Evaluation of the methods for first flush analysis in urban watersheds

J.H. Lee, M.J. Yu*, K.W. Bang and J.S. Choe*****

Department of Environmental Engineering, Chongju National College of Science & Technology, Chungbuk 367-701, Korea (E-mail: *jlee@cjnc.ac.kr*)

* Division of Environmental Engineering, University of Seoul, Seoul 130-743, Korea (E-mail: *myong@.uos.ac.kr*)

** Division of Civil, Environmental and Urban Engineering, Hanbat National University, Daejon 305-719, Korea (E-mail: *bangkw@hanbat.ac.kr*)

*** Land Research Institute, Korea Land Corporation, Kyunggi 463-010, Korea (E-mail: *jongsoo@koland.co.kr*)

Abstract The general tendency between the ratio of cumulative pollutant loads and the ratio of cumulative runoff appears as a nonlinear form which can be expressed in the form of a third polynomial. In this paper third degree polynomials were applied to represent the first flush curves based on the relationship between the cumulative pollutant load ratio and cumulative runoff ratio. The quantity of stormwater runoff and quality constituents, including chemical oxygen demand (COD), suspended solids (SS), total Kjeldahl nitrogen (TKN), ortho-phosphorus (PO_4-P), total phosphorus (TP), n-hexane extracts (HEM), and iron (Fe) were analysed. The objectives of this study were (1) to characterize the quality of stormwater runoff (2) in order to analyse the cumulative curve area ratio and to calculate the first flush coefficients, (3) while also representing the first flush with a third polynomial equation.

Keywords Cumulative load curve; first flush; separated sewer overflow; third degree polynomial; urban runoff

Introduction

It is commonly thought that the concentration of pollutants is substantially higher at the beginning of storm runoff than during the rest of the event (so-called first flush phenomenon) (Gupta and Saul, 1996; Deletic, 1998). The concept of the first flush phenomenon was first advanced in the early 1970s. Many research studies have been accomplished using multiple regression to examine the importance of the relevant factors which influence the first flush. During the first flush, an enormous quantity of pollutants is discharged into the receiving waters (Lee and Bang, 2000). Stormwater runoff has been identified as one of the leading causes of degradation in the quality of receiving waters, especially during the first flush. Many researches have assumed that the first flush results in a substantial peak concentration at the beginning of storm events (Bertrand *et al*., 1998). However, the peak concentration may vary with different pollutants during the same storm events, or with the same watershed during different storm events (Gupta and Saul, 1996). Several methods have been proposed to evaluate the first flush. Generally, a first flush is based upon the relationship between the cumulative mass curve and the cumulative runoff volume curve. A first flush was observed when the cumulative pollutant load ratio curve had an initial slope greater than that of 45º. The 45º line represented the case when the concentration of pollutants remained constant throughout the runoff. Conversely, dilution occurred when the slope of this line was less than 45º (Bedient *et al*., 1978; Choe *et al*., 2002; Gupta and Saul, 1996). First flush occurs when the cumulative load curve is positioned above the cumulative runoff curve. Sansalone and Buchberger (1997) proposed that the ratio of cumulative load curve

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area to the cumulative runoff curve area is a measurement based on the strength of the first flush. Bertrand *et al*. (1998) proposed to define the first flush by the fact that at least 80% of the pollutant load was transported in the first 30% of the runoff volume. Another approach calculates the correlation coefficients between the cumulative pollutant mass and the cumulative runoff volume. The percentage of deviation for the cumulative pollutant load curve of the diagonal was used as a measure to determine the strength of the first flush (Gupta and Saul, 1996). Most research focused on the existence or non-existence and strength of the first flush. There are few studies on a function formula for that of the first flush phenomenon. Bertrand *et al*. (1998) proposed that for every cumulative load curve, M could be fitted with cumulative storm runoff, F approximately by a power function as following Eq. (1). The value of the first flush coefficient was computed by using a regression method and it was suggested that the lower the value of λ, the more pronounced the first flush.

