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Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities

A high-resolution field-scale survey of bioretention basin performance in treating 15 water quality parameters (including nitrogen and phosphorus species) in the data-scarce tropics is critically evaluated. Practical engineering strategies to design and manage bioretention basins are also presented here.

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Evaluation of pollutant removal efficiency of a bioretention basin and implications for stormwater management in tropical cities†

Jia Wang,[a] Lloyd H. C. Chua[b] and Peter Shanahan*[a]

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Non-point source pollution is a prevalent problem throughout the world. Bioretention basins have been deployed worldwide to treat stormwater runoff and alleviate eutrophication in downstream water resources. However, basin performance in the tropics is poorly understood. Given the distinctly different rainfall-runoff characteristics of tropical climates, whether basins that are built according to temperate design guidelines are effective is questionable. There have been no field studies based on continuous, high-resolution, long-term monitoring in the tropics. In this study, 96 storms were monitored in the first bioretention basin in Singapore. Of these, flow measurements were made during 80 events and samples were collected and analyzed for 15 water quality parameters (including nitrogen and phosphorus species, total suspended solids, and chemical oxygen demand) during six events. The mean removal rates were 25%, 46%, and 53% for total nitrogen, total phosphorus, and total suspended solids respectively. Results show that a lack of storage capacity and resulting high overflow reduce pollutant removal efficiency for high-rainfall-depth events. The transition from efficient to non-efficient removal occurs at a rainfall depth between 10 and 30 mm. Low EMC (event mean concentration) and weak first flush as a result of frequent and intense rainfall in the tropics also contribute to low removal rate. The results suggest a need to revise bioretention basin design guidelines for the tropics to be based on WQV or WQD (water quality volume or depth) instead of ARI (average recurrence interval). A larger basin volume (WQD between 10 to 30 mm) is recommended.

Water impact

The bioretention basin is a form of stormwater best management practice that originated in temperate regions and is becoming increasingly popular in tropical regions. Nevertheless, it is a poorly evaluated system in the tropics due to the limited availability of long-term, high-resolution hydrological and multi-component water quality data on completed basins. The resulting gaps in data and knowledge limit the ability of environmental managers to control pollution by stormwater runoff. This study provides a complete survey of basin performance in treating 15 water quality parameters (nitrogen and phosphorus species, total suspended solids, and chemical oxygen demand) and also recommends practical engineering strategies to design and manage bioretention basins in the tropics.

1 Introduction

Hydrologic modification brought about by traditional concrete-lined drainage systems due to urbanization have unwanted consequences such as raised peak discharge, reduced groundwater recharge, and non-point source pollution.[1,2] BMPs (best management practices) or LID (low impact development) entail decentralized strategies that aim to reinstate pre-development hydrological features through detention and treatment of polluted runoff at its source.[3–6]

BMPs such as bioretention basins (also known as rain gardens) have been shown to be effective in reducing runoff volume and removing pollutants.[7–12] Tang *et al.*[12] showed that even if bioretention basins occupy a small fraction of the city area, they can substantially reduce the adverse hydrological effect brought about by imperviousness. Zhang and Guo[11] derived an analytic probabilistic expression to approximate the efficiency of bioretention basins in capturing stormwater over the long term. Hunt *et al.*[8] found such

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[a] *Department of Civil and Environmental Engineering, Massachusetts Institute of Technology, 77 Massachusetts Avenue, Cambridge, MA 02139, USA. E-mail: peteshan@mit.edu*

[b] *School of Engineering, Faculty of Science Engineering & Built Environment, Deakin University, 75 Pigdons Road, Waurn Ponds, VIC 3220, Australia*

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basins achieved significant reduction of most pollutant concentrations including total nitrogen (TN), total Kjeldahl nitrogen, ammonia, biochemical oxygen demand, total suspended solids (TSS), copper, zinc, lead, fecal coliform, and *Escherichia coli*. DeBusk and Wynn[10] found over 99% cumulative mass reductions for sediment, TN, and total phosphorus (TP), 97% flow volume reductions, and 99% peak flow rate reductions. Reviews by Davis *et al.*[7] and Roy-Poirier[9] both recognized the need to conduct further research to answer persisting design questions such as basin sizing and soil media composition as adoption of bioretention basins grows worldwide. Roy-Poirier[9] also urged the development of bioretention models that include both hydrologic and water quality processes as a tool to compare and verify the suitability of currently inconsistent design guidelines.

Field studies have been carried out in various climatic conditions around the world to evaluate the effectiveness of bioretention basins in removing pollutants. Early studies have primarily been conducted in temperate regions such as North Carolina,[13–15] Maryland,[16] Connecticut,[17,18] and Virginia[10] in the USA; Victoria[19] and Queensland[20] in Australia; and Auckland in New Zealand.[21] More recent studies include semi-arid climate regions like Utah[22] in the USA and cold climate regions like Québec[23] and Calgary[24] in Canada. For the tropics, there has been a lack of field studies although there are several lab and mesocosm studies that investigated the impact of media composition on nutrient removal.[25–27] Our field study attempts to bridge the gap in understanding basin removal efficiency in the tropics and aims to suggest effective management guidelines.

Bioretention basins are generally required to remove 80–92% of TSS, 30–65% of TN, and 30–90% of TP in various parts of the world.[28–34] In order to achieve these pollutant removal targets, stormwater regulations usually require that basins be designed to capture a certain volume of runoff so as to ensure most of the annual pollutant load is treated.[35] The term "water quality volume" or WQV refers to the runoff volume specified to be captured and treated. Water quality depth (WQD) is the unit WQV per catchment area. These recommendations have largely originated from countries that have predominantly temperate climates, including the United States and Australia.

In most of the U.S., basins are set to capture a WQD that corresponds to the first half to one inch (12.7–25.4 mm) of runoff depending on the water quality of the discharge and the requirements of the receiving water body.[28–30] These requirements are based on results from Novotny's[36] initial studies in Florida that the first flush contains 90% of total pollutant load in an event. New Hampshire standardized one inch of runoff for all discharges on the basis of a "90 percent rule" that supposes that in the northeastern U.S., the cumulative volume from the first inch of runoff from each event will amount to 90% of the total runoff in a year.[29,37] In Australia, stormwater guidelines are written in terms of both WQD and ARI (average recurrence interval). In western Sydney, Upper Parramatta River Catchment Trust (UPRCT)[38] recommends retaining a WQD of 15 mm for a 24 hour period and 20 mm for a 48 hour period to capture 60% of the average yearly rainfall. The Australian Capital Territory requires that models such as MUSIC (Model for Urban Stormwater Improvement Conceptualization),[39] which generate WQVs, be used to analyze large catchments. For smaller catchments, runoff resulting from a 3 month ARI event must be retained and discharged over one to three days.[40] In Europe, stormwater management authorities generally do not have a regulatory procedure for approving green sustainable urban drainage system (SUDS) infrastructure such as bioretention basins.[34,41]

Currently, design guidelines in Singapore are modeled after those of temperate areas, primarily Australia.[42] For instance, basins in Singapore must be designed to accommodate a critical design flow rate for a 3 month ARI event and WQV generated with the MUSIC model.[31] The targeted removal rates are 80% of TSS, 45% of TN, and 45% of TP. However, sustainable practices from temperate regions may not apply to tropical climates such as Singapore with its distinctly different rainfall-runoff characteristics. Nevertheless, the null hypothesis for this study is the implicit assumption by Singapore: that bioretention basins built according to existing guidelines from temperate regions are able to meet the intended removal targets in tropical climates.

Recent field studies have mostly focused on basin performance. Little attention has been paid to the relationship between observed removal rates and hydrology in the context of rainfall and runoff characteristics. There has also been a lack of field studies in the tropics. However, field studies based on continuous, high-resolution, long-term rainfall and actual flow records (*i.e.* non-synthetic runoff) as well as complete pollutographs (*i.e.* non-composite sampling) are important for developing appropriate management and design guidelines, evaluating their suitability in the tropics, and validating hydrological and water quality models. There is also an urgent need to develop management measures to meet removal targets in the tropics.

In this paper, we present research on bioretention basin performance in terms of removal efficiency of various pollutants in six storms of varying rainfall characteristics and hydrology in a basin in Singapore. The objectives of this study were to:

1) Assess whether a bioretention basin built according to temperate guidelines is able to remove pollutants at targeted rates in a tropical setting;

2) Analyze the factors behind observed removal efficiency in terms of rainfall characteristics such as rainfall depth, rainfall intensity, and antecedent dry period (ADP) as well as runoff characteristics such as event mean concentration (EMC) and first flush; and,

3) Investigate the suitability of current design guidelines for the tropics and suggest improved guidelines if necessary.

