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Determination of stormwater first flush treatment strategies at tropical urban catchments

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ABSTRACT

This study was conducted to determine the first flush magnitude and treatment strategies of stormwater pollutants at tropical urban catchments. Stormwater samples were manually grabbed and the flow rates were measured during 52 storm events at residential, commercial and industrial catchments. The mass based first flush (MBFF) ratio was used to quantify the first flush magnitude of stormwater pollutants. The treatment effectiveness factor [$E(v)$] was determined in order to identify the treatment strategies for first flush runoff volume at different urban land uses. The results showed that commercial catchment has the strongest MBFF for BOD, COD, TSS, NO_3–N and SRP. Residential catchment showed the highest MBFF for NH_3–N and Zn while industrial catchment exhibited the highest MBFF for O&G, TP and NO_2–N. The study found that treating the first 10% of runoff volumes can remove most of the pollutant loadings for NH_3–N, SRP, TP and Zn at residential and commercial catchments. Meanwhile, majority of the stormwater pollutants at industrial catchment could only be treated effectively in the first 30%–50% of runoff volumes.

Keywords: Event mean concentration; Mass based first flush; Stormwater; Treatment strategy; Tropical urban catchment

1. Introduction

Developing countries in Southeast Asia are experiencing rapid urban development and industrialization processes due to population and economic growth in the recent decades [1]. Increasing urban areas with high imperviousness surface has promotes the build-up of various pollutants that readily to be flushed away into the drainage system during storm event [2,3]. The non-point source (NPS) pollution due to urban stormwater runoff has degraded the quality of receiving water body significantly [4–7]. The stormwater pollution in urban cities is of great concern nowadays and many efforts have to be carried out in order to control this alarming situation. Since it is not possible to design and construct best management practices (BMPs) that can treat all of the stormwater runoff from urban catchment for every storm event, there must be cost-effective alternative treatment strategies for urban stormwater runoff. Many researchers in various countries have found high concentration in stormwater runoff at the early part of storm event which also known as first flush phenomenon [8–13]. The existence of a first flush may present alternative opportunities for stormwater pollutant reduction strategies. In order to effectively quantify the first flush runoff volume, different definitions have been proposed by various researchers from different countries based on a threshold ratio of percentage of cumulative pollutant mass over percentage of cumulative runoff volume (%M /%V). For examples, 40–60/25 [14]; 40/20 [15]; 50/25 [2]; 80/30 [16] and 80/20 [17] of M/V ratios were applied. These mass based first flush (MBFF) ratio can help the stormwater manager to design a cost effective capacity of BMPs facilities [5,18,19]. This is mainly because of the treatment cost for

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stormwater BMP is more dependent on the runoff volume to be treated than the contaminant concentrations. It was also found out that the removal efficiency of BMP facilities is always greater at higher concentration of stormwater pollutant [20]. Successful treatment of first flush runoff volume by BMPs structures will definitely reduce the stormwater pollution at urban cities [21,22].

The evaluation of MBFF for stormwater pollutant can be influenced by many factors including catchment characteristics [23,24], imperviousness area [5,8,24–26], land use [27–31], mean rainfall intensity [15,23,24,32], maximum rainfall intensity [15,33–35], antecedent dry day [5,33,35–37], and rainfall duration [33,34]. Although, studies on first flush effect of urban stormwater runoff have started over the past two decades, only very limited studies have been carried out in the tropical regions. This issue is especially important for developing countries in the tropics because of the rapid urban development processes and the rainfall pattern and distribution are totally different from those in the temperate countries. Short and intense storms which are common in the tropics tend to produce highly polluted runoff at the beginning of a storm event. Therefore, better understanding of this first flush effect could provide important information to design the BMP facilities for urban stormwater pollution control. Thus, the objectives of this study were 1) to identify the MBFF ratios for selected stormwater quality parameters; and 2) to determine the treatment strategies for treating the first flush runoff volume at different urban land uses.

