Stormwater quality and pollution loading from an urban residential catchment in Johor, Malaysia

R. Nazahiyah*, Z. Yusop** and I. Abustan***

*Faculty of Civil and Environmental Engineering, Universiti Tun Hussein Onn Malaysia (UTHM), Batu Pahat, Johor, Malaysia (E-mail: *nazahiya@ uthm.edu.my*)

**Institute of Environmental and Water Resource Management, Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai 81310, Johor, Malaysia

***School of Civil Engineering, Universiti Sains Malaysia, Nibong Tebal, Pulau Pinang, Malaysia

Abstract Sampling of urban runoff was carried out in a small catchment, which represents a residential area (3.34 ha) in Skudai, Johor. One hundred and seventeen runoff samples from ten storm events were analysed. Runoff quality showed large variations in concentrations during storms, especially for SS, BOD_5 and COD. Concentrations of NO_3—N, NO_2—N, NH_3—N, and P were also high. Lead (Pb) was also detected but the levels were low (< 0.001 mg/L). In general, the river quality is badly polluted and falls in Class V based on the Malaysian Interim National Water Quality Standards. Event mean concentrations for all parameters were found to vary greatly between storms. The values (mg/L) were BOD_5 (72), COD (325), SS (386), NO_3—N (2.5), NO_2—N (0.58), NH_3—N (6.8), P (3.4), respectively. First flush phenomena were observed for BOD, COD, SS, NO_3—N, NH_3—N and P. The first 20–30% of the runoff volume evacuated between 20–59% BOD, 15–69% COD, 15–78% SS, 14–49% NO_3—N, 14–19% NO_2—N, 23–53% NH_3—N and 23–43% P.
Keywords First flush; pollutant loading; residential catchment; water quality

Introduction

Urban runoff and water quality are significantly affected by catchment development. Urbanisation alters the natural vegetation, the physical characteristics of the catchment and reduces the infiltration capacity. As a result, the runoff is increased and the duration during which runoff occurs is shortened. In many areas, stormwater runoff is a major contributor to river pollution (Adams and Papa, 2000; Yusop *et al.*, 2005).

The sources of urban pollutants are diverse and associated with both natural and human activities. They can be broadly categorised into point sources (PS) and non-point sources (NPS) pollution. NPS refers to the pollutants that have no readily identify source and are transported into receiving waters in diffuse manner. Sources of this pollution include precipitation, soil erosion, accumulation and wash-off of atmospheric dust, wash-off of street dirt, fertilisers and pesticides, and direct discharge of pollutants into storm sewers (Novotny and Olem, 1994). Generally, NPS is more difficult to control and, there-fore, catchment planners need to be able to estimate non-point source loads to the receiving water courses if they are to formulate effective management strategies (Brezonik and Stadelmann, 2002). Storm event sampling program and runoff quality analysis are funda-mental for estimating pollutant mass loads in both natural and disturbed ecosystems (Ellis and Hvitved-Jacobsen, 1996; McLeod *et al.*, 2006; Yusop *et al.*, 2006). This study is aimed at understanding the pollutant behaviour with response to rainfall size and inten-sity and quantify the loadings of major pollutants in a residential catchment.

Methods

Study site

The study site is located in Skudai, Johor, Malaysia (Figure 1). The residential catchment is 3.34 ha with 147 single storey houses. The catchment is typical of high density low cost residential area (Figure 2). Approximately 15% of the catchment is still pervious while the rest are rooves, pavement and road surfaces. The catchment drainage system separates stormwater system from the sewer system. The catchment physiographical conditions are shown in Table 1.