2 Methodology

2.1 Data collection

Flow and level measurement. A real-time monitoring system that consisted of flow and water-level measurement equipment and automatic water quality samplers was installed and operated from April to November 2013 at Balam Estate Rain Garden in Singapore. A full description of the study site can be found in the ESI.† Four Doppler ultrasonic area-velocity level sensors (ISCO-2150 Area Velocity Module with 2105 Interface, Teledyne Isco, Lincoln, Nebraska, USA) were used to continuously monitor flow rates at the inlet, outlet, and overflow culvert as well as ponding water level at one minute intervals. Fig. S-1† shows the placement of these four sensors. Weekly basin maintenance was carried out to prevent sensor blockage by fallen leaves and trash.

Event statistics. Rainfall intensity (1 min interval) was measured with a tipping bucket rain gauge (Model TB4, Hydrological Services PTY Ltd., Liverpool, NSW, Australia) at 3 m above ground. Per-minute precipitation records from the rain gauge were used to calculate the total rainfall, event duration, and ADP for each event. Two neighboring events are defined to be separated by an inter-event time of at least six hours without rainfall.[43] Intermittent light drizzles with a total rainfall amount of less than 2.54 mm were excluded from the event count consistent with Driscoll *et al.*[43]

Sampling strategy and water quality. Water quality was monitored by collecting water samples throughout the storm duration and subsequent ponding and drainage of the basin using four autosamplers (two ISCO-Avalanche refrigerated portable samplers each equipped with fourteen 950 ml polypropylene bottles and two ISCO-3700 portable full-size samplers equipped with 24 one liter bottles). Samples were conveyed to the autosamplers *via* 1.0 cm-diameter Teflon-lined suction tubing connected to sample-collection strainers. The autosamplers automatically evacuated the tubes once prior to collection of the first sample of each storm. The four sampling points were at the inlet, outlet, overflow culvert, and on the basin floor (Fig. S-1†).

Table S-1† shows the time-based discrete sampling scheme followed. Surpassing a pre-defined threshold level triggered the inlet sampler which in turn triggered the other three samplers with a time delay of 0, 5, and 10 min for the outlet, pond, and culvert samplers respectively. Table S-2† shows a comparison with sampling strategies used in other studies reported in the literature. Discrete sampling, instead of commonly practiced composite sampling, was followed in this study. Discrete sampling has a clear advantage over composite sampling in terms of resolving data variability over time by delineating an entire pollutograph. Although there are studies that have incorporated discrete sampling, most have been done in the laboratory and few have been done in the field. Analysis of discrete samples comes at considerable expense, but capturing full pollutographs is important to ensure that the data collected are suitable for future research involving calibration and validation of hydrological and water quality models. Preliminary sampling trials were conducted during events in April 2013 to ensure that the total sampling time imposed by the time-based sampling scheme in Table S-1† was suitable for capturing full pollutographs during both small and large events.

During six events of varying characteristics (Table 1), discrete water samples were collected and then tested for concentrations of 12 parameters including various species of nitrogen and phosphorus (Table S-3†). Three additional parameters (organic nitrogen, ON; total particulate inorganic phosphorus, TPIP; and total particulate organic phosphorus, TPOP) were derived (eqn (S-1†)). Heavy metals are not measured as the main motivation for this study was eutrophication of the downstream reservoir that receives the effluent from this bioretention basin. The total number of samples analyzed from the six events for the different parameters range over 102–121, 122–144, and 48–60 for the inlet, outlet, and culvert respectively (Table S-4†). Table S-4† also lists the number of samples analyzed for each parameter in each event. Samples were transported from the site to the laboratory within 30 hours after the start of the event and were preserved and processed according to Standard Methods.[44] For every 20 samples, a duplicate and a standard curve check were made for all parameters and their recovery rates were within acceptable limits (89–110% for sample duplicates and 83–117% for standards). Blanks (deionized water) for all the parameters in all the events were below method detection limits.

2.2 Data analysis

Pollutant loading. Total cumulative pollutant loads at the inlet, outlet, and culvert were estimated for each sampled event by aggregating flow measurements over the time scale of samples according to eqn (1):

$$\begin{aligned} V_j &= \sum_{i=-N/2}^{-1} Q_i \Delta t + Q_\mathrm{c} \Delta t + \sum_{i=1}^{M/2} Q_i \Delta t \\ \text{Load} &= \sum_{j=1}^{S} V_j C_j \end{aligned} \tag{1}$$

where Q_c (L s^{-1}) is the flow rate at the current sampling time point; Q_i (L s^{-1}) is the flow rate at the current sampling time point plus or minus $i\Delta t$; Δt is the time interval between two readings of flow rate which in this study is one minute; N and M are the number of readings of flow rate between the current and previous sampling time point and between the current and next sampling time point respectively; C_j (mg L^{-1}) is the concentration measured at sampling time point j; V_j (L) is the total flow volume assigned to the j^th sample; and, S is the total number of samples.

Removal rate as a measure of performance efficiency. The mass removed is taken as the mass that is either retained in the basin or eliminated by biochemical reactions in the basin. The removal rate was calculated by comparing the

Table 1 Event statistics and hydrologic performance metrics of six sampled events

Event date and number	26/08/2013 (#3)	04/08/2013 (#2)	25/06/2013 (#1)	09/10/2013 (#5)	27/10/2013 (#6)	29/09/2013 (#4)
Rainfall (mm)	3.2	8.0	10.2	29.4	33.2	40.2
Storm duration	10 min	32 min	26 min	1.7 h	2 h	5.1 h
10 min peak intensity (mm h^{-1})	16.8	22.8	38.4	86.4	44.4	69.6
ADP (days)	9.08	2.06	8.25	2.88	5.42	2.75
ARI[a]	3 month	3 month	3 month	<1 year	3 month	<1 year
No. of inlet samples	8	24	24	20	21	24
No. of outlet samples	24	24	24	24	24	24
No. of culvert samples	0	12	7	14	14	13
No. of basin samples	1	14	10	14	14	14
Inflow volume (m^3)	15	73	94	424	527	667
Outlet volume (m^3)	24	34	60	55	60	76
Culvert volume (m^3)	1	20	34	404	502	543
Water balance[b] (%)	63	−26	1	8	7	−7
Culvert/inflow (%)	5	28	37	95	95	81
Outlet/inflow, f_{V24}[c] (m^3 m^{-3})	1.63	0.74	1.01	1.08	1.07	0.93
R_{peak}[c] ((L s^{-1}) (L s^{-1})$^{-1}$)	0.10	0.04	0.05	0.03	0.04	0.11
R_{delay}[c] (h h^{-1})	5.8	5.6	2.2	4.2	0.9	1.0
Ponding duration (h)	0.8	10.0	5.8	9.9	10.4	13.4

[a] Based on intensity-duration-frequency (IDF) curve from PUB.[65] [b] Water balance (%) = (total outflow − total inflow)/total inflow. [c] Hydrologic performance metrics: f_{V24}, R_{peak}, R_{delay}.[45]

difference in mass between the inflow and outflow (*via* both the culvert and the outlet) of the basin, as shown in eqn (2):

$$\text{Removal rate}(\%) = \frac{\text{Inlet mass} - (\text{Culvert mass} + \text{Outlet mass})}{\text{Inlet mass}} \times 100\% \tag{2}$$

Event mean concentration (EMC). The EMC of the influent measures the flow-averaged concentration of runoff reaching the basin and can be taken as a single index that represents the water quality of runoff during a particular event. It is defined according to eqn (3):

$$\text{EMC} = \frac{\text{Cumulative influent mass}}{\text{Cumulative influent volume}} = \frac{\sum_{j=1}^{S} V_j C_j}{\sum_{i=1}^{n} Q_i} \tag{3}$$

where Q_i (L s^{-1}) is the flow rate measured at one minute intervals over the entire event and n is the total number of flow-rate readings.

3 Results

3.1 Hydrologic performance

Fig. 1 shows the hyetographs and hydrographs for the inlet, outlet, and culvert discharges of the six sampled events, arranged in order of increasing rainfall depth. The hydrologic effectiveness of the bioretention basin in managing stormwater runoff often lies in its ability to reduce peak flow rate, delay the time to peak outflow, and delay hydrologic volume *via* runoff storage and holdup. These three aspects are quantified using three metrics defined by Davis:[45] R_{peak} (peak flow reduction ratio, $R_{\text{peak}} = q_{\text{peak-out}}/q_{\text{peak-in}}$); R_{delay} (peak delay ratio $R_{\text{delay}} = t_{q\text{-peak-out}}/t_{q\text{-peak-in}}$); f_{V24} (fraction of input water leaving the bioretention basin within 24 h, $f_{V24} = V_{\text{out-24}}/V_{\text{in}}$) where $q_{\text{peak-out}}$, $q_{\text{peak-in}}$, $t_{q\text{-peak-out}}$, $t_{q\text{-peak-in}}$, V_{in} and $V_{\text{out-24}}$ are peak outflow (L s^{-1}), peak inflow (L s^{-1}), time to peak outflow (h), time to peak inflow (h), total inflow volume (m^3), and total outflow volume (m^3) after 24 hours respectively. The target values recommended by Davis are $R_{\text{peak}} < 0.33$, $R_{\text{delay}} \geq 6$, and $f_{V24} < 0.33$.[45] In this study, for the six sampled events, mean R_{peak} (0.06) meets the target while mean R_{delay} (3.3) and mean f_{V24} (1.08) fail to meet targets (Table 1). This shows that the basin is effective in reducing peak flow rate (R_{peak}) across events of varying rainfall depths (Table 1). The ability to delay peak timing (R_{delay}) is better for small events (event #3, #2) than large events (event #6, #4). The ability to store and hold up runoff (f_{V24}) is poor in general.