2. Materials and methods

2.1. Study sites

Three different urban catchments located in Skudai, Johor Bahru, Malaysia, namely residential, commercial and industrial land uses were selected as the study sites (Fig. 1). This study area has a typical tropical climate with a mean annual temperature of 30ºC and mean annual rainfall of 2481 mm. The catchment area for residential, commercial and industrial sites is 32.77 ha, 34.21 ha and 4.38 ha, respectively. The percentage of impervious surface is estimated as 85% for residential catchment, 95% for commercial catchment and 93% for industrial catchment. The residential catchment has an underground stormwater drainage system whereas the commercial and industrial catchments have open channel systems. None of these catchments has wastewater treatment plant within it, thus the effect of land use could be easily singled out. All the study catchments are located within 3 km from the water quality analysis laboratory in University of Technology Malaysia. Thus, the sampling personnel were able to reach the sampling sites for stormwater samples collection prior to the beginning of

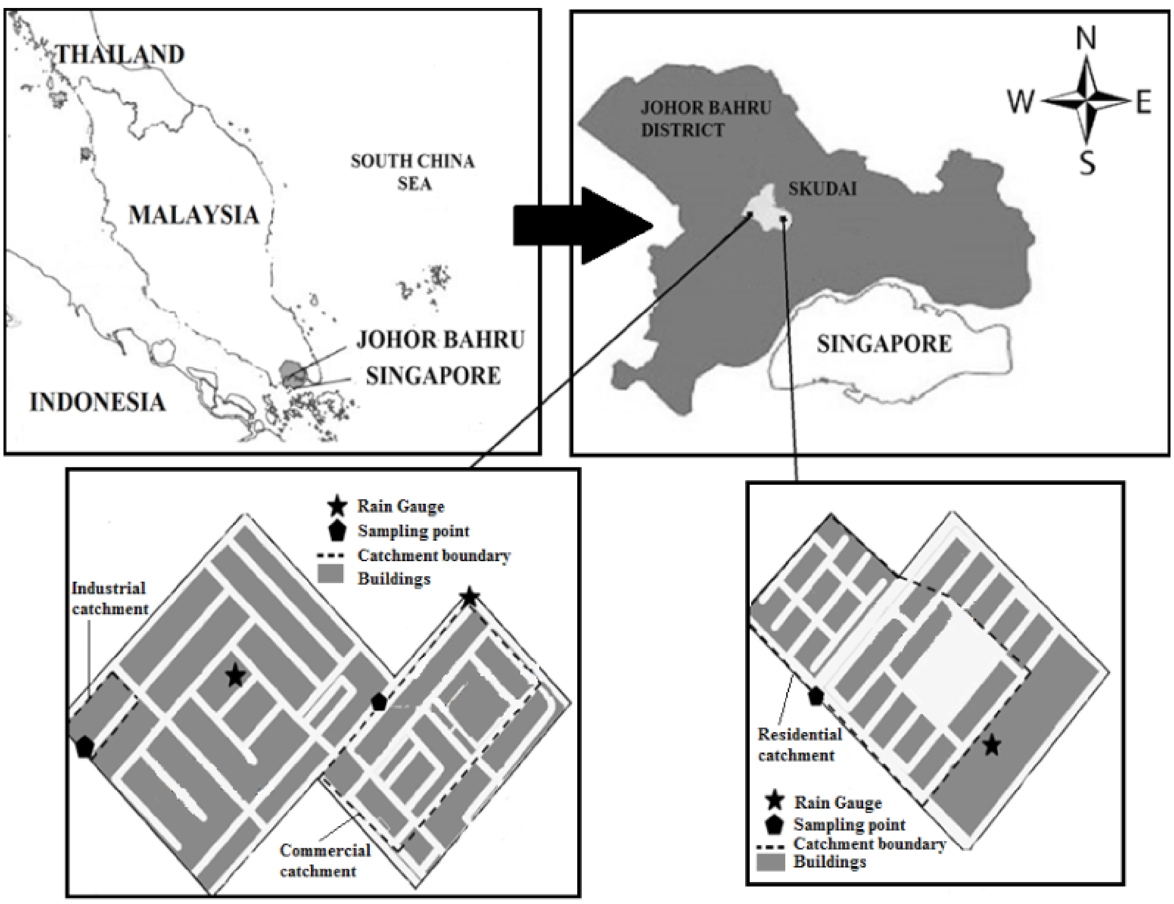


Fig. 1. The locations of studied catchments and sampling points for stormwater runoff.

storm event. The characteristic for each studied catchment is summarized in Table 1.