Methodology

Rainfall and runoff

Rainfall was monitored continuously using a tipping bucket rain gauge (ISCO™). The rain gauge was installed on a levelled platform on a house roof to provide sufficient exposure and minimise any obstacles. The streamflow was determined by velocity-area method. A current meter (Model SWOFFER 2100) was used to measure the flow velocity at the catchment's outlet. Stream discharges were calculated as the product of flow velocities and the drain cross section areas at various water levels. Flow gauging was
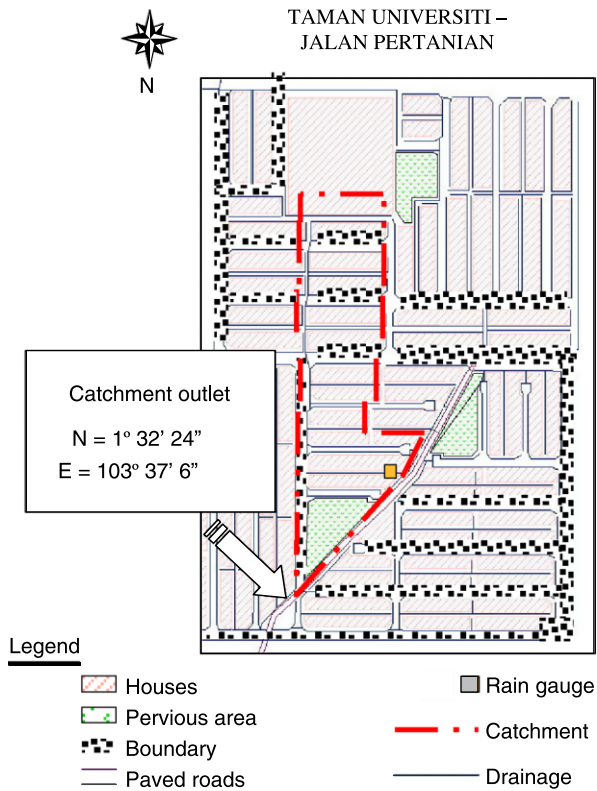

Figure 1 Location of the study site

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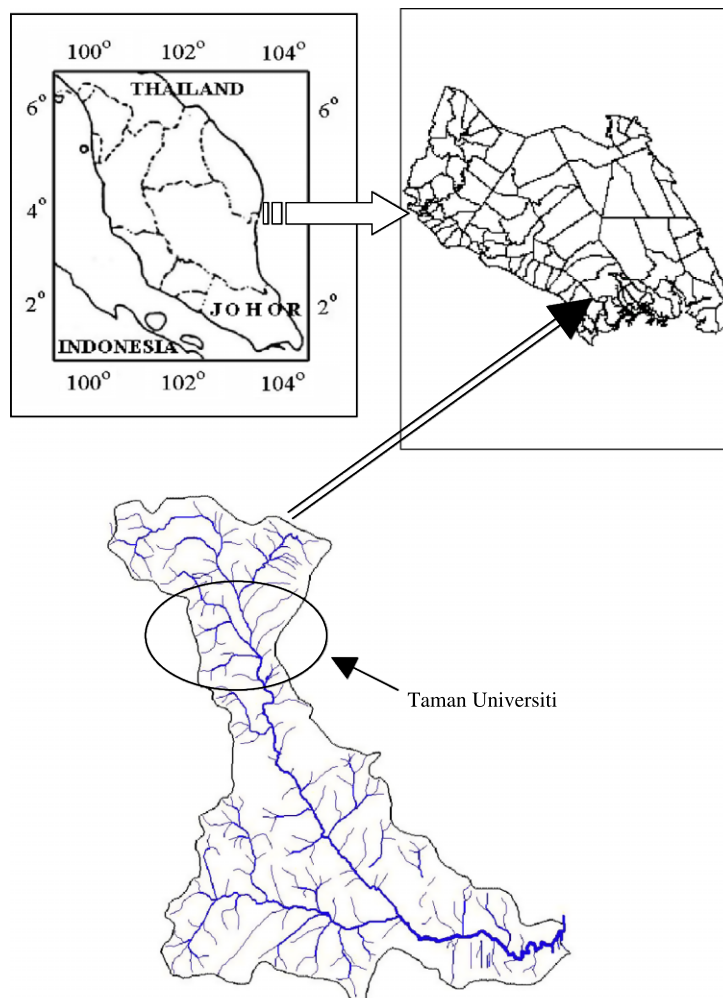
Figure 2 The catchment layout

only carried out in the initial stage of the sampling program, during the first three events. Once sufficient flow data were obtained for a wide spectrum of flow conditions, a water level-discharge rating curve was developed. This level-discharge rating curve was then used to convert the water level into discharge of the subsequent event sampling.

