First Flush Concepts for Suspended and Dissolved Solids in Small Impervious Watersheds

John J. Sansalone[1] and Chad M. Cristina[2]

Abstract: Eight rainfall-runoff events were examined from each of two small paved urban transportation land use watersheds ($A = 544$ m^2 and 300 m^2) in an attempt to distill multiple definitions of the first flush phenomenon into a consistent framework and examine common volumetric capture requirements. Results indicated that two separate criteria must be employed to describe the delivery of suspended sediment concentration (SSC) and total dissolved solids (TDS) as aggregate indices of entrained particulate and dissolved matter. The concentration-based first flush criterion is defined by high initial SSC or TDS concentration in the early portion of a rainfall-runoff event with a subsequent rapid concentration decline. In contrast, the mass-based first flush (MBFF) has several published forms, shown to be equivalent herein. The MBFF is defined generally as a disproportionately high mass delivery in relation to corresponding flow volume. For mass-limited events, mass delivery was skewed towards the initial portion of the event while the mass delivery in flow limited events tended to follow the hydrograph. This study also investigated published estimates of the water quality volume (WQV); assuming that an in-situ Control Strategy or Best Management Practice (BMP) captures and treats only this WQV, while flows in excess of this volume bypass the BMP. For the two watersheds, results indicate that a relatively large runoff volume must be captured to effect meaningful reductions in mass and concentrations (as event mean concentrations) despite a disproportionately high mass delivery early in the event. Results suggest the potential for misinterpretation of overall BMP effectiveness may be significant based on use of a number of these common published estimates based on a WQV.

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CE Database subject headings: First-flush; Rainfall-runoff; Suspended solids; Unit operations; Best management practice; Water quality; Watershed management.

Introduction

The advent and popularization of motor vehicle and truck transport has changed the characteristics of urban rainfall-runoff from conventional wastewater-type concepts of organic matter and biochemical oxygen demand. Primary water quality characteristics are now understood to be mainly inorganic particulate matter; chemical oxygen demand (COD); phosphorus; and metal species (Novotny and Olem 1994). Particulate matter as suspended, and settleable solids, and sediments can be generated through pavement-tire interaction and abrasion of metallic vehicular components that occurs during vehicular operation (Kobriger and Geinopolous 1984). Metal concentration of urban rainfall-runoff has been found to be between 10 and 100 times the average concentration of sanitary sewer influent water (Wanielista et al. 1977). For a given urban area, solids and chemical oxygen demand loads in discharges from interstate and arterial pavement have been shown to be greater than that of untreated domestic wastewater from the same urban area (Sansalone et al. 1998).

At the start of the 20th century, it was well known that constituents transported in runoff from urban surfaces could be more concentrated at the beginning of a storm event than at the end of the same event. The phenomenon was described as the "first foul flush" or the "first flush" (Metcalf and Eddy 1916). The constituents of greatest concern at the time were the high degree of suspended and dissolved organic matter originating from equine fecal matter that was subsequently washed into receiving bodies. In contrast, modern transportation and urban activities generate suspended and dissolved solids generally characterized as aggregate parameters [for example suspended solids concentration (SSC) and total dissolved solids (TDS)] that are of concern not only as anthropogenic solids but also because such solid matter may serve as a vehicle for transport of constituents such as metal species and generate an oxygen demand in receiving waters.

Concepts and Definitions of First Flush

In general the term "first flush" has been utilized to indicate a disproportionately high delivery of either concentration or mass of a constituent during the initial portions of a rainfall-runoff event. The concentration-based first flush (CBFF) indicates a disproportionately high constituent concentration during the rising limb of the runoff hydrograph or the early portion of the runoff hydrograph. The CBFF has been observed for a variety of events including the removal of heavy metals from rooftops (Forster 1996; He et al. 2001), the removal of oil and grease from roadway

[1]Associate Professor (corresponding author), Dept. of Civil and Environmental Engineering, Louisiana State University, 3418 CEBA Bldg., Baton Rouge, LA 70803. E-mail: jsansal@lsu.edu

[2]Dept. of Civil and Environmental Engineering, Louisiana State Univ., 3502 CEBA Bldg., Baton Rouge, LA 70803.

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Table 1. Summary of Methodologies Utilized to Determine First Flush