2.2. Stormwater samples and flow measurements

The rainfall data was measured by a HOBO tipping bucket rain gauge (Model RG3) with resolution of 0.2 mm in each catchment during the monitoring period. The water level of stormwater runoff was measured and converted into flow rate by using the stage-discharge rating curve that developed earlier at each sampling site. Stormwater samples were manually grabbed by using 1 L polyethylene bottles at the catchment outlet. Manual grab sampling technique is preferred due to inappropriate sampling of oil and grease (O&G) by automatic sampler [38]. The sampling was commenced at 1–10 min interval when the water level started to rise and 10–20 min interval on the falling limb of the hydrograph. More samples were collected on the rising limb in order to minimize the risk of missing the peak concentration of pollutants. Between eight and fifteen samples were collected during each storm event. This sampling protocol was followed according to the guidelines recommended by Caltrans [39]. The water quality parameters such as total suspended solids (TSS), biochemical oxygen demand (BOD), chemical oxygen demand (COD), O&G, nitrate-nitrogen (NO_3–N), nitrite-nitrogen (NO_2–N), ammonia-nitrogen (NH_3–N), soluble reactive phosphorus (SRP), total phosphorus (TP) and zinc (Zn) were analyzed for each stormwater sample by following the standard methods for the examination of water and wastewater [40]. The TSS concentrations were analyzed according to Standard Method 2540B [40] by filtering sample aliquots through pre-weighted glass fiber filters (Whatman GF/A filter), dried at 105° for 1 h and weighed again (detection limit of 5 mg/L). The filtered samples were analyzed for PO_4, NO_3–N, NO_2–N and NH_3–N using HACH DR5000 spectrophotometer (detection limit of 0.001 mg/L for NO_2–N, 0.01 mg/L for NO_3–N, NH_3–N and PO_4) by following standard methods of 4500 P.E, 4500 B, 4500 B, and 4500 F, respectively [40]. The unfiltered samples were analyzed for TP using the potassium persulfate digestion method followed by PO_4 analysis as described above. The water quality parameters of BOD, COD, O&G and Zn were analyzed based on the standard methods of 5210B, 5220B, 5520B and 3120 B respectively [40].

Table 1
Characteristics of the studied urban catchments

Site	Residential	Commercial	Industrial
Coordinates	1°32′17′′ N 103°40′40′′ E	1°32′26′′ N 103°37′45′′ E	1°32′21′′ N 103°37′20′′ E
Area (ha)	32.77	34.21	4.38
No. of shops/ houses/factories	473	609	25
Impervious area (%)	85	95	93
Average daily traffic (vehicles/day)	7811	33286	3148

2.3. Data analysis

2.3.1. Mass based first flush (MBFF)

Mass based first flush (MBFF) is a ratio of normalized cumulative pollutant mass to the normalized cumulative runoff volume as described by Ma et al. [26]. MBFF ratio for stormwater constituent can be calculated by using Eq. (1) as below:

$$MBFF_n = \frac{\dfrac{\int_0^t C(t)Q(t)dt}{M}}{\dfrac{\int_0^t Q(t)dt}{V}} \quad (1)$$

Where t is lapsed flow time (min) corresponding to n% total flow volume, $C(t)$ is concentration of pollutant at time t (mg/L), $Q(t)$ is runoff flow rate at time t, M is total pollutant mass (kg), V is total flow volume (m^3). The first flush phenomenon occurs if MBFF is greater than 1.0 [26].