Sampling and analysis

Stormwaters were grab-sampled using 1L polyethylene bottles. Although laborious, the manual sampling provides the opportunity to collect more samples at preferred time intervals. All sampling bottles were washed with dilute acid (sulphuric or hydrochloric) and thoroughly rinsed with deionised-distilled water.

Approximately 10 to 15 samples were collected during each storm on both the rising and falling limbs of the hydrograph. As suggested by Bedient and Huber (2002), at least four samples were taken during the period of increasing flow to obtain a better

Table 1 Physiographical conditions of the catchment

Catchment characteristics	Unit	
Area	Ha	3.34
Elevation		
Maximum	m.a.s.l	66
Minimum	m.a.s.l	45.5
Aspect		N – E
Average slope	%	2.53
Average drain gradient	%	1.08
Drainage density	km/km^2	78.3
Total drainage length	M	2,613.6

description of the first flush phenomenon. For every sample taken, the sampling time and water level were recorded. Ten storm events were monitored between November 2003 and September 2004 with a total of 117 samples.

Samples were brought to the Environmental Laboratory at Universiti Teknologi Malaysia immediately after sampling and analysed for biochemical oxygen demand (BOD_5), chemical oxygen demand (COD), suspended solids (SS), nutrients (NO_3—N, NO_2—N, NH_3—N and P) and Pb. The laboratory analyses followed the *Standard Methods for the Examination of Water and Wastewater* (APHA *et al.*, 1995). The analysis of phosphorus was carried out using inductively coupled plasma–mass spectrometry (ICP–MS).

Data analysis

Stormflow quality was first examined by plotting pollutographs (Adam and Papa, 2000). Pollutant loadings were calculated as the product of event mean concentration (EMC) and runoff volume, expressed in per unit area (kg/ha). EMC is defined as the total constituent mass discharged during an event, divided by the total runoff volume (Adam and Papa, 2000) as in Equation (1).

$$\text{EMC} = \frac{M}{V} = \frac{\sum Q_i C_i \Delta t}{\sum Q_i \Delta t} \tag{1}$$

where M is total mass of pollutant over the entire event duration (g), V is total volume of flow over the entire event duration (m^3), t is time (min), $Q_i(t)$ is the time-variable flow (m^3/min), C_i is the time-variable concentration (mg/l) and Δt is the discrete time interval (min) measured during the runoff event.

The presence or absence of first flush phenomenon was assessed using a dimensionless representation of cumulative loading ratio against cumulative runoff ratio (Bertrand-Krajewski *et al.*, 1998). The first flush phenomenon can be represented in the following forms:

$$L = m(t)/M \tag{2}$$

$$F = v(t)/V \tag{3}$$

where L is dimensionless cumulative load; $m(t)$ is pollutant mass up to time t (g); M is total mass of pollutant over the entire event duration (g); F is dimensionless cumulative runoff flowrate; $v(t)$ is flow volume up to time t (m^3) and V is total volume of flow over the entire event duration (m^3).

Results and discussion

Characteristics of rainfall events

The characteristics of rainfall and runoff over the study period are summarised in Table 2. Observed antecedent dry days ranged from 21 to 120 h and the rainfall size ranged from 1.52 to 65 mm. The storm depth and intensity are important for the transport of particulates whereas the length of dry periods indicate the amount of accumulated pollutant since the preceding event (Lee *et al.*, 2002).

Event mean concentration (EMC)

Table 3 presents the EMC values for various parameters together with their site mean concentrations (SMC) or the average EMC. Pollutant concentrations vary considerably from storm to storm. Based on the Interim National Water Quality Standards for Malaysia (INWQS), the runoff is highly polluted, especially in terms of SS, BOD and COD with maximum EMCs of 1,024, 190 and 728 mg/L, respectively. Storm size did not seem to

Table 2 Storm characteristics of the sampled runoff

Date	Rainfall (mm)	Intensity (mm/hr)	Duration since last storm (hr)
08-Nov-03*	–	–	
11-Nov-03*	–	–	
11-Jan-04	1.5	3.5	120
02-Mar-04	1.5	2.5	23
04-Mar-04	18.8	16.0	45
06-Mar-04	2.8	9.3	46
12-July-04	19.0	16.0	24
08-Sep-04	6.8	8.8	50
04-Nov-04	65.0	27.0	21
27-Dec-04	8.0	9.6	–

Note.*rainfall data not available.

