	1.7	7.2
Pb	0.22	1.2	13.9	9.7

et al. 2011; Teemusk & Mander 2011; Razzaghmanesh *et al.* 2014), higher than the runoff from a rooftop farm ($NO_3^- = 4.95$ mg/L, Whittinghill *et al.* 2016) and comparable to agricultural runoff (0–75 mg/L, up to 376.4 mg/L in nursery farms, cited in Whittinghill *et al.* 2016), highlighting a significant eutrophication risk for downstream waterways/waterbodies from nitrogen pollution.

The previous studies have shown that the green roof vegetation aided in nutrient removal (e.g., Kohler *et al.* 2002; Berndtsson *et al.* 2006, 2009; Aitkenhead-Peterson *et al.* 2011; Vijayaraghavan & Joshi 2014). The results from this study were mixed for N and P nutrients. For phosphate (PO_4^{3-}-P), grass configurations removed phosphate for both the SOIL and COMMERCIAL substrates, with lower runoff concentrations, compared to the bare configurations. For N-nutrients, the SOILgrass removed both N-nutrients from the RAINFALL with removal efficiencies of 41.7 and 97.9% for NO_3^--N and NH_4^+-N, respectively. However, the COMgrass configuration units resulted in NO_3^--N and NH_4^+-N concentrations that were 10 times and 2.4 times higher than the bare configuration (Table 5). The reason for the poor runoff quality may be due to the high organic content in the substrate which decomposed, converting organic N into more labile forms, NH_4^+-N and NO_3^--N as well as the nitrification of existing NH_4^+-N in the substrate into NO_3^--N. Kuoppamäki & Lehvävirta (2016) also found that their vegetated configuration units had higher concentrations of total nitrogen (approximately 2–7 times higher) and total phosphorus (3–5 times higher) compared to the bare configurations due to the decomposition of dead vegetation and nitrogen-fixing leguminous plants (*Trifolium repens* and *Lotus corniculatus*). Plant growth was particularly luxurious for the COMgrass units, possibly attracting birds, whose faeces contribute NH_4^+-N which quickly nitrifies to NO_3^--N (Berndtsson 2010; Buffam & Mitchell 2015). Others have also acknowledged the role of birds on green roof nutrient runoff quality (e.g., Teemusk & Mander 2011).

3.2.3. Trace metals

The SOIL substrate removed the potentially toxic metals such as Pb and Cd, with high RE (>80%) when compared against the RAINFALL samples. The COMMERCIAL configurations, by comparison, released these metals; Pb concentrations were 13.9 (COMbare) and 9.7 (COMgrass) times higher than they were in the RAINFALL samples. The Cd concentrations in COMgrass runoff were 7.2 times higher than they were in the RAINFALL samples (Table 5). Despite their proximity to an industrial area, the green roof runoff concentrations were below the USEPA (2009) guideline values for drinking water and freshwater and Singapore's guidelines for the trade effluent into a controlled waterway (Table 4). The higher trace metal concentrations from the green roof configuration units, in comparison to the leaching samples, highlighted the effect of field exposure which subjects the green roofs to additional inputs of trace metals from metal-enriched roadside sediments via wind resuspension (Yuen *et al.* 2012). The Fe (1.7–13.7 ppb) and Cu (1.3–2.3 ppb) concentrations in this study were also approximately an order of magnitude lower than the concentrations obtained from a nearby study (Fe: 43–113 ppb, Cu: 37–56 ppb, Vijayaraghavan *et al.* 2012). These differences in runoff concentrations between the two studies can be attributed to the roof exposure, substrate and vegetation.

Grass vegetation generally had a positive effect on trace metal concentrations in green roof runoff. The removal performance was better for the SOIL substrate, especially the SOILgrass configuration which removed toxic metals, such as Zn and Cd, effectively (RE > 80%). The COMgrass configurations also removed Fe, Cu and Zn, with lower removal efficiencies of 21.3, 33.7 and 4.7%, respectively. Cu and Zn retention by grass configurations reflects the vegetation uptake as these trace metals are micronutrients for plant growth (Whittinghill *et al.* 2015).

3.2.4. Carbon

Carbon concentrations in green roof runoff were higher than the RAINFALL (Table 4). The SOIL configurations resulted in TOC concentrations 2.1–2.7 times higher than the RAINFALL. This difference increased to 16.8–22.4 times higher for the COMMERCIAL configurations (Table 5) The differences in TOC concentrations in runoff from the two substrates reflect the higher organic content in the COMMERCIAL substrate (Table 1).