In terms of hydraulic retention time, for the 96 storm events that occurred during the monitoring period, statistics based on 80 events with usable flow data indicate that within the bioretention basin, the ponding duration is 12.5 ± 5.5 h.[46] For the 59 events with sufficient influent to cause a culvert overflow, overflow stops at a mean pond water level of 13.9 cm or equivalently a surface storage of 40 m^3 during the receding phase. The mean ponding duration between zero culvert overflow and zero pond water level during this phase is 10.1 h. Drainage of surface ponding of 40 m^3 over a basin area of 240 m^2 in 10.1 h gives an estimated infiltration rate of 1.7 cm h^{-1}.[46] This phase of infiltrating ponded water results in an increase in subsurface storage of 23.7 m^3, corresponding to about 100% of the total available porous space in the unsaturated zone (estimated to be about 23.3 m^3).[46] This implies that the unsaturated zone is likely to stay

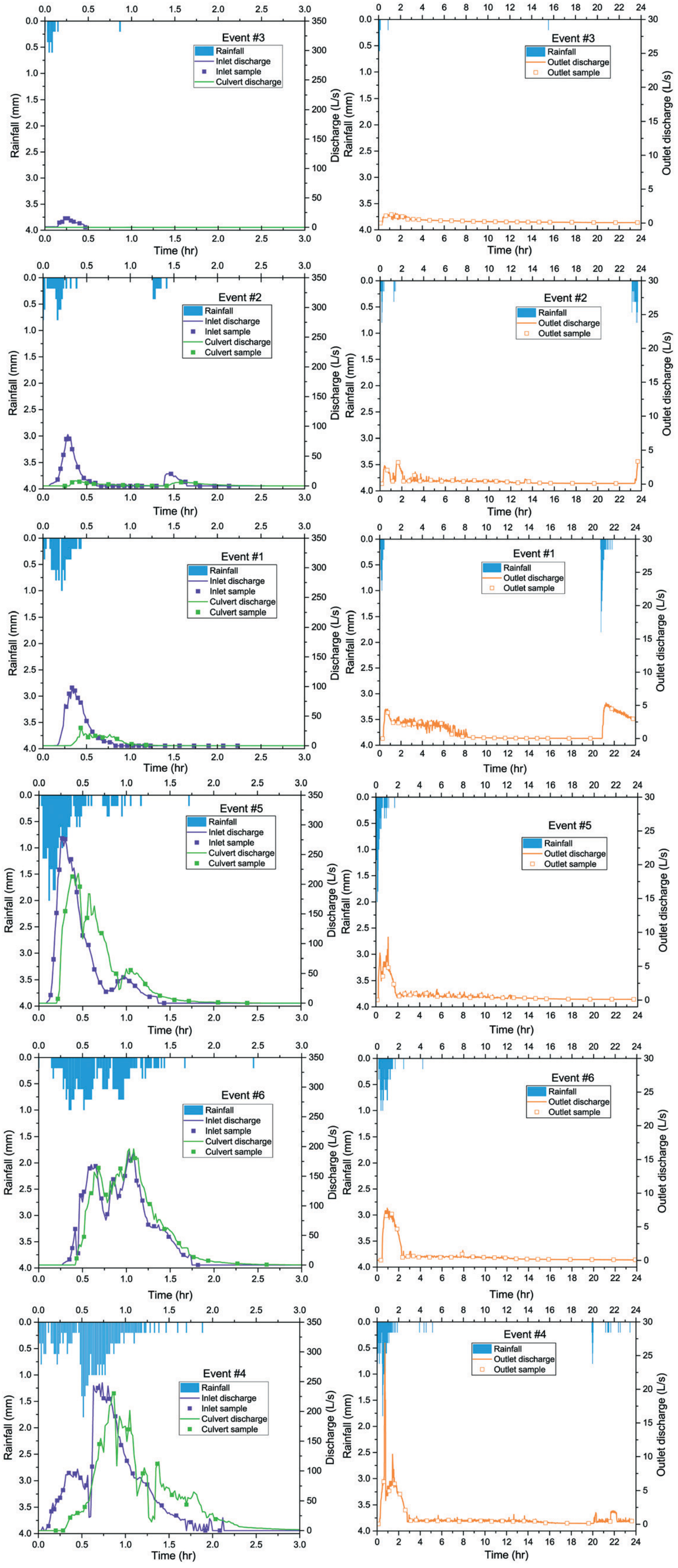

Fig. 1 Hyetographs and hydrographs for the inlet, outlet, and culvert of six sampled storm events at per-minute intervals. Time 0 indicates the start of rainfall. Sampling times for water quality analysis are also shown on the hydrographs. Sampling schedule and locations are shown in Table S-1 and Fig. S-1 in the ESI† respectively. Events are arranged in order of ascending rainfall depth.

saturated under a ponding condition. The infiltration rate of 1.7 cm h^{-1} is within the same order of magnitude as field measurement of 4.4 cm h^{-1} using a double-ring infiltrometer.[46] As water continues to drain from the basin, the mean gravity drainage rate is 0.3 cm h^{-1} under an unsaturated condition.[46]

3.2 Pollutant removal efficiency

3.2.1 Parameter removal rates. Treatment of runoff is achieved by various physical and biochemical processes such as sedimentation,[47] filtration,[48] adsorption,[49] biodegradation,[50] and plant uptake[51] within the basin. Table 2 summarizes the mean and one standard deviation of the inlet, outlet, and culvert concentrations of the 15 parameters in all samples across the six sampled events. Pollutant concentration decreases successively from the inlet to culvert to outlet which reflects the improvement in water quality as runoff is routed through the basin. Pollutographs of TN, TP, and TSS for each of the six sampled events are shown in Fig. S-2.† Greater improvement in water quality is seen if water is filtered through the soil media (outlet concentrations) than if it passes through the surface basin only (culvert concentrations). Reduced concentrations of TSS, TPIP, and TPOP at the culvert reflect sedimentation of particulates in the surface basin.[16,47] Reduced concentration at the outlet reflects additional subsurface treatment such as filtration,[48] adsorption,[49,51] and plant uptake[51] for phosphorus species[52] as well as aerobic and anaerobic biochemical transformations by soil bacteria for nitrogen species.[50] Reduced COD concentration reflects possible removal mechanisms including biodegradation, sorption to bioretention media, and plant uptake of organic compounds (likely sources being natural organic materials as well as petroleum hydrocarbons from carparks and the main road servicing the residential estate).[53]

The total mass of each of the 15 water quality parameters passing the inlet, culvert, and outlet during the six sampled events is shown in Table S-5.† The resultant net removal rate for each parameter is shown in Table 2. TSS has the highest mean removal rate of 52.8%, followed by ON (52.7%), TP (46%), and PO_4–P (45%). Although there is a net removal of TN of 25%, there is net export instead of removal of NO_2–N (−56%) which suggests incomplete denitrification. Although the presence of a saturated anoxic zone should improve nitrogen removal,[54] denitrification is found to occur mainly during dry periods.[55] The export of NO_x–N was also observed in other field studies.[19,56] Among the 15 parameters, three species (ON, TDP, and PO_4–P) show positive removal rates (6–80%, 4–66%, and 4–75% respectively) in all six events. COD removal rate (15%) is low although bioretention basins have been reported to be 85% or more effective in removing hydrocarbons (*e.g.* polycyclic aromatic hydrocarbons including naphthalene).[53,57]

3.2.2 Event removal rates. Basin performance is often assessed in terms of the removal rate of three water quality parameters: TSS, TN, and TP. Bioretention basins are

Table 2 Concentration (mg L^{-1}) of all samples collected during all the six events at the inlet, culvert, and outlet; event-specific removal rates (%); and influent EMCs (mg L^{-1}) for each of 15 water quality parameters