Table 3 Event mean concentration (EMC) of water quality parameters

Events	BOD$_5$ (mg/L)	COD (mg/L)	SS (mg/L)	NO$_3$—N (mg/L)	NO$_2$—N (mg/L)	NH$_3$—N (mg/L)	P (mg/L)	Pb (mg/L)
8-Nov-03	73	238	274	0.69	0.02	0.66	1.11	0.05
11-Nov-03	54	136	259	0.07	0.03	0.73	0.60	0.07
11-Jan-04	85	296	1,024	0.91	0.13	8.70	7.30	0.03
2-Mar-04	190	675	742	3.90	0.06	7.00	7.80	<0.002
4-Mar-04	123	316	259	3.30	0.07	9.12	1.24	0.002
6-Mar-04	156	728	374	1.70	0.82	3.60	3.44	<0.002
12-July-04	68	181	85	6.00	–	0.37	0.93	–
8-Sept-04	39	98	152	0.17	–	0.37	4.52	–
4-Nov-04	47	118	21	3.70	–	0.80	0.01	–
27-Dec-04	113	320	405	3.10	–	3.70	1.60	–
SMC	95	311	364	2.40	0.1	3.50	3.00	0.02

be a single factor influencing the EMC values. For example, the highest SS was registered on 11 January 2004 with rainfall of only 1.52 mm. Similarly, the highest COD value was recorded on 6 March 2004 following 2.8 mm rainfall. The concentrations of SS were high during most of the storms. This was likely due to sediment sources from a playing ground located close to the catchment outlet. Concentrations of NH$_3$—N and P were also high and could be associated with sullage.

Figure 3 shows selected pollutographs and hydrographs resulting from single-peaked storms. The pollutographs generally exhibit rather simple patterns which are characterised by rapid increases and followed by gradual decreases. The hydrographs show a rapid response to rainfall with a short time to peak (average 9 min). Such a flashy characteristic of a small urban catchment was also observed elsewhere (Lee *et al.*, 2002; Yusop *et al.*, 2005).

First flush phenomenon

For a given catchment, the pollutographs and hydrographs vary from one storm event to another depending on the rainfall intensity, the antecedent dry weather period, the condition of the sewer system, the dry deposits and the accumulation of pollutants. The presence of first flush phenomenon was assessed by plotting the dimensionless cumulative load ratio and volume ratio using values derived from Equations 2 and 3 (Figure 4). The diagonal line represents the loading of a hypothetical pollutant with constant concentrations.