$$M = F^{\lambda} \tag{1}$$

It is possible that the general tendency between the ratio of cumulative pollutant load and the ratio of cumulative runoff can be shown as a nonlinear form which can be expressed in the form of a third polynomial (Lee and Bang, 2000; Demir, 1995). In this study, a third polynomial was proposed to represent a first flush along with watershed area and rainfall intensity. This equation which represents the third degree polynomial is based upon the relationship between the cumulative pollutants load ratio and cumulative runoff ratio as in Eq. (2).

$$L = \alpha V^3 + \beta V^2 + \gamma V \tag{2}$$

where L is the cumulative pollutant load ratio, V is the cumulative runoff ratio, and α, β, γ are constants. In this study, two storm events were examined at single residential areas, apartment complexes and commercial areas in November 1999. The quantity of stormwater runoff and quality constituents, including chemical oxygen demand (COD), suspended solids (SS), total Kjeldahl nitrogen (TKN), ortho-phosphorus (PO_4-P), total phosphorus (TP), n-hexane extracts (HEM), and iron (Fe) were analysed (*Standard Methods*, 1992). The objectives of this study were (1) to characterize the quality of stormwater runoff, (2) to analyse the cumulative curve area ratio and to calculate the first flush coefficients, (3) to represent the first flush with a third polynomial equation.

Methodology

Experimental sites

The experimental watershed in Yongam is located in Chongju, Korea. Four small watersheds were selected for monitoring the rainfall events in November 1999. All watersheds are served with a separated sewer system. The watershed area of YAM is 92 ha, average impervious area is approximately 68%, and average watershed slopes are 1.5%. The land uses of YAM watershed are predominately apartment complex areas, single residential houses, schools, parks, and commercial buildings. YAM watershed has been sub-divided into a single residential area (RES), an apartment complex area (APT), and a commercial area (COM). The total area of RES, COM, and APT is less than 5 ha. The stormwater runoff from the YAM watershed was discharged into the upper parts of Musim stream by overflow box weir. A summary of site characteristics, rainfall intensity, days since last storm and number of samples collected during the storm event are given in Table 1.

Sampling and analysis

Two litre samples were taken manually at either 5-min. or 10-min. intervals for increasing

Table 1 Summary of studied watershed's characteristics

Site	Land use	Drainage area	Percent of impervious area	Slope (%) (mm/hr)	Rainfall intensity last storm (days)	Days since	Sampling date
RES	Single residential house area	3.25	87	2.6	1.45	8	Nov. 11, 1999
					3.50	13	Nov. 24, 1999
APT	Apartment complex area	4.81	85	1.0	1.45	8	Nov. 11, 1999
					3.50	13	Nov. 24, 1999
COM	Commercial area	0.74	89	1.1	1.45	8	Nov. 11, 1999
					3.50	13	Nov. 24, 1999
YAM	Mixed urban area	92.0	68	1.5	1.45	8	Nov. 11,1999
					3.50	13	Nov .24, 1999

flow stage and 1 h intervals for receding flow stage. Flow measurements were made by using depth-of-flow determinants from the overflow weir. Precipitation measurements were taken at the rain gauge station located near the drainage area. The samples were transported to the laboratory and analyzed for COD, SS, TKN, PO_4-P, TP, n-hexane extracts (HEM), and Fe. Analyses were performed using techniques according to *Standard Methods* (1992). COD was measured following the open reflux method using dichromate for oxidation. SS was measured by filtrating, drying at 103–105°C and weighing. TKN was analyzed by digestion, the distillation method, and PO_4-P and TP were measured by persulfate digestion and the ascorbic acid method. HEM was n-hexane extraction followed by weighing (Korea standard method, Section 4–9) and Fe was analyzed by atomic absorption spectrophotometer after digestion assisted microwave.