	Concentration (mg L^{-1})[a]						Removal rate (%)								Influent EMC (mg L^{-1})							
	Inlet		Culvert		Outlet																	
	Mean	SD	Mean	SD	Mean	SD	#3	#2	#1	#5	#6	#4	Mean	SD	#3	#2	#1	#5	#6	#4	Mean	SD
TN	2.45	1.93	1.76	1.42	0.61	0.48	68	58	35	10	−24	4	25	35	4.02	0.58	5.09	1.24	1.43	0.81	2.20	1.88
TKN	1.25	1.42	0.60	0.76	0.36	0.37	72	63	61	58	−46	12	37	46	3.07	0.39	4.13	0.36	0.18	0.30	1.41	1.74
ON	0.97	1.03	0.36	0.37	0.19	0.18	75	80	74	69	6	12	53	34	2.41	0.14	2.74	0.46	0.15	0.26	1.03	1.21
NH_3–N	0.48	0.62	0.24	0.43	0.17	0.28	61	−23	36	96	−120	12	10	76	0.66	0.26	1.39	0.10	0.05	0.04	0.42	0.53
NO_3–N	0.81	0.58	0.78	0.53	0.05	0.16	96	82	−55	−14	−31	−22	9	63	0.46	0.00	0.54	0.77	1.01	0.31	0.52	0.35
NO_2–N	0.08	0.12	0.04	0.08	0.05	0.11	98	69	−118	−234	−129	−25	−56	128	0.36	0.00	0.14	0.00	0.01	0.00	0.09	0.14
TP	0.20	0.17	0.11	0.04	0.04	0.01	73	75	69	33	−7	32	46	32	0.31	0.04	0.40	0.19	0.11	0.11	0.19	0.14
TDP	0.08	0.04	0.05	0.02	0.02	0.01	55	58	59	4	4	66	41	29	0.08	0.02	0.16	0.05	0.06	0.07	0.07	0.05
PO_4–P	0.06	0.04	0.04	0.02	0.01	0.01	66	54	60	10	4	75	45	30	0.04	0.02	0.12	0.05	0.05	0.05	0.05	0.03
TOP	0.04	0.05	0.02	0.01	0.01	0.01	74	74	64	−13	−15	2	31	44	0.13	0.01	0.08	0.02	0.01	0.02	0.05	0.05
TDOP	0.01	0.01	0.01	0.00	0.00	0.00	35	73	53	−65	−22	56	22	54	0.02	0.00	0.02	0.00	0.00	0.01	0.01	0.01
TPIP	0.10	0.13	0.05	0.02	0.01	0.01	73	83	77	51	−25	−7	42	47	0.14	0.01	0.20	0.11	0.04	0.04	0.09	0.07
TPOP	0.03	0.04	0.02	0.01	0.01	0.00	82	74	67	5	2	−70	27	59	0.11	0.00	0.06	0.02	0.01	0.01	0.03	0.04
TSS	45	64	23	12	2	2	92	91	86	31	−12	29	53	43	65	3	64	51	26	30	40	24
COD	57	74	32	20	24	15	55	60	56	22	−94	−8	15	60	104	20	80	59	22	38	54	34

[a] Total number of samples used is indicated in Table S-4.

typically designed with removal targets of 80–92% for TSS, 30–65% for TN, and 30–90% for TP.[28–34] Fig. 2 singles out removal rates of TN, TP, and TSS during individual events for closer evaluation. The removal rate and its associated uncertainty are computed according to eqn (2) and (S-2†), respectively.

The removal targets for TN, TP, and TSS are generally met only for small events (events #3, #2, and #1) but not for large events (events #5, #6, and #4) (Fig. 2). The mean removal rates for TN, TP, and TSS are 54%, 72%, and 90% respectively for small events, compared to −3%, 19%, and 16% for large events. For all three pollutants, as rainfall depth increases, removal rate generally decreases. This is mirrored by the upward trend seen in the fraction of culvert-overflow as event size increases. The high culvert-overflow fraction during large events reduces the removal rate since the overflowed portion of runoff failed to infiltrate and receive soil treatment. A noticeable drop in removal rate is seen in the transition from event #1 (3 month ARI) to event #5 (<1 year ARI) for all three parameters. This drop is especially evident in phosphorus species and TSS, which are predominantly in particulate form. These results point to an undersized basin with insufficient treatment efficiency.

EMC might play a role in affecting removal rate. Higher removal rates for TN and TP are observed when the influent

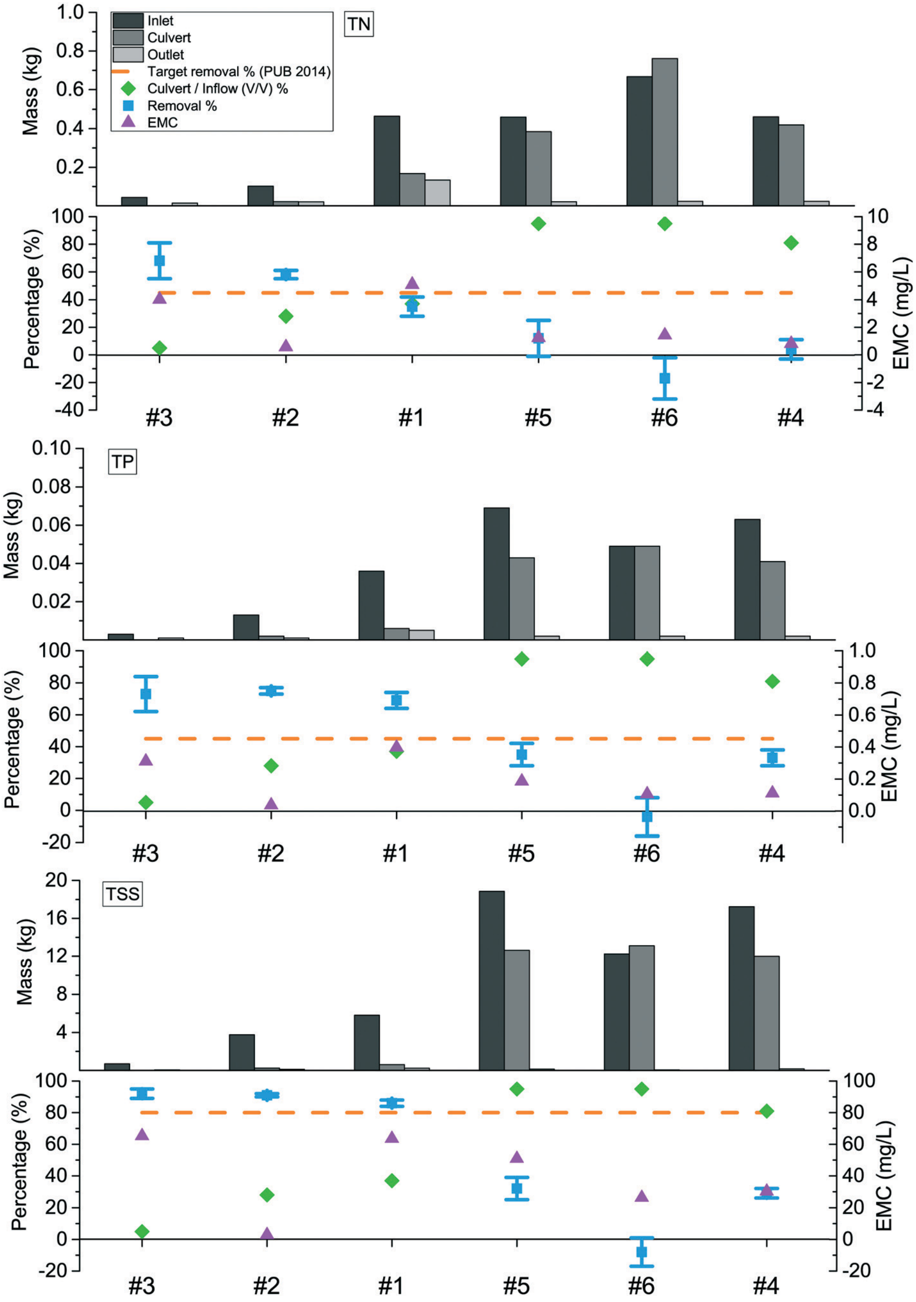

Fig. 2 Mass load (kg) at the inlet, culvert, and outlet; removal rate (%) with uncertainty calculated using eqn (S-2†); culvert flow volume as percentage of inlet flow volume; and EMC of each of the six sampled events for TN, TP, and TSS.

concentration is greater.[58] However, the extent of the effect of EMC could not be distinguished in this study (Fig. 2). Although all the large events with low EMC (events #4, #5, and #6) show low removal rates, a small event with a low EMC (event #2) still achieved a high removal rate since the majority of inflow was contained within the basin and received full treatment. Based on these results, a high culvert-overflow fraction appears to be the driver in reducing removal rate.

3.3 Water quality of influent

3.3.1 EMC of influent. The influent EMCs of 15 parameters for the six sampled events are shown in Table 2. TN, the most comprehensive measure of the nitrogen pollutant load, has a mean EMC of 2.20 mg L^{-1}. The majority of nitrogen comes into the basin in the form of ON (1.03 mg L^{-1}) which is the least available form and is most likely in particulate form. Some of the nitrogen load comes in as the dissolved and reduced form NH_3–N (0.42 mg L^{-1}) while the rest is in the oxidized dissolved forms of NO_3–N (0.52 mg L^{-1}) and NO_2–N (0.09 mg L^{-1}).