Data points above the diagonal line represent a higher loading during storms and suggest the presence of first flush phenomenon (Lee *et al.*, 2004). The graphs indicate that the first 20 to 30% of the discharges volume evacuated between 20 and 59% of the total BOD loading. For the same portion of runoff, the corresponding loadings of COD, SS, NO$_3$—N, NO$_2$—N, NH$_3$—N and P were 15–69, 15–78, 14–49, 14–19, 23–53 and
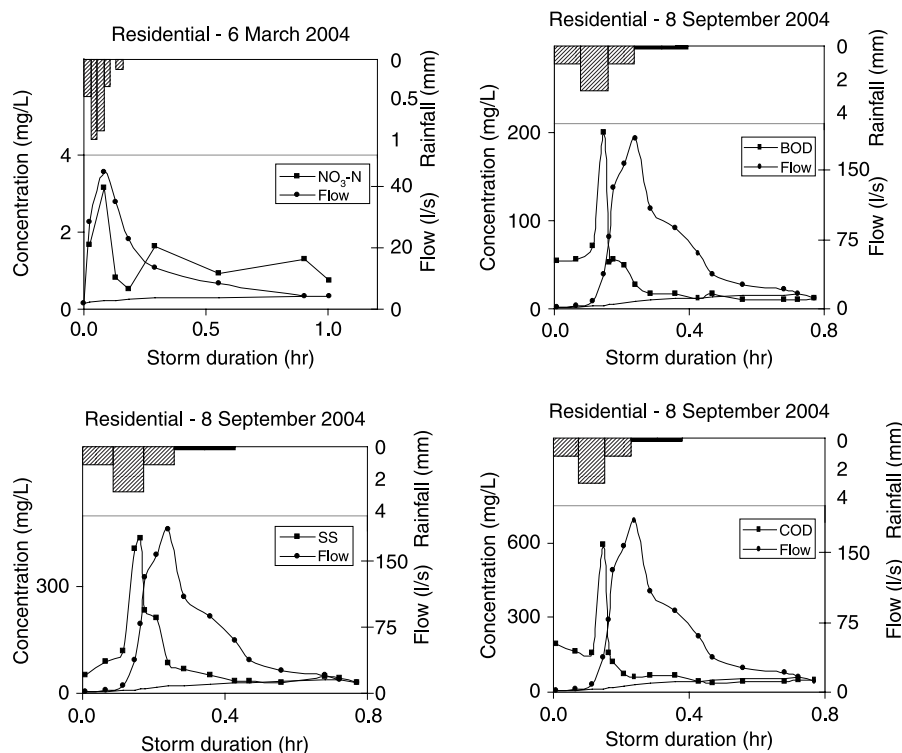
Figure 3 Pollutographs and hydrographs of the selected pollutants

23–43% of the total loading, respectively. First flush was not evident for NO_2—N as most of the data points fell below the diagonal line.

Table 4 shows the averages cumulative pollutant loadings that fall in the 20–30% range of runoff volume. The mean values ranged from 0.17 to 0.47. Since the average cumulative loading of the 20–30% runoff volume is considered, a first flush exists if the mean value is equal or greater than 0.25. SS showed the strongest first flush with mean mass to volume ratios from 0.15 to 0.78, whereas NO_2—N was the weakest, from 0.14 to 0.19.

First flush phenomena were observed for most of the parameters. The degree of first flush phenomenon was influenced by the storm characteristics and the antecedent dry period. A large storm usually dilutes the pollutant concentration but the resulting loading is higher due to a much larger increase in the stormflow volume.

Pollutant loading

The pollutant loading obtained during a storm event is the product of EMC and runoff volume (Table 5) which comprises both point source (PS) and non-point source (NPS) pollution. In this analysis, the fraction of NPS loading is given by the difference between the PS loading from the total loading during a storm event. Water samples for determining the PS were collected during low flow.