Vegetation had a minimal impact on TOC concentrations in green roof runoff for both substrates as did Harper *et al.* (2015) who suggested that the carbon in green roof runoff originates from the substrates.

3.2.5. Other ions

The green roof configurations elevated cation and anion concentrations, particularly Ca^{2+} (COMgrass = 17.8 ± 6.0 ppm) and K^+ (SOILbare = 9.3 ± 8.2 ppm) when compared against the RAINFALL inputs (Table 4). Cation and anion concentrations in this study were lower than the concentrations recorded by Vijayaraghavan *et al.* (2012) as well as other green roofs elsewhere (Ca: 0.07–32.5 ppm, Mg: 2.8–12.1 ppm; Berndtsson *et al.* 2009; Berghage *et al.* 2009; van Seters *et al.* 2009; Teemusk & Mander 2011).

The grass configuration had minimal impact on runoff quality for the SOIL substrate, given the similar runoff concentration levels as the bare configuration. For the COMMERCIAL substrate, the COMgrass configuration resulted in poorer runoff quality, with higher outflow concentrations of Ca^{2+}, Mg^{2+} and K^+ that were at least four times higher than the bare configuration units (Table 5). Vijayaraghavan *et al.* (2012) found that *S. mexicanum* had a positive effect by reducing the concentrations of these ions in the runoff when compared against their bare configurations.

3.3. Environmental controls on green roof runoff quality

Environment conditions such as rainfall properties and antecedent dry weather affect the runoff quality from green roofs. Our results showed that as rainfall amount increases, the green roof runoff concentrations decrease for almost all water quality parameters, especially for events sampled during Periods 2 and 3 ($p < 0.05$). This trend was also observed in other studies (e.g., Zhang *et al.* 2014; Gong *et al.* 2019). However, other studies have reported higher runoff concentrations for larger rainfall events, especially for soluble nutrients (NO_3^--N, NH_4^+-N and PO_4^{3-}-P), which are readily flushed out of green roofs (e.g., Kuoppamäki & Lehvävirta 2016; Wang *et al.* 2017b; Gong *et al.* 2019). Bigger and more intense rainfall events cause rapid water flow through green roof systems, reducing the residence time needed for pollutant adsorption and increasing the likelihood of flushing (Wang *et al.* 2017b). The negative relationship between the rainfall amount and the green roof runoff concentration observed in this study reflects the dominant effect of frequent and heavy wet season rainfall events on green roof runoff quality just before and during the Northeast Monsoon wet season. This seasonal influence was also observed in Chongqing where a negative relationship between rainfall amount and green runoff concentrations was observed for the wet season (Zhang *et al.* 2015). Buffam *et al.* (2016) found a weak relationship between the rainfall amount and the runoff concentration due to the over-riding effect of temperature and antecedent dry weather on green roof runoff quality probably through their influence on plant nutrient cycling. Although this study focused only on concentrations, it is important to incorporate load estimates of water quality variables in future work on green roof runoff quality. The greatest water quality impact on downstream systems from a mass load perspective will be from high rainfall events with high concentrations from green roof configurations using the COMMERCIAL substrate, conditions likely to occur at the beginning of the wet season.

Antecedent dry weather is also an important factor affecting the green roof runoff quality in this study. Our results showed that both the RAINFALL (e.g., NH_4^+, Na^+ and SO_4^{3-}) and the green roof runoff quality were poorer when the 7-day antecedent precipitation rainfall (ADP7) was lower. For green roof configurations, significant positive correlations were observed for almost all configurations, mainly for cation and anion concentrations for events from Periods 2 and 3 (Ca^{2+}, Na^+, K^+, Cl^- and SO_4^{3-}, $p < 0.05$). Other studies also found a positive relationship between antecedent dry weather and runoff concentrations (e.g., Zhang *et al.* 2014; Buffam *et al.* 2016). Longer dry periods increase the accumulation of pollutants from sources such as dry deposition and weathering of building material onto green roofs (Berndtsson 2010).

3.4. Change in runoff quality over the first 9 months

The RAINFALL quality changed over the monitoring period. The highest concentrations for most water quality parameters examined were observed for Period 1 samples (Period 3/Period 1 ratio < 1). Nitrate-N showed the greatest change over the monitoring period (Period 3/Period 1 = 0.13), whereas Mg^{2+} and K^+ showed minimal changes (Period 3/Period 1: $Mg^{2+} = 1.0$, $K^+ = 1.07$; Table 6, Figures 3 and 4).