2.3.2. Treatment effectiveness factor

In order to estimate the potential benefits of treating pollutants in the early runoff, a treatment effectiveness factor, $E(v)$ as a function of $MBFF_n$ was determined in this study. The effectiveness factor $E(v)$ at a specific cumulative runoff volume, v is calculated as in Eq. (2) [20].

$$E(v) = \frac{(M_v / v)}{(1 - M_v)/(1 - v)} \quad (2)$$

where M_v is the normalized cumulative mass at a specific normalized cumulative runoff volume, v. The $E(0.1)$ of 5 represents that treating the first 10% of stormwater runoff volume will be 5 times more effective than treating an equal volume of runoff at the later part of storm event.

3. Results and discussion

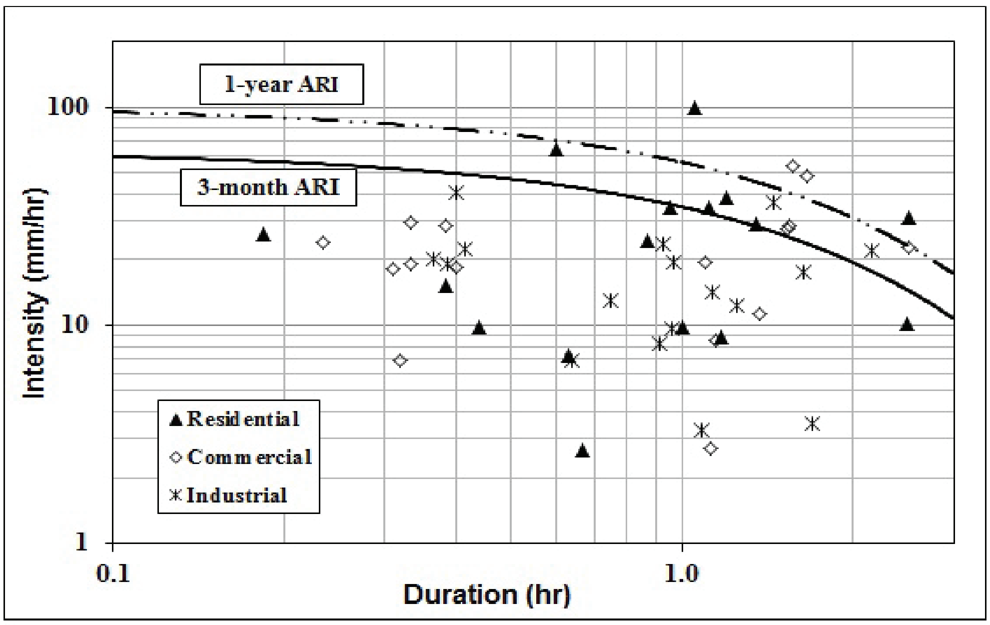
3.1. Storm characteristics

A total of 52 storm events were collected at the studied catchments as shown in Fig. 1, which consisted of 18 events for residential catchment, 17 events for commercial catchment and 17 events for industrial catchment, respectively. The storm characteristics including grain fall depth (R_d), duration (R_{dur}), hourly mean intensity (I), max 5 min intensity (I_{max5}) and antecedent dry days (ADD)were analyzed in detailed for each storm event and the statistical results were summarized in Table 2. The observed rainfall depths ranged from 1.8 mm to 107.4 mm while the intensity varies from 2.7 mm/h to 99.5 mm/h. These collected storm events mainly represent the frequent or common storms in the study area, with mostly having average recurrence interval (ARI) less than 3 month as shown in Fig. 2. As stated in the Urban Stormwater Management Manual for Malaysia (MASMA) [41], storms of 3 month ARI or less produces over 90% of annual runoff volume in the country. Thus, the results in this study will provide the representative criteria for the first flush treatment design of BMP facilities.