The EMCs of phosphorus species are in general lower than those of nitrogen species in the runoff. Most of the phosphorus exists in particulate form as the mean EMC of TP is 0.19 mg L^{-1} compared to 0.07 mg L^{-1} of TDP. Among the four phosphorus species analysed (TPIP, TPOP, PO_4–P, and TDOP), the inorganic phosphorus species exhibit higher EMCs than the organic species. Specifically, the dissolved (PO_4–P) and particulate (TPIP) inorganic phosphorus species have mean EMCs of 0.05 mg L^{-1} and 0.09 mg L^{-1} respectively. The dissolved (TDOP) and particulate (TPOP) organic phosphorus species have mean EMCs of 0.01 mg L^{-1} and 0.03 mg L^{-1} respectively.

A comparison between EMCs in this study and published data (Table S-6†) shows that EMCs are generally lower in the tropics than in temperate climates. The EMC of TSS (40 mg L^{-1}) found in this study is comparable to those in the literature for tropical studies but is 61–79% lower than those found in temperate studies. Similarly, the EMC of COD (54 mg L^{-1}) is lower by 18–46% (Table S-6†).

3.3.2 First flush of influent. Bioretention basins are typically designed in temperate countries with the expectation of capturing the first flush of runoff. However, given that rainfall in tropical climates tends to be frequent and intense, a strong first flush might not exist. Thus, the presence or absence of a strong first flush in an urban catchment in the tropics may be important to assessing whether a bioretention basin will perform as intended.

Fig. S-3† shows the event-wise cumulative-mass-cumulative-runoff curves of TSS, TN, and TP. Among the three parameters, TSS shows the most prominent first-flush phenomenon, followed by TP and TN. Table 3 uses established literature criteria to evaluate the presence of first flush for all the water quality parameters.[59–61] The parameters that most frequently exhibit first flush (in at least five out of six events) according to Geiger's[59] criterion are particulate forms (TN, TKN, ON, TP, TOP, TPIP, TPOP, TSS, and COD). Le and Chua[62] similarly see a stronger first flush for particulates than dissolved substances. TSS exhibits first flush in all events while TN, TKN, ON, TP, and TPIP exhibit first flush in all but the smallest event (#3). The dissolved species like NH_3–N, NO_3–N, TDP, PO_4–P, and TDOP exhibit first flush less frequently, in at most three out of six events. When more stringent criteria are used to assess the presence of first-flush behavior, fewer water quality parameters exhibit first flush during fewer events. Only ON exhibited first flush in as many

Table 3 Presence of first flush (FF) in the six events based on three criteria of different level of stringency[a]

	Geiger (1987) criterion: above bisector line						Deletic (1998) criterion: 40% mass in 20% volume						Bertrand-Krajewski (1998) criterion: 80% mass in 30% volume					
	#3	#2	#1	#5	#6	#4	#3	#2	#1	#5	#6	#4	#3	#2	#1	#5	#6	#4
TN		■	■	■	■	■						■						
TKN		■	■	■	■	■				■	■	■						
NH_3–N				■		■				■						■		
NO_3–N				■	■	■						■						
NO_2–N		■		■	■	■				■	■	■						
ON		■	■	■	■	■			■	■	■	■						
TP		■	■	■	■	■			■	■								
TDP			■						■									
PO_4–P			■						■									
TOP	■		■	■	■	■			■	■								
TDOP			■	■	■				■									
TPIP		■	■	■	■	■		■	■	■								
TPOP	■		■	■	■	■			■	■		■						
TSS	■	■	■	■	■	■		■		■								
COD	■		■	■	■	■			■	■		■						

[a] Shaded cells indicate the presence of FF and unshaded ones indicate the absence.

as four out of six events under Deletic's[60] criterion of 40% mass in 20% volume while the other parameters exhibit first flush in at most three out of six events. NH_3–N is the only parameter that exhibited first flush, and then in only one event, based on Bertrand-Krajewski *et al.*'s[61] criterion of 80% mass in 30% volume. Therefore, the first-flush phenomenon is not found to be prominent in this study if a stringent criterion is imposed.

3.4 Rainfall characteristics

The low removal rates seen in this study can be attributed to the distinct rainfall patterns of the tropics. Histograms and cumulative probability curves of rainfall characteristics observed during this study are shown in Fig. S-4.† A total of 96 storm events occurred during the eight month monitoring period of April–November 2013. The recorded rainfall tends to be heavy with 46% of the storms having a total rainfall >10 mm; 19% storms >30 mm; and 3% storms >70 mm. The storm events also tend to have short durations. Of the 96 events, the maximum event duration is 11 hours with 10% of the events <0.25 h; 50% <1.5 h; and 90% <6 h duration. Storms were frequent during the monitoring period and 42% of storms have an antecedent dry period (ADP) <1 day; 71% <2 days; and 99% <9 days. The mean rainfall intensity, event duration, and ADP are 7.49 mm h^{-1}, 2.8 h, and 2 days respectively (Table S-7†). These characteristics are all typical of a tropical climate, in which frequent, short, intense thunderstorms are the norm.

4 Discussion

4.1 Frequent heavy flushing in tropical catchment appears to lead to low inflow concentration

High-intensity rainfall events are less common in temperate climates than in the tropics. For instance, the 10 min peak rainfall intensities of the six sampled events in this study are below the 1 year ARI for Singapore (Table S-8†). However, if these tropical storms were to occur in temperate regions, they would be assigned higher ARIs (Table S-8†). For example, if events #4 and #5 were to occur in Seattle, they would be considered 100 year events.

The regular flushing of the Balam Estate catchment by frequent and intense storms appears to have led to reduced pollutant accumulation. Table 2 shows that the events (event #2, #6, #5, and #4) with either short ADP (*i.e.* recent flushing) or high rainfall depth tend to have lower EMCs compared to events (event #1 and #3) with long ADP (*i.e.* sufficient time for pollutant accumulation) and low rainfall depth (Table 1).

The high EMCs of the two long-ADP events (events #3 and #1) increase the overall mean EMC for each of the 15 water quality parameters (Table 2). Event #1 (25 June 2013) is unique because it was the first storm after a historically severe trans-boundary air pollution episode in Singapore. The air quality Pollutant Standards Index on 21 June 2013 surpassed the previous record in 1997. Coupled with a long ADP of 8.25 days, event #1 has the highest EMC for almost all of the parameters including TN, TKN, ON, NH_3–N, TP, TDP, PO_4–P, and TPIP. Event #3 is also unusual because it is a very small event (3.2 mm total rainfall) preceded by a very long ADP of 9.08 days (Table 1). Event #3 has the highest EMC of NO_2–N, TOP, TDOP, TPOP, TSS, and COD. Even with the two long-ADP high-EMC events, the overall mean EMCs in this study are low compared to temperate studies (Table S-6†).

4.2 Lack of storage capacity affects removal efficiency

Removal efficiency is an important assessment criterion for bioretention basins as it reflects the basin's performance in improving water quality. Results from this study demonstrate that performance of the bioretention basin in Singapore is sub-optimal for large storm events. The main reason is insufficient storage capacity which causes most runoff to bypass the basin with minimal treatment during large, but still common, storm events.

Comparison of three events (#2, #1, and #5) illustrates the need for greater storage capacity in tropical basins (Fig. 2). In event #2 (a small event of 8.0 mm), the storage capacity is sufficient since only 28% of the inflow exits the basin by culvert overflow (Table 1). As most of the inflow is soil-filtered and fully treated, a satisfactory removal rate is achieved (91%, 58%, and 75% for TSS, TN, and TP respectively, in Fig. 2 and Table 2). The removal targets of 80%, 45%, and 45% are also fully met. The rainfall characteristics of event #2 (8.0 mm of total rainfall, 32 min of event duration, and 2.06 days of ADP, in Table 1) lie close to the median storm characteristics observed in this study (8.2 mm of total rainfall, 1.5 hours of event duration, and 1 day of ADP, in Fig. S-4†) and the basin is able to treat these smaller storms adequately. This shows that a tropical basin can perform acceptably when adequately sized.

Event #1 is similar in rainfall depth (10.2 mm) to event #2 but has a significantly higher EMC (Table 2) and load (Fig. 2, Table S-5†) due to the severe haze during the ADP of 8.25 days. The basin storage capacity is sufficient to retain 63% of the inflow (Fig. 2). Despite the higher loading, the removal targets are still generally met and within expectations (86%, 35%, and 69% for TSS, TN and TP respectively, in Fig. 2, Table 2). Therefore, removal targets are still achievable for a heavily-polluted storm if sufficient storage capacity is provided. Hence, the inherent pollutant removal mechanism in a sufficiently-sized basin is not the limiting factor in affecting removal rates.

In contrast to events #2 and #1, event #5 is a large event (29.4 mm of rainfall). Storage capacity is insufficient for event #5 since almost all of the inflow (95%) exits the basin by culvert overflow (Fig. 2). Hence, the removal rates for event #5 are below targets (31%, 10%, and 33% for TSS, TN, and TP respectively, in Fig. 2 and Table 2). However, events of such rainfall depth are not uncommon in Singapore as 19% of the events in this study have >30 mm of rainfall (Fig. S-4†).