The general trend for green roof runoff quality was a reduction in median concentrations over the monitoring period, often >50%, for many water quality variables measured, especially seen for both the SOIL configurations (Table 6). Visible changes in vegetation and the substrate were observed over the 9-month monitoring period. The grass configurations established well without additional watering, fertilisation or maintenance (e.g., plant trimming, Figure 5). For the SOIL configurations, important exceptions to the general trend included trace metals, including large increases in Fe concentrations (both SOIL configurations), while Cu (SOILgrass) and Cd (SOILbare) concentrations were largely unchanged over the wet seasons (Table 6). All other important differences were associated with the COMgrass configuration, including large increases in NO_3^--N (Monsoon/Dry = 5.44), NH_4^+-N (Period 3/Period 1 = 2.46) and SEC (Period 3/Period 1 = 2.1) and small increases in Ca^{2+} (Period 3/Period 1 = 1.16) and PO_4^{3-}-P (Period 3/Period 1 = 1.07) over time.

Many water quality variables (e.g., SEC, NO_3^--N, NH_4^+-N, PO_4^{3-}-P, Na^+, K^+ and Cl^-) exhibited high concentrations for events sampled in Period 2, just before the start of the Northeast Monsoon wet season, especially for the COMgrass configuration units. Highest concentrations were recorded for most water quality parameters

Table 6 | Period ratio values for RAINFALL and the green roof configurations

	Sampling periods	RAINFALL	SOILbare	SOILgrass	COMbare	COMgrass
TOC	Period 3/Period 1	0.21	0.46	0.36	0.11	0.15
SEC	Period 3/Period 1	0.09	0.11	0.18	0.27	2.10
Ca^{2+}	Period 3/Period 1	0.51	0.17	0.20	0.31	1.16
Mg^{2+}	Period 3/Period 1	1.00	0.10	0.13	0.13	0.61
Na^+	Period 3/Period 1	0.53	0.03	0.08	0.06	0.05
K^+	Period 3/Period 1	1.07	0.03	0.08	0.01	0.12
NO_3^--N	Period 3/Period 1	0.13	0.05	0.08	0.96	5.44
NH_4^+-N	Period 3/Period 1[a]	0.31	–	–	0.93	2.46
PO_4^{3-}-P	Period 3/Period 1[a]	0.00	–	0.38	0.00	1.07
Cl^-	Period 3/Period 1	0.37	0.02	0.07	0.01	0.04
SO_4^{2-}	Period 3/Period 1	0.44	0.03	0.15	0.12	0.10
Fe	Period 3/Period 2[b]	0.22	3.65[c]	4.42[c]	0.42	0.30
Cu	Period 3/Period 2[b]	0.45	0.29	1.02	0.37	0.29
Zn	Period 3/Period 2[b]	0.44	0.37	0.42	0.41	0.56
Cd	Period 3/Period 2[b]	0.47	0.90	0.37	0.35	0.72
Pb	Period 3/Period 2[b]	0.23	0.58	0.70	0.24	0.24

The period ratio shows the change in water quality over time for two time periods chosen for comparison.
[a]Insufficient data to calculate the ratios because samples were often below the detection limit.
[b]Trace metals were only sampled for the Periods 2 and 3.
[c]High enrichment ratios are noted for Fe for both SOIL treatments. The concentrations for Period 3 are below the USEPA drinking water guidelines (USEPA 2009) (300 ppb) and the USEPA national recommended guidelines for aquatic life (1,000 ppb). Refer to Supplementary Material, Appendix B.