Experimental results

Stormwater quality and first flush curves

Figures 1 and 2 represent the measured runoff, SS and COD concentration for each watershed during two storm events. Table 2 shows the flow-weighted average concentration for an individual storm event. The values of flow-weighted average concentrations for COM were generally higher than those for other sampling sites. The peaks of SS and COD preceded that of runoff flow, except for YAM watershed. The first flush effect of water quality was studied by plotting the cumulative load ratio against the cumulative runoff ratio as shown in Figure 3 and Figure 4. A first flush occurs when the cumulative pollutant load curve area is in excess of the cumulative runoff curve area. When the storm event has no first flush, the value of this curve area ratio is unity. The strength of the first flush is in proportion to the value of this curve area ratio. The curve area ratios for the cumulative load to cumulative runoff of each watershed are tabulated in Table 3. From Figure 3 and 4, most cumulative load curves of the COD, SS, and TP were above the 45° line, suggesting a first flush effect. Bertrand *et al.* (1998) proposed to define the first flush by the fact that at least 80% of the pollutant mass is transported in the first 30% of the volume. However, such instances are extremely rare and found in only 1% of the events. Both the Nov. 11, 1999 and Nov. 24, 1999 events exhibit a pronounced first flush except for Nov. 11 at the YAM watershed. For the Nov. 11 event the SS and TP exhibited a pronounced first flush whereas PO_4-P exhibited a weak first flush. Harrison and Wilson (1985) reported a first flush effect is often seen for dissolved constituents such as PO_4-P. A general tendency of the first flush shows that the relative strength of the first flush is COD > SS > TP > Fe > HEM > TKN > PO_4-P. In the case of the Nov. 24 event for YAM, the peak concentrations of SS and COD and the peak runoff flow occurred at the same time. As shown in Figure 4(d), most of the cumulative load curves indicated the S type tendency for YAM. The cumulative curve area ratio shows an inverse relationship against the watershed area.