Extrapolating from the hydrological performance of events during the monitoring period, at the current storage capacity, the Balam Estate Rain Garden would not be able to meet pollutant removal targets during many events (Fig. 3). The transition between the sampled events that meet removal targets and those that do not occurs at a rainfall depth between 10 mm and 30 mm. Based on the cumulative probability curve of rainfall amount in Fig. S-4,† this range of rainfall depth translates to 19% (>30 mm events) to 46% (>10 mm events) of events. Therefore, at the current storage capacity, as many as 46% of the events during this monitoring period would not have met pollutant removal targets.

A comparison between mean removal rates in this study and published data for basins under various climate conditions and configurations (Table 4) shows that removal of TSS in this basin is lower while TN and TP are within observed ranges. The rates for TN and TP in this study are close to those found by Brown and Hunt[14] for undersized basins, which highlights the adverse effect of overflow on removal rates. Li and Davis[16] similarly noted the close relationship between hydrologic and water quality performance. Ong *et al.*'s[27] study at the same site yields higher removal rates than this study, however, they used a different definition of removal rate. In particular, they did not deduct culvert mass load from inlet mass load in eqn (2), thus treating culvert mass bypass as removal too. Further studies need to be conducted to determine the removal efficiencies of basins in other tropical regions. In Europe, the bioretention basin is considered a green sustainable urban drainage system (SUDS) and Dierkes *et al.*[34] reported that SUDS as a group was able to achieve removal of 50–90% of TSS, 30–60% of TP, and 10–40% of TN.

The presence of a saturated internal water storage zone (IWS) seems to enhance denitrification and TN removal. An IWS not only provides additional storage volume and increases hydraulic retention time, it also provides an anoxic environment which promotes denitrification. In all basins with IWS cited in Table 4, but not in this study, the general target of >30% removal of TN is achieved. In contrast, only 55% of the bioretention basins without IWS are able to meet the target.

The removal rate of TP shows more variability than TN and TSS. A larger deviation in removal rates is seen across various studies (Table 4). In several studies, export of TP is observed and this could be attributed to leaching of P from the bioretention media itself which often consists of mulch and other organic matter. For effective P removal, soil media with high cation exchange capacity and low P-index has been recommended.[63]

Although TSS removal in this study (53%) is the lowest among all the studies in Table 4, it has the highest mean removal rate among the water quality parameters assessed in this study. Li and Davis[64] note that as soil media capture TSS, finer particles become trapped in the upper layer leading to media stratification and reduced hydraulic conductivity. This could partially explain the reduction in TSS removal in this study (five years after construction) compared to Ong's[27] (one year).

4.3 Design guidelines for sizing bioretention basins in the tropics need to be revised

Bioretention basins were originally designed based on studies done and experience gathered in temperate places. Current design guidelines in the tropics are adopted from those developed for temperate climates. As discussed above, in Singapore the basin size or WQV is based on water quality performance predicted by design curves generated using MUSIC, a model developed based on studies done in Australia.[31,39] Following after Australia, basins in Singapore are also designed to treat a critical design flow rate equivalent to the

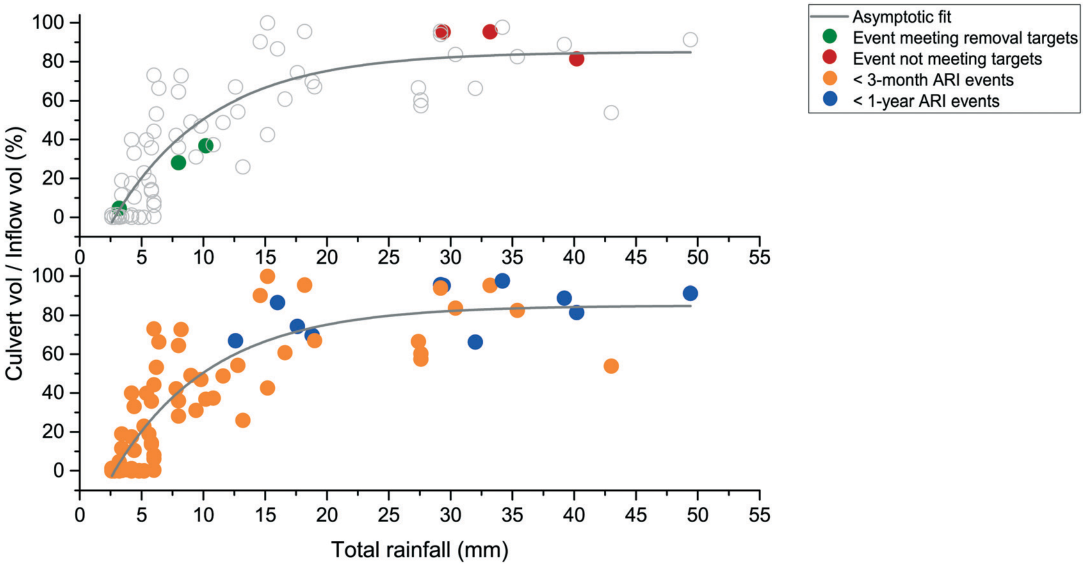

Fig. 3 Culvert discharge volume as percentage of total inflow volume, highlighting the water quality performance of the six sampled events (top) and categorization of events in the monitoring period into <3 month and <1 year ARI events (bottom) (adapted from Wang *et al.*[46]).

Table 4 Comparison of pollutant removal rates in this study to literature values for bioretention basins

	Köppen climate classification		Location	Media	Saturated zone present?	TN	TP	TSS
This study	Tropical	Af	Singapore	Sandy loam, fine sand, wood chip and hard rocks	Yes	25%	46%	53%
Ong *et al.*[27]	Tropical	Af	Singapore	Sandy loam, fine sand, wood chip and hard rocks	Yes	64%	51%	73%
Brown and Hunt[13]	Temperate	Cfa	USA, North Carolina	Sandy clay loam	Yes	88%	85%	95%
Brown and Hunt[13]	Temperate	Cfa	USA, North Carolina	Sand	Yes	99%	99%	99%
Brown and Hunt[14]	Temperate	Cfa	USA, North Carolina	Loamy sand (0.6 m)	No	12%	5.3%	71%
Brown and Hunt[14]	Temperate	Cfa	USA, North Carolina	Loamy sand (0.9 m)	No	13%	44%	84%
Passeport *et al.*[15]	Temperate	Cfa	USA, North Carolina	Expanded slate fines, sand, organic matter (south cell)	Yes	56%	58%	
Passeport *et al.*[15]	Temperate	Cfa	USA, North Carolina	Expanded slate fines, sand, organic matter (north cell)	Yes	47%	63%	
Li and Davis[16]	Temperate	Cfa	USA, Maryland	Sandy loam (college park cell)	No	−3%	−36%	96%
Li and Davis[16]	Temperate	Cfa	USA, Maryland	Sandy clay loam (silver spring cell)	No	97%	100%	99%
DeBusk and Wynn[10]	Temperate	Cfa	USA, Virginia	Medium sand, clay, silt fines, leaf compost	Yes	99%	99%	99%
Dietz and Clausen[18]	Temperate	Cfa	USA, Connecticut	Loamy sand, shredded hardwood bark mulch.	No	32%	−111%	
Dietz and Clausen[17]	Temperate	Cfa	USA, Connecticut	Loamy sand, shredded hardwood bark mulch	Yes	69%	−98%	
Trowsdale and Simcock[21]	Temperate	Cfb	New Zealand	Topsoil (pumice sand, horticultural soils), subsoil (clay and weathered limestone)	No			90%
Hatt *et al.*[19]	Temperate	Cfb	Australia, Victoria	Cell 1: sandy loam, cell 2: sandy loam, vermiculite, perlite, cell 3: sandy loam, compost, hardwood mulch	No	−7 ± 72%	−398 ± 559%	76 ± 25%
Hatt *et al.*[19]	Temperate	Cfa	Australia, Queensland	Sandy loam	No	37 ± 21%	86 ± 3%	93 ± 4%
Mangangka *et al.*[20]	Temperate	Cfa	Australia, South East Queensland		No	48 ± 31%[a] 39 ± 33%[b]	75 ± 14%[a] 36 ± 37%[b]	81 ± 8%[a] 62 ± 25%[b]
Houdeshel *et al.*[22]	Semi-arid/ continental	BSk/Dfa	USA, Utah	Top soil (sand, silt, clay) (wetland cell)	No	59%	55%	
Houdeshel *et al.*[22]	Semi-arid/ continental	BSk/Dfa	USA, Utah	Top soil (sand, silt, clay) (upland cell)	No	22%	60%	
Géhéniau *et al.*[23]	Cold (continental)	Dfb	Canada, Québec	Coarse sand (sand, silt, clay)	Yes		−65.3%[c]	74.5%[c]
Khan *et al.*[24]	Cold (continental)	Dwb	Canada, Alberta	Sandy loam	No	92%	95%	99%

[a] Long dry period. [b] Short dry period. [c] Only changes in concentration are reported.