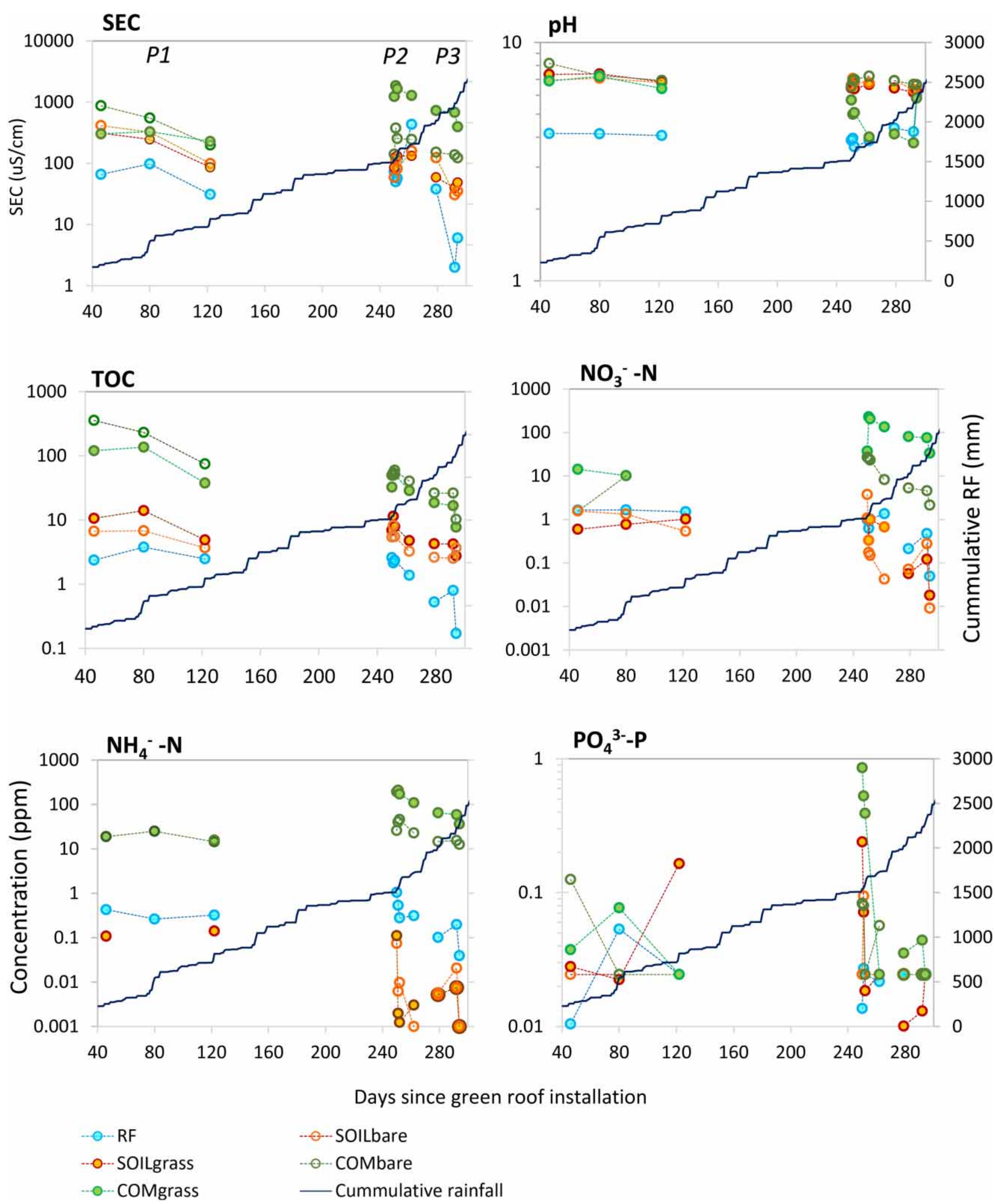

Figure 3 | Concentrations (median values, ppm) of the RAINFALL and the green roof runoff samples for 10 rainfall events (April–December 2014) and the cumulative daily rainfall measured since 1 January 2014. The three periods, Periods 1, 2 and 3, are denoted as P1, P2 and P3, respectively. The concentration values are plotted on a logarithmic scale.

in the second or third event of a series of four events, especially for NO_3^--N and NH_4^+-N (Figure 3). This was most likely due to the accumulation of organic matter and their subsequent decomposition and mineralisation when the substrate wetted up with rainfall events from Period 2 as well as from rainfall inputs that had relatively higher NH_4^+-N concentrations (RAINFALL: Period 2/Period 1 = 1.31) (Buffam *et al.* 2016). The first event of Period 2 just wetted up the green roofs given the low ADP7 (2.3 mm), which increased to 33.8 mm after the second event (Table 2). Between the two substrates tested, the COMMERCIAL configurations recorded highest N and P concentrations during this period: NO_3^--N (144 ± 61.1 ppm) and NH_4^+-N (172 ± 58.1 ppm) due to its high organic content.