The pollutant loadings obtained from this study are much higher compared to another nearby residential catchment (Yusop *et al.*, 2005). The discrepancy can be explained in terms of catchment size. Yusop *et al.* (2005) used a much larger catchment (17.1 km²). Due to high spatial variation of rainfall in the tropics, the areal rainfall of the entire catchment tends to be smaller than the point rainfall used in the analysis. As such, the storms tend to produce smaller loadings when the values are expressed as per unit area basis.
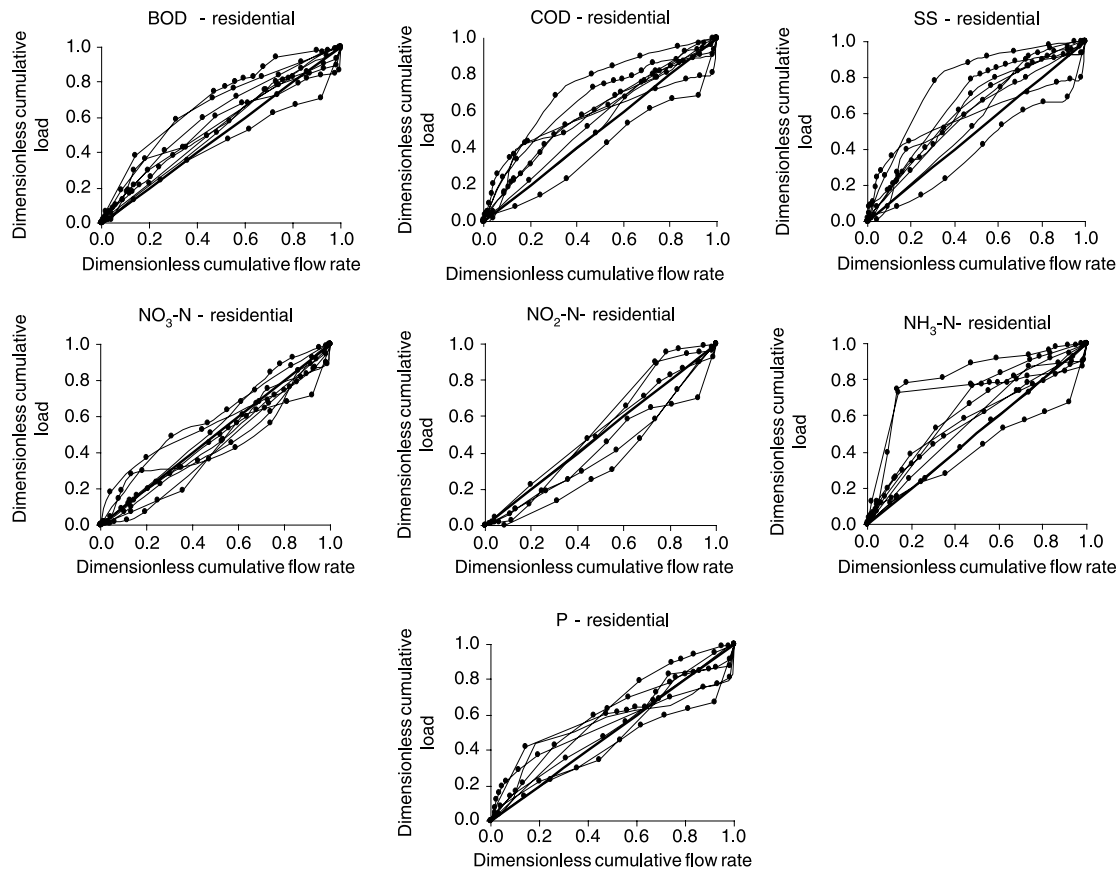
Figure 4 Mass Volume, $M(V)$ ratios of BOD, COD, SS, NO_3-N, NO_2-N, NH_3-N and P

Table 4 Cumulative load at 20−30% of the runoff volume in the residential catchment

	BOD	COD	SS	NO$_3$—N	NO$_2$—N	NH$_3$—N	P
Min	0.2	0.15	0.15	0.14	0.14	0.23	0.23
Max	0.59	0.69	0.78	0.49	0.19	0.53	0.43
Mean	0.4	0.42	0.47	0.30	0.17	0.38	0.33

Table 5 Summary of event pollutant loadings

Parameters	Loading (kg/ha)	
	Range	Mean
BOD$_5$	0.5−16.5	4.9
COD	1.2−27.5	9.0
SS	2.2−22	7.5
NO$_3$—N	0.001−1.5	0.35
NO$_2$—N	0.0003−0.01	0.004
NH$_3$—N	0.013−1.2	0.2
P	0.002−0.14	0.05
Pb	<0.001	0.001

Conclusions

Information derived from this study is useful as a basis for improving river water quality in urban areas, especially in the tropics. The important findings as follows:

(i) Based on the Interim National Water Quality Standards for Malaysia, the storm-water quality from the urban residential catchment was severely polluted and fall in class V water.

(ii) Event mean concentrations for all parameters were found to vary greatly between storms.

(iii) First flush phenomena were detected in this study. For the residential catchment, the relative strength of the first flush was: SS > COD > BOD$_5$ > NH$_3$—N > P > NO$_3$—N > NO$_2$—N.

In view of the large temporal and spatial variations of EMC value, a more intensive stormwater monitoring program is recommended. Preferably, the sampling design must include various storm sizes and be replicated for different land-use types. Consideration on the antecedent conditions of the catchment is also crucial for a better understanding of the pollutant transport mechanism. An important issue to be addressed is the influence of dry weather periods and rainfall intensity on the water quality and pollution loading. Continuous water quality monitoring programmes with reliable rainfall data, though expensive, are useful for obtaining reliable data for estimating pollutant loading.

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