3 month ARI storm (PUB 2014).[31] The performance of Balam Estate Rain Garden, as shown in this study, does not meet the pollutant removal rates forecasted for large but still common storm events (Fig. 2). These results suggest that design guidelines and sizing curves developed for temperate settings cannot simply be transferred to tropical regions. Rather, there is a need to develop design guidelines specifically for tropical applications.

4.3.1 WQV or WQD is a better parameter for sizing basins than ARI in the tropics. This study recommends that design guidelines for the tropics be given in terms of the more definitive quantity, WQV or WQD, instead of ARI.

ARI is an inferior design parameter because it covers a wider spectrum of events with different combinations of intensity and duration and thus includes distinctly different rainfall depths. Singapore's IDF curves show that the 3 month ARI corresponds to an approximate range of 5 to 35 mm of rain.[65] A 3 month ARI event could be intense and short (*e.g.* event #1) or mild and long (*e.g.* event #6). The term, ARI, fails to distinguish events such as these even though they generate vastly different runoff amounts. For instance, events with rainfall depth >12 mm could be either <3 month ARI or <1 year ARI and they lead to vastly different culvert overflow rates (Fig. 3). Thus, events that are mild in rainfall intensity but high in rainfall depth (*e.g.* event #6) could still exceed the basin capacity and fail to meet removal targets.

ARI is ambiguous in describing events in the tropics because a modest increase in ARI can lead to a more significant increase in rainfall intensity in the tropics than in temperate regions. Fig. S-5† compares the 10 min rainfall intensity of events of various ARIs in Singapore, Melbourne, and selected cities in the U.S. The 10 min rainfall intensity in Singapore is higher than that of temperate regions in the U.S. and is similar to that of the sub-tropical city of Miami. In this study, storms that are only slightly higher in ARI terms (events #4 and #5) are in fact much more intense and generate much higher runoff volumes (Table 1).

Since ARI is not fully definitive, it fails to pinpoint a definite runoff volume (WQV) that needs to be retained in order to achieve the desired removal rate. However, this is the volume that ultimately determines bioretention basin performance. As demonstrated in this study, in tropical events of slightly higher ARI, the higher runoff volume results in a sharp drop in removal rates (Fig. 2, Table 2). Therefore, WQV is a better parameter for sizing bioretention basins than ARI in the tropics.

4.3.2 Recommended value of WQV or WQD for the tropics. Based on water quality considerations, this study recommends a WQD range of 10–30 mm. This is the same as that recommended by Wang *et al.*[46] based on a hydrological analysis of 80 events (Fig. 3). The exact amount of runoff (WQV or WQD) that needs to be retained for a tropical catchment in order to meet removal targets requires further analysis based on hydrologic and water quality modeling. In the U.S., Roesner *et al.*[37] found that capturing a WQD of one inch (25.4 mm) of runoff is sufficient to capture 90% of the annual runoff in a broad cross sample of U.S. cities. However, from results of this study, if Singapore were also to capture 90% of annual runoff, a WQD of about 32 mm would be required. This equates to a WQV of 540 m^3 for the Balam Estate Rain Garden, which is about 16 times the volume of the current basin (33 m^3). Basins of this size would be difficult to site in land-limited urban catchments. Therefore, other strategies to increase storage volume would need to be explored or pollutant removal targets would need to be re-evaluated. Alternatively, as Strecker *et al.*[66] point out, a maximum effluent concentration instead of removal targets could be imposed for basin discharges. In contrast to concentration targets, removal percentages can underestimate basin effectiveness in the case of cleaner influent.

5 Conclusions

Performance of the first bioretention basin in Singapore was assessed based on 96 storms, of which 80 storms yielded useful recorded flow data and six storms were sampled for 15 water quality parameters using a discrete time-based sampling strategy. A combination of hydraulic data and rainfall-runoff characteristics was used to assess system performance in a tropical setting and recommend practical engineering strategies to design and manage bioretention basins in the tropics. The following may be concluded from this study:

1. The Balam Estate Rain Garden is very effective in reducing peak flow rate (mean $R_{\text{peak}} = 0.06$) but is not effective in delaying peak timing (mean $R_{\text{delay}} = 3.3$) and reducing hydrologic volume *via* runoff storage and holdup (mean $f_{V24} = 1.08$). The ponding duration is 12.5 ± 5.5 h and the estimated infiltration rate based on statistics of 59 overflow events is 1.7 cm h^{-1}. This implies that the unsaturated zone is likely to stay saturated under a ponding condition. Under an unsaturated condition, the mean gravity drainage rate is 0.3 cm h^{-1}.

2. The Balam Estate Rain Garden is able to improve water quality. Higher removal is seen at the outlet when runoff is allowed to filter through the soil media than if it overflows *via* the culvert. The highest mean removal rate of 53% was seen in TSS. The dissolved specie NO_2–N most often showed net export instead of removal (mean removal of −56%). This might suggest extensive nitrification but incomplete denitrification within the soil media. ON, TDP, and PO_4–P show positive removal rates in all six events.

3. In terms of event-specific removal rates, removal targets for TN, TP, and TSS are generally met only for events with small rainfall depths (events #3, #2, and #1) and not for those with greater rainfall depths (events #5, #6, and #4). The mean removal rates for TN, TP, and TSS are 54%, 72%, and 90% respectively for small events, compared to −3%, 19%, and 16% for large events. A lack of storage capacity and resulting high culvert overflow is the main driver in reducing removal efficiency for large, but still common, storm events. The transition from efficient to non-efficient treatment occurs at a rainfall depth between 10 and 30 mm. At the current storage capacity, the basin performance during as many as 46% of

the events in this monitoring period would not meet the pollutant removal targets.

4. The range of influent EMCs observed in this study are comparable to those in tropical catchments presented in the literature but are lower than temperate counterparts. The frequent and intense rainfall of the tropical climate likely leads to lower EMCs than in temperate climates. The first-flush phenomenon of the influent is not found to be prominent if a stringent criterion is imposed. Low influent EMC and weak first flush appear to contribute to low pollutant removal rate. Further research is required to confirm this.

5. There is a need to revise design guidelines for sizing bioretention basins in tropical catchments. This study recommends design guidelines in the tropics be specified in terms of the more definitive quantity WQV or WQD instead of ARI. A larger basin storage volume (WQD in the range of 10 to 30 mm) is needed in the tropics in order to treat the intense but common events in the tropics.

Study impact and future work

Results from this study could be of use to water resource managers who are utilizing bioretention basins and other BMPs to improve the water quality of stormwater runoff in a similar tropical climate setting. Basin designers should especially take high-rainfall-depth events into consideration when sizing for tropical bioretention basins since they tend to produce basin bypass which leads to poor pollutant removal efficiency. The exact amount of runoff (WQV or WQD) that needs to be retained in order to meet removal targets requires additional research employing long-term water quality and hydrological models that are specific to bioretention basins. The long-term, continuous, high-resolution, and complete hydrographs and pollutographs available from this study can serve as sources of observed measurements for calibration and validation of such models.

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References

1 B. He, Y. Wang, K. Takase, G. Mouri and B. H. N. Razafindrabe, *Water Resour. Manage. Ser.*, 2009, **23**, 1863–1873.

2 O. V. Barron, M. J. Donn and A. D. Barr, *Water Resour. Manage. Ser.*, 2013, **27**, 95–115.

3 U. S. EPA, *Low impact development (LID): A literature review, Report EPA-841-B-00-005*, U.S. Environmental Protection Agency, Washington, D.C., USA, 2000.

4 E. S. Bedan and J. C. Clausen, *J. Am. Water Resour. Assoc.*, 2009, **45**, 998–1008.

5 Z. M. Xuan, N. B. Chang, M. P. Wanielista and E. S. Williams, *J. Environ. Qual.*, 2013, **42**, 1086–1099.

6 *Prince George's County, Bioretention Manual*, Prince George's County (MD) Government, Department of Environmental Protection, Watershed Protection Branch, Landover, MD, 2002.