Table 2
Characteristics of the monitored storm events

Catchment	Depth [R_d] (mm)	Duration [R_{dur}] (h)	Mean intensity [I] (mm/h)	Max 5 min intensity [I_{max5}] (mm/h)	Antecedent dry day [ADD] (d)
Residential (n = 18)					
Minimum	1.8	0.18	2.7	9.6	0.1
Maximum	46.0	2.5	99.5	151.2	8.53
Median	19.6	0.91	25.2	57.6	1.7
Mean ± SD	21.7 ± 15.4	1.01 ± 0.62	27.9 ± 24.8	64.9 ± 45.9	2.3 ± 2.2
Commercial (n = 17)					
Minimum	2.0	0.23	2.7	4.8	0.03
Maximum	107.4	4.85	53.7	146.4	16.53
Median	11.0	1.12	22.1	50.4	3.74
Mean ± SD	30.2 ± 33.4	1.22 ± 1.14	23.0 ± 13.3	65.6 ± 42.0	2.12 ± 3.14
Industrial (n = 17)					
Minimum	3.6	0.37	3.3	9.6	0.02
Maximum	53.2	2.16	40.5	127.2	13.02
Median	9.8	0.96	17.6	48.0	1.89
Mean ± SD	16.6 ± 14.4	1.01 ± 0.51	17.2 ± 10.3	56.3 ± 31.6	2.68 ± 3.33

n: number of events; SD: standard deviation



ARI: Average recurrence interval

Fig. 2. Intensity-Duration-Frequency (IDF) curves for the monitored storm events.

3.3. Mass based first flush analysis

Mass based first flush (MBFF) ratios were evaluated for all stormwater quality parameters at residential, commercial and industrial catchments. The MBFF ratio was calculated for every normalized cumulative runoff volume of 0.1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8 and 0.9, respectively. The median MBFFs for each runoff volume interval at every studied catchment are summarized in Table 3. Some water quality parameters such as BOD, COD, TSS, and NH_3–N exhibited consistently median MBFF ratios greater than 1.0 which suggested the first flush effect. Park et al. [42] and Li et al. [5] also found similar observations at the urban catchment in Korea and China, respectively. Commercial catchment had exhibited the strongest MBFFs (greater than 2.0) for BOD, TSS, NH_3–N and SRP at the first 20% of the runoff volume. The mean MBFFs for NO_3–N,