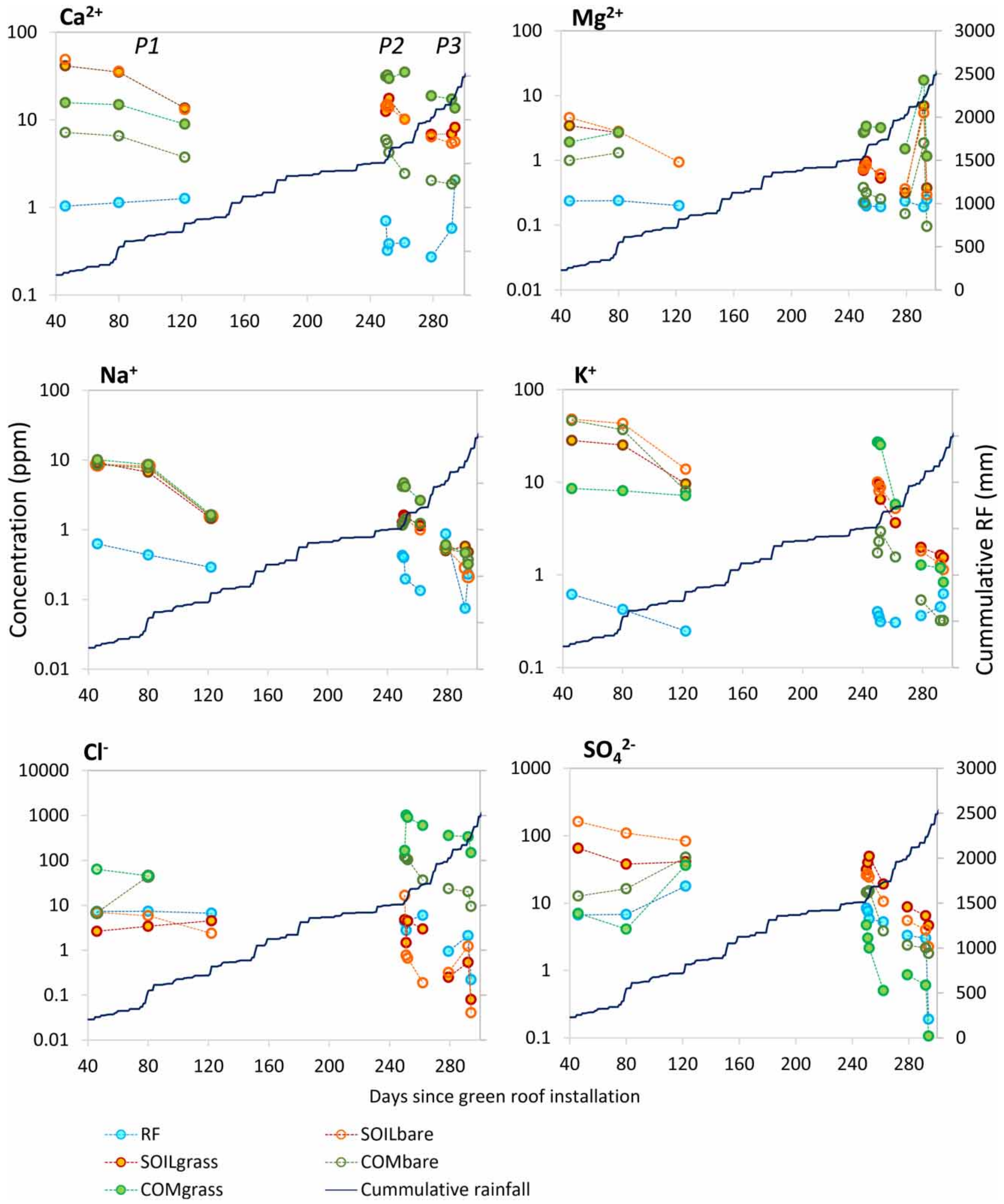

Figure 3 | continued.

By the end of the monitoring period, runoff concentrations from the SOIL configurations were lower than the samples collected at the start of the study (Period 3/Period 1 <0.7) and were also close to or below RAINFALL concentrations. This was not the case for the COMMERCIAL configurations, especially the COMgrass configuration, which recorded high concentrations of NO_3^--N (67.7 ± 17.1 ppm) and NH_4^+-N (53 ± 12.0 ppm) for Period 3 (Supplementary Material, Appendix B). The NO_3^--N concentration was above the USEPA guidelines for drinking water, Singapore's trade effluent guideline concentration for discharge into a controlled watercourse (4.4 mg/L NO_3-N) and more than an order of magnitude higher than stormwater runoff concentrations for different urban catchments in Singapore (0.038–2.77 ppm, Lim 2003; Wang *et al.* 2017a).