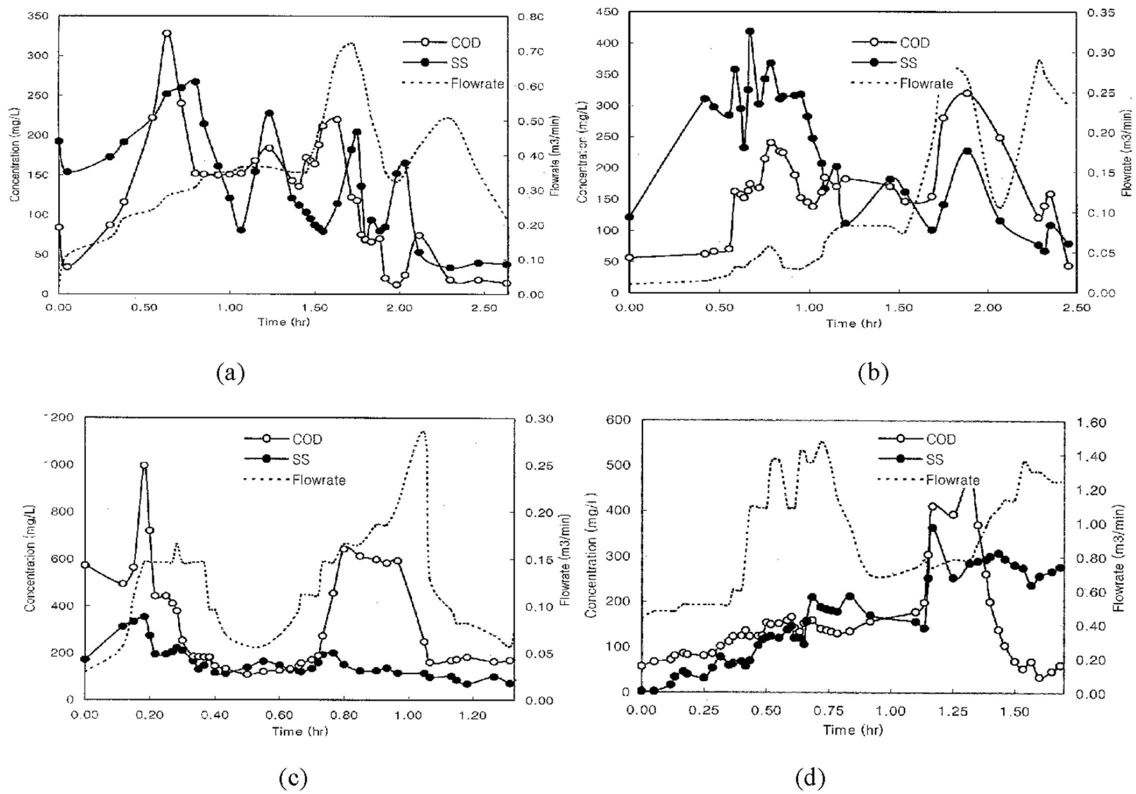
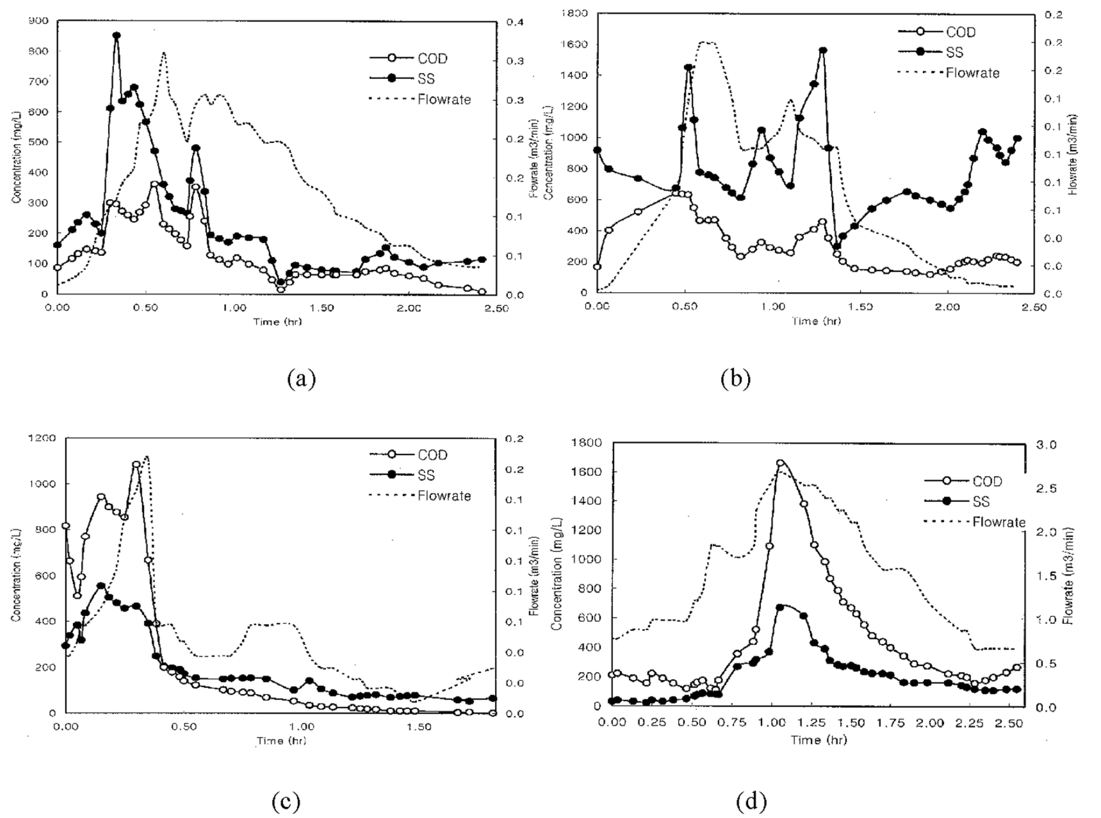


Figure 1 Pollutographs for November 11, 1999. (a) Apartments (b) Commercial (c) Single residential (d) Mixed area



(a) (b) (c) (d)

Figure 2 Pollutographs for November 24, 1999. (a) Apartments (b) Commercial (c) Single residential (d) Mixed area