7 A. P. Davis, W. F. Hunt, R. G. Traver and M. Clar, *J. Environ. Eng.*, 2009, **135**, 109–117.

8 W. F. Hunt, J. T. Smith, S. J. Jadlocki, J. M. Hathaway and P. R. Eubanks, *J. Environ. Eng.*, 2008, **134**, 403–408.

9 A. Roy-Poirier, P. Champagne and Y. Filion, *J. Environ. Eng.*, 2010, **136**, 878–889.

10 K. M. DeBusk and T. M. Wynn, *J. Environ. Eng.*, 2011, **137**, 800–808.

11 S. H. Zhang and Y. P. Guo, *Water Resour. Manage. Ser.*, 2014, **28**, 149–168.

12 S. Tang, W. Luo, Z. Jia, W. Liu, S. Li and Y. Wu, *Water Resour. Manage. Ser.*, 2016, **30**, 983–1000.

13 R. A. Brown and W. F. Hunt, presented in part at the *World Environmental and Water Resources Congress 2011*, 2011.

14 R. A. Brown and W. F. Hunt, *J. Irrig. Drain. Eng.*, 2011, **137**, 132–143.

15 E. Passeport, W. F. Hunt, D. E. Line, R. A. Smith and R. A. Brown, *J. Irrig. Drain. Eng.*, 2009, **135**, 505–510.

16 H. Li and A. P. Davis, *J. Environ. Eng.*, 2009, **135**, 567–576.

17 M. E. Dietz and J. C. Clausen, *Environ. Sci. Technol.*, 2006, **40**, 1335–1340.

18 M. E. Dietz and J. C. Clausen, *Water, Air, Soil Pollut.*, 2005, **167**, 123–138.

19 B. E. Hatt, T. D. Fletcher and A. Deletic, *J. Hydrol.*, 2009, **365**, 310–321.

20 I. R. Mangangka, A. Liu, P. Egodawatta and A. Goonetilleke, *J. Environ. Manage.*, 2015, **150**, 173–178.

21 S. A. Trowsdale and R. Simcock, *J. Hydrol.*, 2011, **397**, 167–174.

22 C. D. Houdeshel, K. R. Hultine, N. C. Johnson and C. A. Porneroy, *Landsc. Urban Plan.*, 2015, **135**, 62–72.

23 N. Géhéniau, M. Fuamba, V. Mahaut, M. R. Gendron and M. Dugué, *J. Irrig. Drain. Eng.*, 2015, **141**, 04014073.

24 U. T. Khan, C. Valeo, A. Chu and B. van Duin, *Can. J. Civ. Eng.*, 2012, **39**, 1222–1233.

25 L. Y. Lee, L. Tan, W. Wu, S. K. Q. Yeo and S. L. Ong, *Sustainable Environ. Res.*, 2013, **23**, 85–92.

26 H. W. Goh, N. A. Zakaria, T. L. Lau, K. Y. Foo, C. K. Chang and C. S. Leow, *Urban Water J.*, 2015, 1–9.

27 G. S. Ong, G. Kalyanaraman, K. L. Wong and T. Wong, presented in part at the *7th International Conference on Water Sensitive Urban Design*, Melbourne Cricket Ground, Melbourne, Australia, 2012.

28 Massachusetts Department of Environmental Protection, *Stormwater Management Standards and Structural BMP specifications, Massachusetts stormwater handbook*, Massachusetts Department of Environmental Protection, Boston, Massachusetts, USA, 2008.

29 New Hampshire Department of Environmental Services, *New Hampshire stormwater manual, Vol 2*, New Hampshire

Department of Environmental Services, Watershed Assistance section, Concord, New Hampshire, USA, 2008.

30 Minnesota Pollution Control Agency, *Minnesota stormwater manual, version 2*, Minnesota Stormwater Steering Committee, Minnesota Pollution Control Agency, St. Paul, Minnesota, USA, 2008.

31 Public Utilities Board of Singapore, *Chapter 7, Bioretention basins, Engineering procedures for ABC waters design features*, Public Utilities Board of Singapore, 2014.

32 Department of Irrigation and Drainage, *Urban stormwater management manual for Malaysia*, Department of Irrigation and Drainage Malaysia, Kuala Lumpur, Malaysia, 2nd edn., 2011.

33 Brisbane City Council, *Water sensitive urban design technical design guidelines for South East Queensland. Version 1*, Brisbane City Council and the Moreton Bay Waterways and Catchments Partnership, Brisbane, Australia, 2006.

34 C. Dierkes, T. Lucke and B. Helmreich, *Sustainability*, 2015, 7, 3031.

35 WEF and ASCE, *Design of urban stormwater controls. Water Environment Federation Manual of Practice No. 23, American Society of Civil Engineers Manual and Report on Engineering Practice No. 87*, New York, 2012.

36 V. Novotny, *Nonpoint pollution and urban stormwater management*, Technomic Publishing Company, Lancaster, Pennsylvania, USA, 1995.

37 L. Roesner, E. Burgess and J. Aldrich, presented in part at the *Water Resources Planning and Management and Urban Water Resources 18th Annual Conference and Symposium*, New Orleans, Louisiana, US, May 20–22, 1991.

38 Upper Parramatta River Catchment Trust, *Water sensitive urban design technical guidelines for Western Sydney*, Upper Parramatta River Catchment Trust, Parramatta, NSW, Australia, 2004.

39 Cooperative Research Centre for Catchment Hydrology, *Model for urban stormwater improvement conceptualisation (MUSIC) user guide*, Cooperative Research Centre for Catchment Hydrology, version 2.0 edn., 2003.

40 Australian Capital Territory Planning & Land Authority, *Waterways water sensitive urban design general code, Report NI2008–27*, Australian Capital Territory Planning & Land Authority, Canberra, Australia, 2008.

41 E. Eriksson, A. Baun, L. Scholes, A. Ledin, S. Ahlman, M. Revitt, C. Noutsopoulos and P. S. Mikkelsen, *Sci. Total Environ.*, 2007, **383**, 41–51.

42 Facility for Advancing Water Biofiltration, *Adoption guidelines for stormwater biofiltration systems*, Facility for Advancing Water Biofiltration, Monash University, Melbourne, Australia, 2009.

43 E. Driscoll, G. Palhegyi, E. Strecker and P. Shelley, *Analysis of storm event characteristics for selected rainfall gages throughout the United States, Report EPA-800-D-89-001*, U.S. Environmental Protection Agency, Washington, D.C., USA, 1989.

44 APHA, AWWA and WPCF, *Standard methods for the examination of water and wastewater*, American Public Health Association, Washington, D.C., USA, 21st edn., 2009.

45 A. P. Davis, *J. Hydrol. Eng.*, 2008, **13**, 90–95.

46 J. Wang, L. H. C. Chua and P. Shanahan, presented in part at the *3rd International Conference on Design, Construction, Maintenance, Monitoring and Control of Urban Water Systems*, *WIT Transactions on The Built Environment*, Urban Water 2016, San Servolo, Venice, Italy, June 27–29, 2016, vol. 165, pp. 177–188.

47 A. Roy-Poirier, P. Champagne and Y. Filion, *Environ. Rev.*, 2010, **18**, 159–173.

48 J. Y. Liu and A. P. Davis, *Environ. Sci. Technol.*, 2014, **48**, 607–614.

49 W. C. Lucas and M. Greenway, *J. Irrig. Drain. Eng.*, 2011, **137**, 144–153.

50 X. L. Chen, E. Peltier, B. S. M. Sturm and C. B. Young, *Water Res.*, 2013, **47**, 1691–1700.

51 C. Henderson, M. Greenway and I. Phillips, *Water Sci. Technol.*, 2007, **55**, 183–191.

52 D. J. Sample, T. J. Grizzard, J. Sansalone, A. P. Davis, R. M. Roseen and J. Walker, *J. Environ. Manage.*, 2012, **113**, 279–291.

53 G. H. LeFevre, K. H. Paus, P. Natarajan, J. S. Gulliver, P. J. Novak and R. M. Hozalski, *J. Environ. Eng.*, 2015, 04014050.

54 Y. Zinger, G. T. Blecken, T. D. Fletcher, M. Viklander and A. Deletic, *Ecol. Eng.*, 2013, **51**, 75–82.

55 D. Subramaniam, P. Mather, S. Russell and J. Rajapakse, *J. Environ. Eng.*, 2016, 04015090.

56 D. E. Line and W. F. Hunt, *J. Irrig. Drain. Eng.*, 2009, **135**, 217–224.

57 C. J. Diblasi, H. Li, A. P. Davis and U. Ghosh, *Environ. Sci. Technol.*, 2009, **43**, 494–502.

58 J. K. McNett, W. F. Hunt and A. P. Davis, *J. Environ. Eng.*, 2011, **137**, 790–799.

59 W. F. Geiger, presented in part at the *IV International Conference on Urban Storm Drainage, XXII Congress International Association for Hydraulic Research*, Topics in Urban Storm Water Quality, Planning and Management, Lausanne, Switzerland, August 31–September 4, 1987.

60 A. Deletic, *Water Res.*, 1998, **32**, 2462–2470.

61 J.-L. Bertrand-Krajewski, G. Chebbo and A. Saget, *Water Res.*, 1998, **32**, 2341–2356.

62 S. H. Le and L. H. C. Chua, presented in part at the *13th International Conference on Urban Drainage*, Sarawak, Malaysia, September 7–12, 2014.

63 W. F. Hunt, A. R. Jarrett, J. T. Smith and L. J. Sharkey, *J. Irrig. Drain. Eng.*, 2006, **132**, 600–608.

64 H. Li and A. P. Davis, *J. Environ. Eng.*, 2008, **134**, 409–418.

65 Public Utilities Board of Singapore, *Code of practice on surface water drainage. 6th ed. with amendments under addendum no.1*, Public Utilities Board of Singapore, 2011.

66 E. W. Strecker, M. M. Quigley, B. R. Urbonas, J. E. Jones and J. K. Clary, *J. Water Resour. Plan. Manage.*, 2001, **127**, 144–149.