The temporal variability in runoff quality observed for the first 9 months of our configuration units agrees with other studies, i.e., green roof runoff quality is the most variable in its first year (e.g., Hathaway *et al.* 2008; Harper

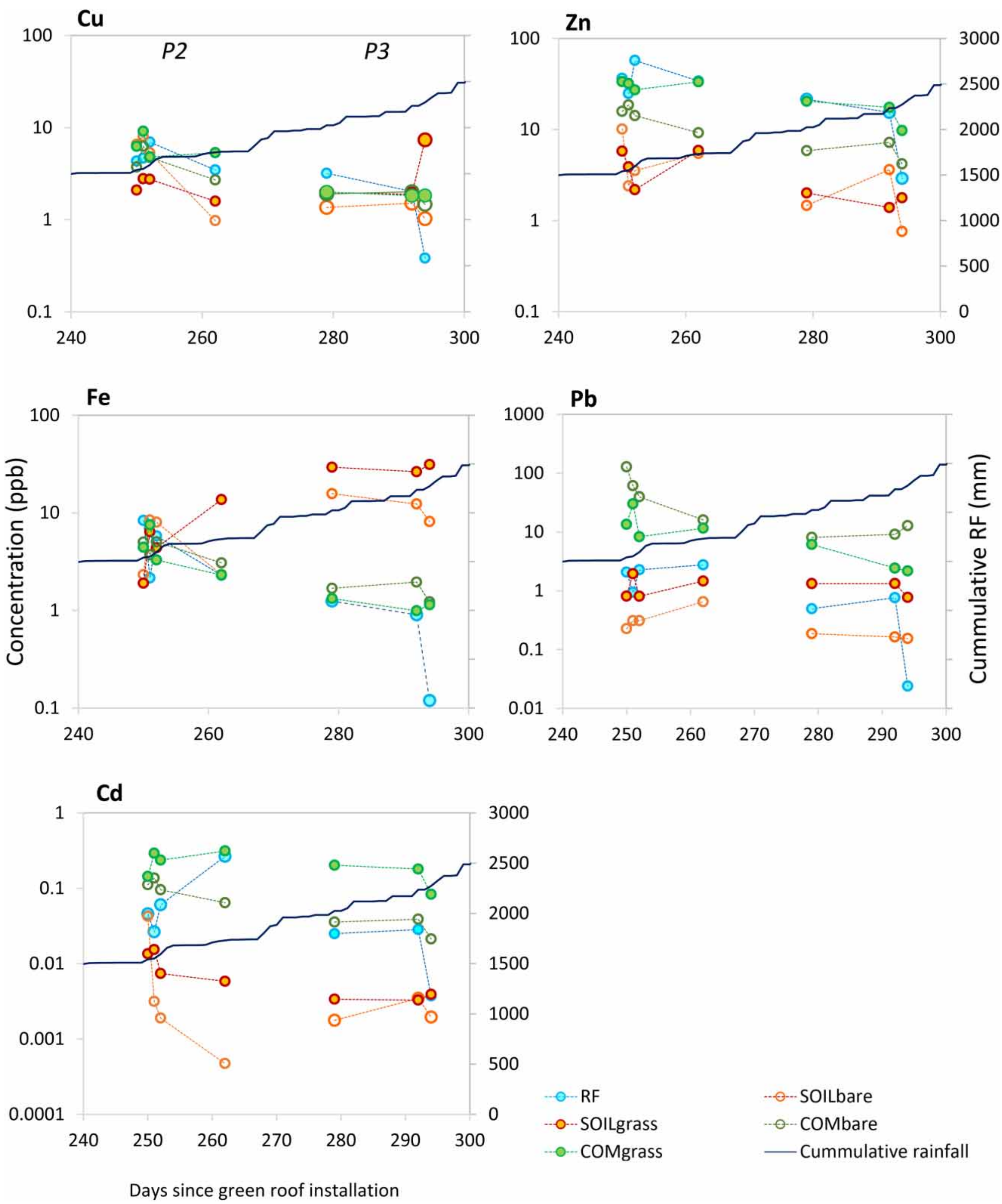

Figure 4 | Trace metal concentrations (median values, ppb) of the RAINFALL and the green roof runoff samples for 10 rainfall events (April–December 2014) and the cumulative daily rainfall measured since 1 January 2014. The three periods, Periods 1, 2 and 3, are denoted as P1, P2 and P3, respectively. The concentration values are plotted on a logarithmic scale.