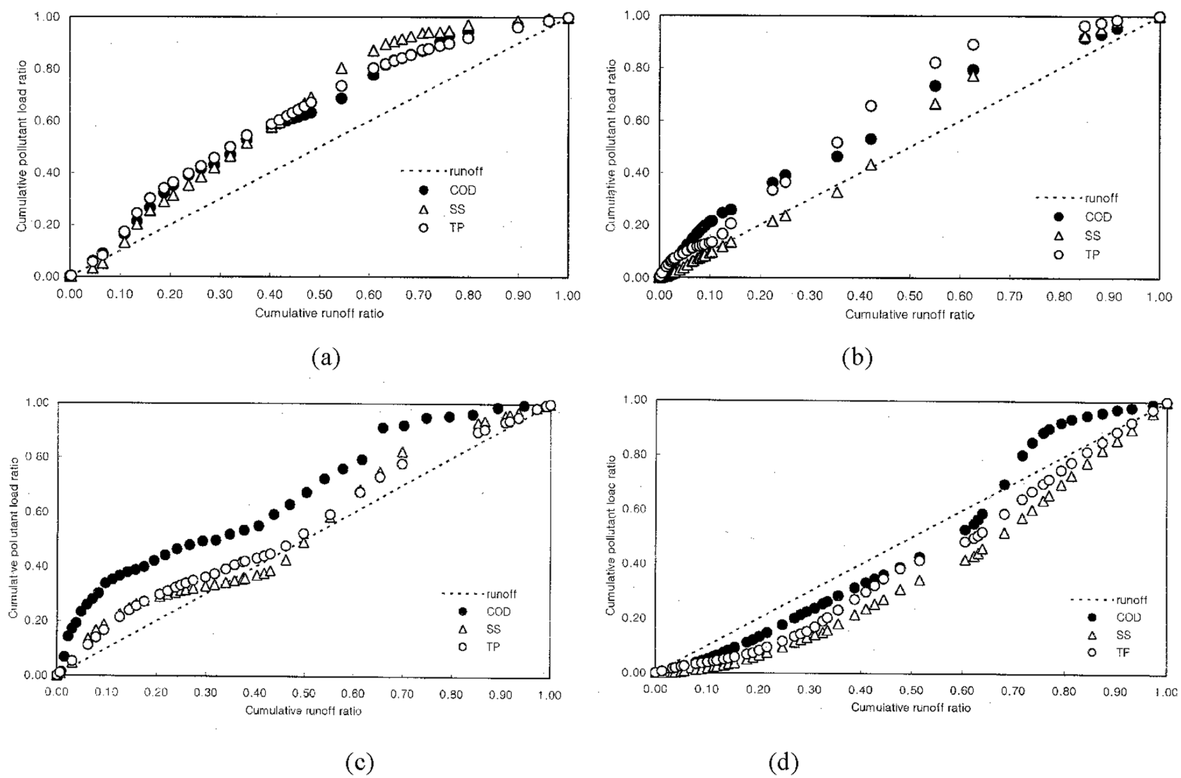


Figure 3 Cumulative curves for Nov. 11, 1999. Apartments (b) Commercial (c) Single residential (d) Mixed area