Table 3
Median $MBFF_n$ ratios for water quality parameters at each study site

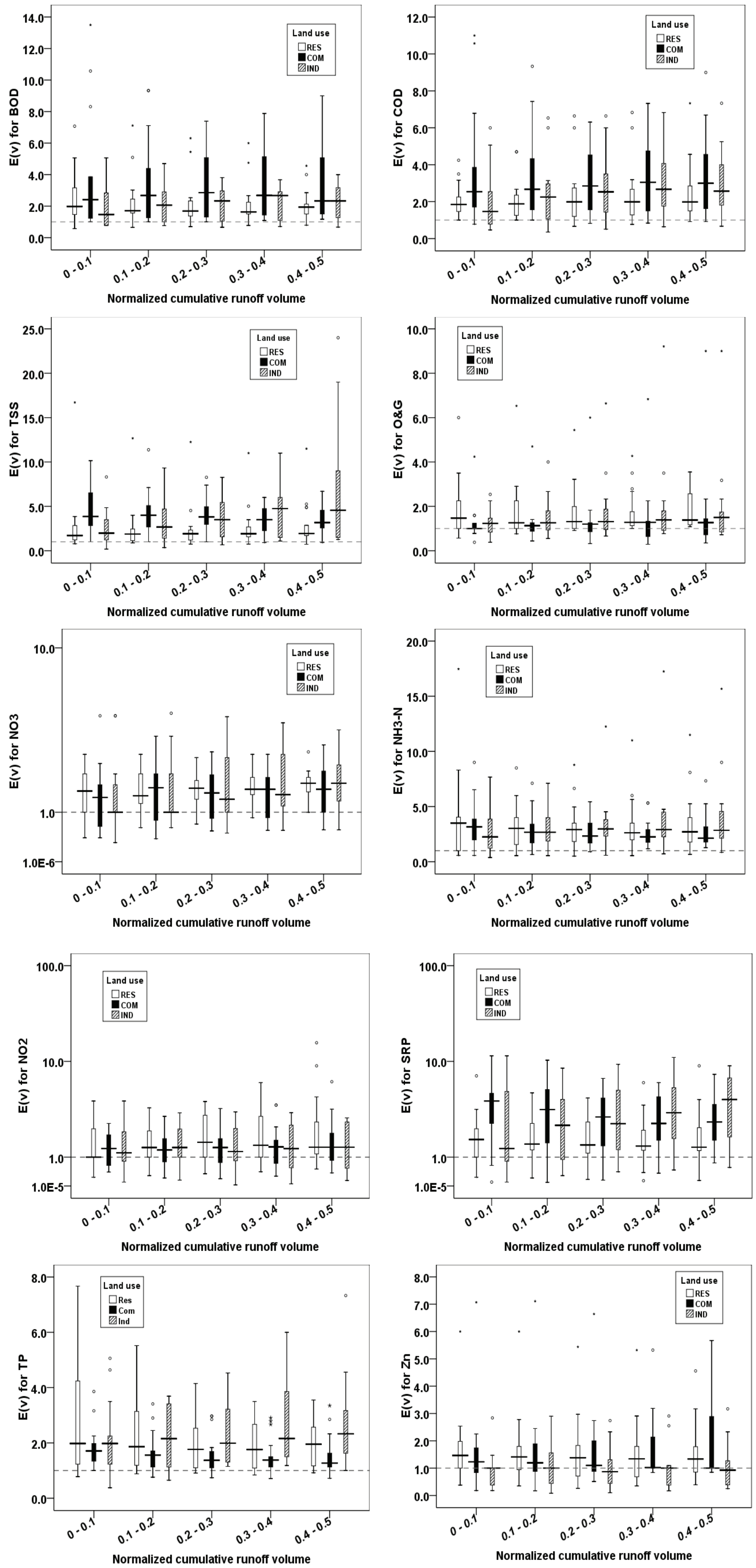
MBFF	BOD			COD			TSS			O&G			NO_3–N		
	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind
FF_{10}	1.80	2.10	1.40	1.70	1.10	1.40	1.60	3.00	1.60	1.40	1.00	1.20	1.30	1.20	1.00
FF_{20}	1.50	2.00	1.70	1.60	2.00	1.80	1.60	2.50	1.80	1.20	1.10	1.20	1.20	1.30	1.00
FF_{30}	1.40	1.83	1.67	1.53	1.83	1.73	1.50	2.07	2.00	1.20	1.13	1.20	1.25	1.20	1.12
FF_{40}	1.30	1.60	1.60	1.43	1.68	1.60	1.40	1.75	1.85	1.15	1.15	1.25	1.20	1.20	1.15
FF_{50}	1.32	1.40	1.40	1.33	1.50	1.44	1.32	1.52	1.64	1.16	1.12	1.20	1.20	1.16	1.16
FF_{60}	1.23	1.28	1.30	1.23	1.40	1.37	1.10	1.40	1.48	0.97	1.10	1.15	1.00	1.15	1.15
FF_{70}	1.19	1.24	1.21	1.19	1.27	1.26	1.10	1.29	1.32	1.00	1.07	1.11	0.99	1.09	1.13
FF_{80}	1.11	1.14	1.13	1.13	1.18	1.15	1.08	1.18	1.20	1.00	1.06	1.08	0.98	1.08	1.09
FF_{90}	1.07	1.07	1.07	1.07	1.09	1.08	1.00	1.09	1.09	0.98	1.03	1.07	0.97	1.04	1.04
Mean	1.32	1.52	1.39	1.36	1.45	1.43	1.30	1.76	1.55	1.12	1.08	1.16	1.12	1.16	1.09
MBFF	NH_3-N			NO_2-N			SRP			TP			Zn		
	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind	Res	Com	Ind
FF_{10}	2.80	2.60	1.80	1.00	1.20	1.10	1.45	3.00	1.20	1.80	1.60	1.60	1.40	1.20	1.00
FF_{20}	2.15	2.00	1.90	1.20	1.15	1.20	1.28	2.20	1.80	1.58	1.40	1.70	1.30	1.15	1.00
FF_{30}	1.85	1.67	1.87	1.27	1.17	1.10	1.22	1.77	1.67	1.43	1.23	1.47	1.23	1.07	1.00
FF_{40}	1.59	1.50	1.60	1.18	1.15	1.13	1.16	1.50	1.65	1.35	1.20	1.45	1.18	1.01	1.00
FF_{50}	1.46	1.36	1.46	1.12	1.12	1.12	1.12	1.40	1.60	1.32	1.12	1.40	1.14	1.00	1.00
FF_{60}	1.22	1.32	1.33	0.93	1.10	1.12	0.93	1.30	1.43	1.10	1.12	1.25	0.95	1.00	1.00
FF_{70}	1.14	1.24	1.20	0.97	1.07	1.10	0.95	1.19	1.30	1.06	1.11	1.20	0.97	1.00	1.00
FF_{80}	1.09	1.15	1.12	0.98	1.05	1.11	0.96	1.13	1.15	1.00	1.08	1.13	0.95	1.00	1.01
FF_{90}	1.01	1.07	1.07	0.98	1.02	1.07	0.95	1.08	1.09	0.97	1.07	1.08	0.94	1.00	1.01
Mean	1.59	1.55	1.48	1.07	1.11	1.12	1.11	1.62	1.43	1.29	1.21	1.36	1.12	1.05	1.00