et al. 2015; Kuoppamäki & Lehvävirta 2016) due to rapid changes in the substrate and vegetation (Monterusso *et al.* 2004; Schrader & Böning 2006). Others have reported delayed increases in N and P nutrient levels due to seasonal effects related to freeze–thaw cycles and additions from the decomposition of organic matter from dead vegetation originating from well-established vegetation or from systems where vegetation is struggling to survive (e.g., Teemusk & Mander 2011; Harper *et al.* 2015; Kuoppamäki & Lehvävirta 2016). Here, the SOIL configurations stabilised and reached low runoff concentrations that were comparable or lower than the RAINFALL within the first 9 months of deployment. The time required for the COMMERCIAL substrate to achieve the same result is unknown and requires longer term monitoring. Other green roof studies have found that it can

Figure 5 | The green roof design configuration units in (a) February 2014 and at the (b) end of the monitoring period showing that grass is well established on the configuration units.

take up to 5 years (Berghage *et al.* 2009) or even 9 years after installation before the green runoff nutrient concentrations are comparable or below rainfall inputs (Berndtsson *et al.* 2006). For a roof in Germany, phosphorus retention increased from 26% in the first year to 80% in its fourth year of installation due to increased P-uptake and substrate retention after the vegetation established (Köhler & Schmidt 2003). Some factors that affect this stabilisation period include plant growth dynamics and changes to the substrate due to environmental exposure (Alsup *et al.* 2010; Buffam *et al.* 2016). Repeated wetting and drying have been found to affect organic matter decomposition and N-mineralisation rates in green roof substrates, affecting their runoff nutrient levels over time (Nagase & Dunnett 2011). The luxuriant grass on the COMgrass configuration suggests that this configuration may be a continual source of nitrogen-N nutrients if such growth is maintained.

3.5. Widespread implementation of green roofs in urban environments

The different water quality results reported by Vijayaraghavan *et al.* (2012) and this study are due to dissimilar substrate and vegetation composition. Comparison of the substrates used in both studies revealed that pH is most similar, while SEC and organic matter content show differences that may account for the variability in green roof runoff quality observed for the two studies (Table 1). Green roof runoff from the study of Vijayaraghavan *et al.* (2012) reported higher concentrations of almost all water quality parameters tested, especially for phosphorus due to the addition of fertiliser in the substrate, whereas nitrogen (NO_3^--N and NH_4^+-N) was a problem identified in this study.

As the SOIL substrate and grass configurations achieved low concentrations of important water quality parameters (N-nutrients, TOC and trace metals) within a relatively short period of 9 months, we recommend this configuration combination for green roof implementation in Singapore and elsewhere. The low organic matter in this substrate (LOI = 16.9%) and lack of fertiliser additions are probably the reasons for the good water quality outcomes for both SOIL configurations. For comparison, the COMMERCIAL substrate contained excess organic content compared to the recommended values between 4 and 12% (FLL guidelines, Whittinghill *et al.* 2016). It is likely that commercial substrates are still preferred because they are designed to provide the nutrient needs of green roof vegetation, water retention requirements as well as the lightweight properties required for deployment on roofs. Of the 44 papers on green roof runoff quality compiled in Supplementary Material, Appendix A, about half of them used commercial substrates (45%) and 60% of those that used commercial substrates, including this study, reported poor green roof runoff quality when compared against rainfall and/or bare roof runoff quality. For widespread green roof implementation, we recommend thorough testing of substrate properties before field deployment for properties such as their pH, SEC, carbon, N and P content. This should be done for commercial substrates as well as for locally designed substrates, which may be the case in Southeast Asia, where commercial substrates may be too expensive. Lab results may be different from field results due to additional pollutant contributions from the atmosphere, urban activities and wildlife, especially for Southeast Asian cities with dense traffic and heavy industrial activities. Regular substrate testing should continue even after green roofs are installed to check if they still contain the necessary nutrient stocks for plant growth as this informs fertiliser application strategies (Rowe *et al.* 2006; Aitkenhead-Peterson *et al.* 2011; Buffam *et al.* 2016).