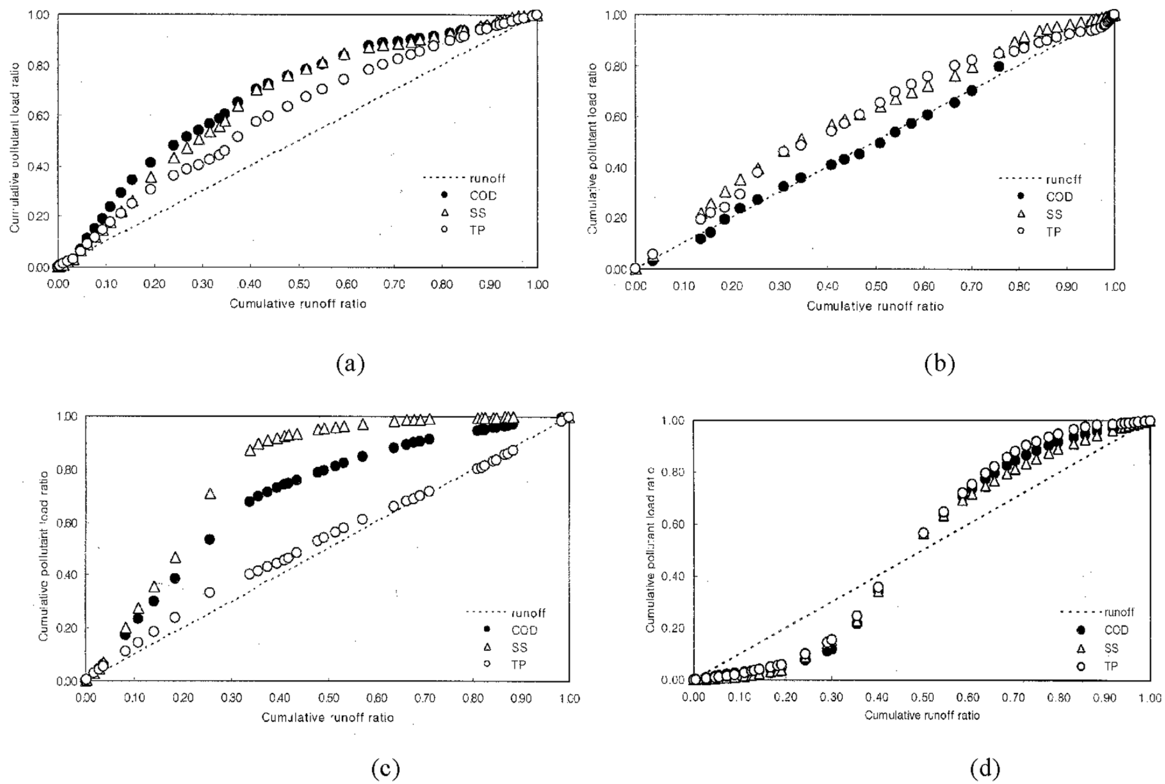


Figure 4 Cumulative curves for Nov. 24, 1999. (a) Apartments (b) Commercial (c) Single residential (d) Mixed area

Analysis by the first flush coefficients

The deviation of the cumulative pollutant mass curve from the diagonal was used as a measure for the strength of the first flush. This deviation is inversely proportional to the first flush coefficient λ. Table 4 represents the range of the first flush coefficient λ for water quality constituents analyzed during each storm event and land use according to Eq. (1). The reported values of λ vary between 0.24 and 2.07 for SS and between 0.27 and 1.40 for COD at small highway catchments of 1.3 ha (Bertrand *et al.*, 1998). The experimental fitting between M and F is usually satisfactory with the correlation coefficient $r^2 > 0.95$. The entire range for the first flush coefficient λ, was as follows; COD 0.83–1.43, SS 0.77–2.15, TKN 0.61–1.61, PO_4-P 0.62–1.50, TP 0.77–1.51, HEM 0.83–2.03, and Fe 0.86–1.73. Based on the minimum value of λ, the relative strength of a first flush is TKN > PO_4-P > SS, TP, HEM > Fe. These results differed with results of the cumulative curve ratio (Table 3).

Third-degree polynomial

As shown in Figure 4(d), the first flush curves have a similar tendency of the S-shape curves for large watersheds (around 100 ha). In the case of application for other watersheds (not shown in this paper), the same tendency of curves was shown. These tendencies appeared along with the differences in time of concentration for various watersheds. Eq. (1) has a limitation to represent the S-shaped curve. It is obvious that the general tendency between the ratio of cumulative pollutant load and the ratio of cumulative runoff appears in the form

Table 2 Flow-weighted average concentration (unit; mg/L)