FF_n – Mass based first flush at *n*% of cumulative runoff volume.

NO_2–N and Zn at all catchments were relatively constant and showed weak first flush effect during the storm event. The relative first flush strength of stormwater pollutants at residential catchment is NH_3–N > COD > BOD > TSS > TP > O&G = NO_3–N = Zn > SRP > NO_2–N, while it is TSS > SRP > NH_3–N > BOD > COD > TP > NO_3–N > O&G > Zn at the commercial catchment. Meanwhile, the relative first flush strength with regards to various pollutants at industrial catchment is TSS > NH_3–N > SRP = COD > BOD > TP > O&G > NO_2–N > NO_3–N > Zn. This study found the MBFFs of TSS > TP> COD at industrial catchment and these observations are similar as Lee et al. [24] in Korea and Li et al. [43] in China. Commercial catchment had exhibited the strongest mean MBFF for most of the stormwater pollutants including BOD, COD, TSS, NO_3–N and SRP. On the other hand, residential catchment showed the strongest mean MBFF for NH_3–N and Zn while industrial catchment only exhibited the strongest mean MBFF for O&G, TP and NO_2–N. Commercial catchments had larger MBFF for COD than that in the industrial catchment as similar with the findings by Lee et al. [24] and Li et al. [43]. The results indicated the different first flush magnitude of stormwater pollutants at urban land uses in the tropics. This implies that taking into account the targeted pollutant at particular land use should be considered in the effective BMP facilities design.

3.4. Treatment strategies for first flush runoff volume

The effectiveness factor was calculated at 5 runoff volume interval for selected water quality parameters at each study catchment and the results are plotted as shown in Fig. 3. The dashed line at 1.0 shows the expected value of *E(v)* for constant pollutant concentrations or no first flush effect. The highest median *E(v)* for stormwater quality parameters at residential, commercial and industrial catchments are summarized in Table 4. Most of the stormwater quality parameters show *E(v)* greater than 1 at every runoff volume interval except Zn in industrial catchment. Low *E(v)* for Zn may suggest that treating the first 50% of runoff volume is not more effective than treating the later part of runoff. Residential and commercial catchments both have the highest *E(v)* for NH_3–N, SRP, TP and Zn at the first 10% of runoff volumes. It is readily apparent that treating these pollutants in the early runoff is several times more effective than treating the later runoff. It is seen that treating the first 10%–20% of runoff volume at commercial catchment can achieve the highest *E(v)*for TSS and NO_3–N. Most of the stormwater quality parameters at industrial catchment could only be treated effectively at the first 30%–50% of runoff volumes. This could be due to the mass emission rate in the middle of storm event is greater than that at the beginning, in spite of lower concentrations in the middle of storm. The results suggested that BMPs removal efficiencies