Vegetation had a positive influence on green roof quality, whether it is grass or sedum varieties. Because green roof vegetation also provides habitats for urban wildlife, cooling benefits and improves liveability, maintenance activities to ensure healthy vegetation should be a priority in green roof management especially in the tropics where warm and wet conditions encourage rapid plant growth. The healthy grass growth achieved in the 9 months of this study will need trimming maintenance to avoid problems of increased roof loading and potential poor water quality from overgrown green roof vegetation (Rowe *et al.* 2006).

By the end of the experiment, the overgrown grass vegetation appeared to be slightly brown which suggested it needed irrigation and fertiliser to maintain healthy growth in the long term. Green roof vegetation tends to experience a boom-and-bust phenomenon due to their exposure to extreme heat and drought (Monterusso *et al.* 2005; Bates *et al.* 2015). The sedum plants on some configurations in Vijayaraghavan *et al.* (2012)'s study also failed to survive. Even though phosphorus was not a problem in this study, P pollution is a common issue due to fertiliser or compost additions to boost plant growth (e.g., Hathaway *et al.* 2008; Vijayaraghavan *et al.* 2012). Rowe *et al.* (2006) found that plants needed a minimum amount of fertilisers (50 g/m^2/year) to sustain healthy vegetation growth. The danger of luxuriant growth may be that vegetation is at risk from greater damage during drought periods (Rowe *et al.* 2006; Nagase & Dunnett 2011). Green roof vegetation in Singapore and other tropical cities will likely require different fertiliser concentrations due to the high plant nutrient demands to sustain their rapid growth in the hot climate. High rainfall in the tropics also encourages frequent flushing of fertilisers out of the root zone before plant uptake occurs (e.g., Wang *et al.* 2017b). In such situations, the solution may lie in the use of slow-release fertilisers at concentrations sufficient just to maintain healthy plant growth. Because of the lack of information relating to plant nutrient needs for green roofs in the tropics, further research on fertiliser applications in terms of their amount, timing and frequency relative to plant needs are urgently required with the widespread implementation of green roofs in this region (e.g., Emilsson *et al.* 2007).

The non-point source pollution from green roofs, especially young installations, can be managed, so that the overall benefits, particularly in urban cooling, is realised for tropical cities (Sangkakool *et al.* 2018). One solution is to connect green roofs to other blue-green infrastructure located downstream for additional water quality configuration or to other urban green spaces (Kuoppamäki & Lehvävirta 2016; Vijayaraghavan 2016). The green roofs in our study could be connected to other green spaces on the university campus to irrigate them, reducing the need for fertiliser applications for these systems. This may be a more practical approach to manage the poor nutrient quality from green roofs for cities in the Southeast Asian region which may not have access to improved green roof substrates that have been modified with materials such as biochar and zeolite (Vijayaraghavan 2016). Furthermore, tropical cities will increasingly face more severe urban water stress due to climate change and population increase, especially for cities located in dry environments as well as megacities (Razzaghmanesh *et al.* 2014; He *et al.* 2021). The capture and reuse of green roof runoff as greywater provides a sustainable approach to augmenting the urban water supply. A holistic approach that includes appropriate green roof design coupled with substrate testing, well-devised fertilisation strategy and long-term green roof monitoring, incorporating pollutant mass load estimates, is required with a widespread implementation of these green infrastructure in order to maximise their benefits in the urban environment.

4. CONCLUSIONS

The green roof runoff quality in its first 9 months is highly dynamic and controlled largely by the substrate. The green roof configurations using the SOIL substrate displayed a gradual decline in concentration levels for most of the water quality parameters. The COMMERCIAL substrate displayed more variable patterns, with highest concentrations for the N and P nutrients observed just before the start of the Northeast Monsoon wet season. Frequent rainfall activity resulted in a gradual decline in concentrations over the course of the wet season. All configuration units neutralised acid rainfall and removed trace metals for a site located close to an industrial area. Runoff from the COMgrass configuration resulted in high concentrations of carbon and N-nutrients that make it suitable as a source of irrigation water for other urban green spaces in Singapore. We recommend the SOIL as a suitable green roof substrate for Singapore and other cities in the region. This substrate supported healthy grass growth during the monitoring period. Runoff concentrations from the SOIL-based configuration units were also similar or lower than the rainfall inputs. We also recommend a thorough testing of substrates before they are used for widespread deployment of green roofs in cities to minimise their water quality impacts while enjoying the benefits they provide for a more sustainable urban environment.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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