Site	Date	COD	SS	TKN	PO_4-P	TP	HEM	Fe
APT	Nov. 11, 1999	130	125	4.35	0.22	0.70	112	3.91
APT	Nov. 24, 1999	292	166	4.56	0.10	1.72	153	5.54
COM	Nov. 11, 1999	169	176	9.56	0.60	1.55	80	5.92
COM	Nov. 24, 1999	849	374	20.02	1.05	2.28	242	6.12
RES	Nov. 11, 1999	161	360	5.31	0.14	0.90	314	5.93
RES	Nov. 24, 1999	291	468	8.25	2.00	4.84	285	11.33
YAM	Nov. 11, 1999	147	176	8.09	0.49	2.09	124	5.51
YAM	Nov. 24, 1999	557	241	13.88	0.60	4.48	567	4.32

Table 3 The ratio of cumulative pollutant load area to cumulative runoff area

Site	Date	Runoff	COD	SS	TKN	PO_4-P	TP	HEM	Fe
YAM	Nov. 11, 1999	1.00	0.95	0.72	1.03	1.06	0.81	0.75	0.83
YAM	Nov. 24, 1999	1.00	1.01	0.99	0.97	1.06	1.04	1.00	0.97
APT	Nov. 11, 1999	1.00	1.28	1.32	1.17	1.01	1.30	1.44	1.43
APT	Nov. 24, 1999	1.00	1.27	1.25	1.05	1.01	1.15	1.15	1.23
RES	Nov. 11, 1999	1.00	1.21	1.09	1.30	0.73	1.12	0.95	0.95
RES	Nov. 24, 1999	1.00	1.37	1.54	1.19	0.99	1.05	1.47	1.50
COM	Nov. 11, 1999	1.00	1.32	1.04	1.73	1.59	1.30	1.09	0.96
COM	Nov. 24, 1999	1.00	1.01	1.10	1.08	1.23	1.07	1.14	1.09

Table 4 Range and average of the first flush coefficient λ

Constituents	APT	RES	COM	YAM
COD	0.88–0.99 (0.93)	0.83–0.93 (0.88)	0.83–0.99 (0.91)	1.08–1.43 (1.30)
SS	1.01–1.02 (1.01)	0.77–9.84 (0.81)	0.99–1.14 (1.06)	1.40–2.15 (1.80)
TKN	0.91–0.97 (0.94)	0.77–1.00 (0.88)	0.61–0.91 (0.76)	0.77–1.61 (1.05)
PO_4-P	0.94–1.10 (1.02)	1.11–1.30 (1.21)	0.62–0.75 (0.68)	0.73–1.50 (0.96)
TP	0.86–0.97 (0.91)	0.97–1.09 (0.97)	0.77–0.91 (0.84)	0.97–1.51 (1.17)
HEM	0.85–1.13 (0.99)	1.10–1.22 (1.16)	0.83–1.06 (0.95)	1.25–2.03 (1.77)
Fe	0.95–1.10 (1.02)	0.86–0.93 (0.89)	0.97–1.20 (1.09)	1.18–1.73 (1.45)

of a third-degree polynomial. It is also possible to represent the S-shaped curve by using the third-degree polynomial. From the results presented in Figures 3–4 and Table 3, the strength of the first flush for COD and SS is distinct. Among the constituents, SS was chosen for application of the polynomial. The results of the best fitting curves by using the least square method are shown in Figure 5. The experimental fitting between the cumulative load curve and cumulative runoff curve was satisfactory. The range of correlation coefficients, r^2 was 0.978–0.999. As for Table 3, when the first flush shows strong tendencies, the values of β were –5.122 for RES, Nov. 24, and 1.701 for APT, Nov. 24. As the value of β decreased, the strength of the first flush increased. The values of β for YAM exhibited 1.055 and 4.301, and represent the first flush curve as the S-type curve, the values of β can usually be around 4. It is conceivable that a first flush is more distinct in small watersheds with higher impervious areas which are influenced by rainfall intensity (Lee and Bang, 2000; Deletic, 1998). As discussed previously, there are few studies on the formulation of the first flush curves because this phenomenon relates with so many parameters. Among the constants of the proposed third-degree polynomial in this paper, β was proportional to watershed areas and inversely proportionate to rainfall intensity. The most influential constant on the shape of the first flush curve was β. When the value of α was increased, the bend of the first flush curve was moved to the left side. The value of α was proportionate to rainfall intensity and inversely proportionate to watershed areas.