* RES-Residential, COM-Commercial, IND-Industrial,

Fig. 3. Box plots of treatment effectiveness factor [$E(v)$] for various pollutants at the residential (RES), commercial (COM) and industrial (IND) catchments.

Table 4
Highest median treatment effectiveness factor for various stormwater pollutants at different land uses

No.	Parameter	Residential	Commercial	Industrial
1.	BOD	1.98 (0.1)	2.85 (0.3)	2.67 (0.4)
2.	COD	1.99 (0.3)	3.05 (0.4)	2.79 (0.4)
3.	TSS	2.08 (0.4)	4.00 (0.2)	4.75 (0.4)
4.	O&G	1.51 (0.5)	1.28 (0.4)	1.50 (0.5)
5.	NO_3–N	1.50 (0.5)	1.41 (0.2)	1.50 (0.5)
6.	NH_3–N	3.50 (0.1)	3.16 (0.1)	2.97 (0.3)
7.	NO_2–N	1.49 (0.3)	1.28 (0.4)	1.27 (0.5)
8.	SRP	1.59 (0.1)	3.86 (0.1)	4.00 (0.5)
9.	TP	1.98 (0.1)	1.71 (0.1)	2.33 (0.5)
10.	Zn	1.59 (0.1)	1.23 (0.1)	1.00 (0.4)

Value in parentheses represents the cumulative runoff volume, *v*.

are higher in runoff with higher concentrations at the initial runoff volume. Strecker et al. [44] and Lau and Stenstrom [45] found that BMPs are generally more effective in treating higher concentration than lower concentration stormwater runoffs (i.e., the removal efficiency of a catch basin insert or a sedimentation basin may be close to zero at low concentrations, and as high as 70% or more at high concentrations) [46,47]. These treatment strategies found in this study are basically determined based on normalized cumulative pollutant mass and runoff volumes, thus eliminating the factors of catchment area and storm sizes. Therefore, it is possible to apply these treatment strategies to other urban catchments in the tropical region. The proposed treatment strategies will also maximize the benefits of the applied BMP as it will provide an estimation of potential treatment efficiencies for the BMP designs.

4. Conclusions

This study investigated the first flush magnitude of selected stormwater pollutants during 52 storm events at residential, commercial and industrial catchments. The transport mechanisms of urban stormwater pollutants and treatment strategies with respect to first flush pollutant loading in tropical region have been identified. The outcomes of this study had provided an essential basis for designing the BMP facilities. The important findings are concluded as follows:

1. The relative first flush strength of stormwater pollutants based on mass based first flush (MBFF) ratio at residential catchment is NH_3–N > COD > BOD > TSS > TP > O&G = NO_3–N = Zn > SRP > NO_2–N, while it is TSS > SRP > NH_3–N > BOD > COD > TP > NO_3–N > O&G > Zn at the commercial catchment. Meanwhile, the relative first flush strength with regards to various pollutants at industrial catchment is TSS > NH_3–N > SRP = COD > BOD > TP > O&G > NO_2–N > NO_3–N > Zn.
2. Residential and commercial catchments both have the highest treatment effectiveness factor for NH_3–N, SRP, TP and Zn at the first 10% of runoff volumes. Meanwhile, majority of the stormwater pollutants at industrial catchment could only be treated effectively at the first 30%–50% of runoff volumes. The study found that treating NH_3–N in the first 30% of stormwater runoff volume is likely three times more effective than treating the later part of runoff at residential, commercial and industrial catchments in the tropical region.

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