Cumulative curves were calculated by changing the constants as shown in Table 5. Case 1–2 curves (large watershed, low rainfall intensity) are used in the case of no first flush, while Case 4–6 curves are used in the case of first flush (small watershed, high rainfall intensity), and Case 3 curve (large watershed, high rainfall intensity) is for large watershed areas (Figure 6).

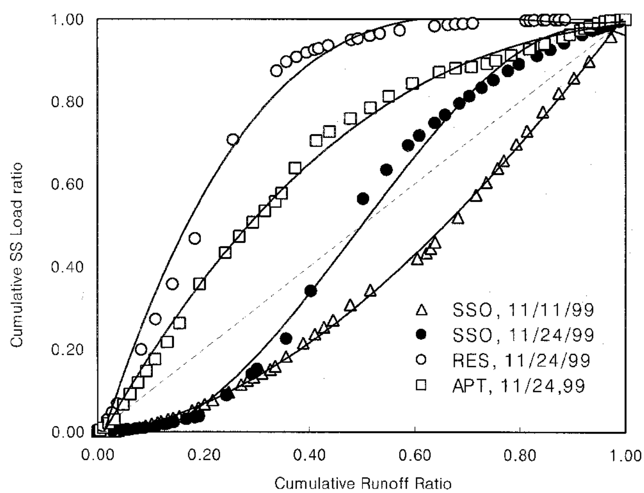


Figure 5 Polynomial equation curves and observed first flush for SS

Table 5 Estimated constants of the third-degree polynomial

Constants	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
α	–0.2	1.0	–3.0	1.0	0.4	2.0
β	1.1	0.1	4.3	–2.0	–1.7	–5.0
γ	0.1	–0.1	–0.3	2.0	2.3	4.0

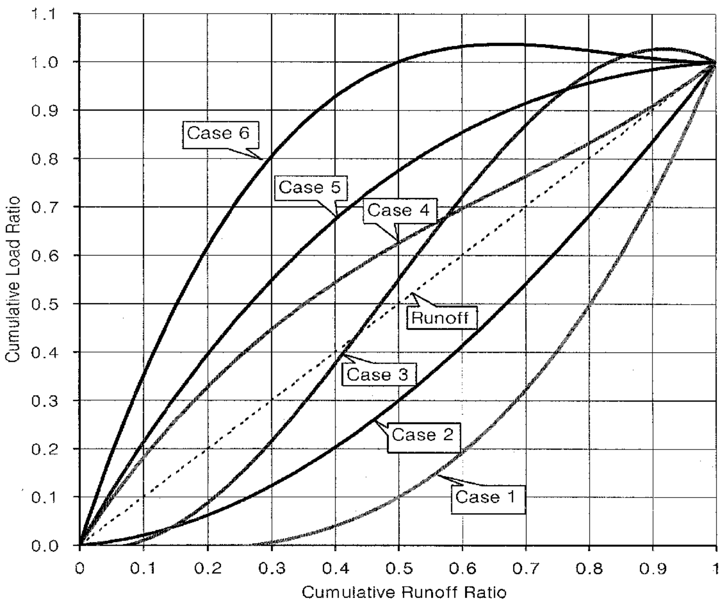


Figure 6 Shape of first flush curves with polynomial equation constants

Conclusions

The objectives of this study were to characterize the quality of stormwater runoff and analyze the cumulative curve area ratio, to calculate the first flush coefficients and to represent the first flush with a third polynomial equation. Two storm events were examined in a watershed while being mixed with single residential, commercial, and apartment complex areas. A general tendency of the first flush shows that the relative strength of the first flush is COD > SS > TP > Fe > HEM > TKN > PO_4-P. The experimental fitting between the cumulative load curve ratio and the cumulative runoff ratio with a third-degree polynomial was satisfied. The most influential constant on the shape of the first flush curve was β. It is concluded that the third-degree polynomial is a useful tool for analysis of the first flush phenomenon.

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