Method	Expression	Land use	Drainage area (ha)	Investigators
Mass based	$M(t) > V(t)$	T	0.03–0.054	Cristina and Sansalone (2003)
		T	0.6	Barbosa and Hvitved-Jacobsen (1999)
		Mixed	0.02–0.03	Deletic (1998)
		Mixed	94	Larsen et al. (1998)
		T	0.03	Sansalone et al. (1998)
		T	0.03	Sansalone and Buchberger (1997)
			NR	Stahre and Urbonas (1990)
	Power law exponent $b < 1$	MS4	NR	Bertrand-Krajewski et al. (1998)
Concentration based	1. High initial concentration 2. Rapid concentration decline 3. Relatively low and constant concentration for duration of event	T	4.3	Farm (2002,)
		R & I	0.7–190	Lee et al. (2001)
		Mixed	233–609	Appel and Hudack (2001)
		RR	NR	He et al. (2001)
		CM & R	87–558	Lee and Bang (2000)
		T	0.03–11.5	Barrett et al. (1998)
		Mixed	0.02–0.03	Deletic (1998)
		T	0.15–0.45	Wu et al. (1998)
		Mixed	NR	Maidment (1993)
		U	NR	Wanielista and Yousef (1993)
		RR	NR	Forster (1996)
		Mixed	658.12	Stenstrom et al. (1984)
		R	55–131	Cordery (1977)
Empirically based	First 1.27 cm of runoff per impervious acre	All	Variable	Schueler (1987)
	First 1.27 cm of runoff per contributing area	All	Variable	Grisham (1995)
	Runoff volume produced by 1.9 cm of rainfall	All	Variable	State of California (2001)
	Exponential decline	T	Variable	Sartor and Boyd (1972)
	Runoff volume produced by 2.54 cm of rainfall	All	Variable	Schueler (1987)
	Linear/multiple linear regression	U	41–121	Gupta and Saul (1996)

Note: T=transportation; RR=roof runoff; I=industrial; U=urban; CM=commercial; R=residential; NR=not reported; $M(t)$=mass; and $V(t)$=volume. $M(t)=(\Sigma_{i=0}^{k}\overline{Q}(t_i)\overline{C}(t_i)\Delta t)/(\Sigma_{i=0}^{n}\overline{Q}(t_i)\overline{C}(t_i)\Delta t)$, $V(t)=(\Sigma_{i=0}^{k}\overline{Q}(t_i)\Delta t)/(\Sigma_{i=0}^{n}\overline{Q}(t_i)\Delta t)$ $M(t)=[V(t)]^b$.

surfaces (Stenstrom et al. 1984), the washoff of nitrate from roadway surfaces (Cordery 1977; Barrett et al. 1997; Lee and Bang 2000) and the removal of particulate matter (Maidment 1993; Wanielista and Yousef 1993; Deletic 1998; Wu et al. 1998; Appel and Hudack 2001; Lee et al. 2001; Farm 2002). A description of the methodologies employed, land use and drainage area for these investigations can be found in Table 1.

While a CBFF definition was the first proposed, and still widely used, it is not the only definition of a first flush. Many investigators have defined a mass-based first flush (MBFF). In order to discuss the MBFF, two dimensionless parameters are typically utilized

Table 2. Hydrologic, Mass, and Traffic Quantities for Mass-Limited High Runoff Volume Events

Event	18 June 1996	7 July 1996	8 Aug 1996	12 June 1997	21 July 2001	7 Aug 2001	13 May 2002	30 May 2002
Runoff duration (min)	65	60	52	57	50	34	35	68
Runoff volume (L)	2,774	9,643	3,877	464	8,369	2,971	1,944	7,336
Total particulate mass (gm)	623	304	631	36	943	434	972	1,469
Total dissolved mass (gm)	237	243	219	64	225	57	282	202
Mean flow per unit width (L/min/m)	2.8	10.7	5.0	0.5	11.2	5.8	3.7	7.2
Rainfall depth (mm)	11.3	40.4	14.1	2.0	22.9	9.4	7.9	41.4
Vehicles during storm	6,496	9,643	3,897	616	2,939	1,531	2,457	8,952
Peak Flow (L/min)	244	322	391	77	300	300	150	300

Note: Events prior to the year 2000 were recorded in Cincinnati. Events after 2000 were recorded in Baton Rouge. Asphalt pavement drainage area for the Cincinnati site=300 m^2 and for the concrete pavement drainage area for the Baton Rouge Site=544 m^2.

Table 3. Hydrologic, Mass, and Traffic Quantities for Flow-Limited Low Runoff Volume Events

Event	30 Apr 1995	8 Sept 1995	25 Nov 1996	16 Dec 1996	19 Jan 2002	11 Apr 2002	16 June 2002	3 Dec 2002
Runoff duration, min	101	79	146	57	28	29	31	56
Runoff volume (L)	281	263	216	79	85	54	52	221
Total particulate mass (mg)	57	51,011	19,414	12	28,111	13,464	10	74
Total dissolved mass (mg)	21	108,692	24,649	128	11,403	16,121	27	59
Mean flow per unit width (L/min/m)	0.19	0.22	0.10	0.09	0.20	0.12	0.11	0.26
Rainfall depth (mm)	1.7	4.4	3.1	1.2	11.9	1.3	1.3	1.3
Vehicles during storm		18,350	10,148	8,970	2,027	2,353	2,099	4,064
Peak flow (L/min)	8	10	9	4	6	5	3	7

Note: Events prior to the year 2000 were recorded in Cincinnati. Events after 2000 were recorded in Baton Rouge. Asphalt pavement drainage area for the Cincinnati site = 300 m^2 and for the concrete pavement drainage area for the Baton Rouge site = 544 m^2.

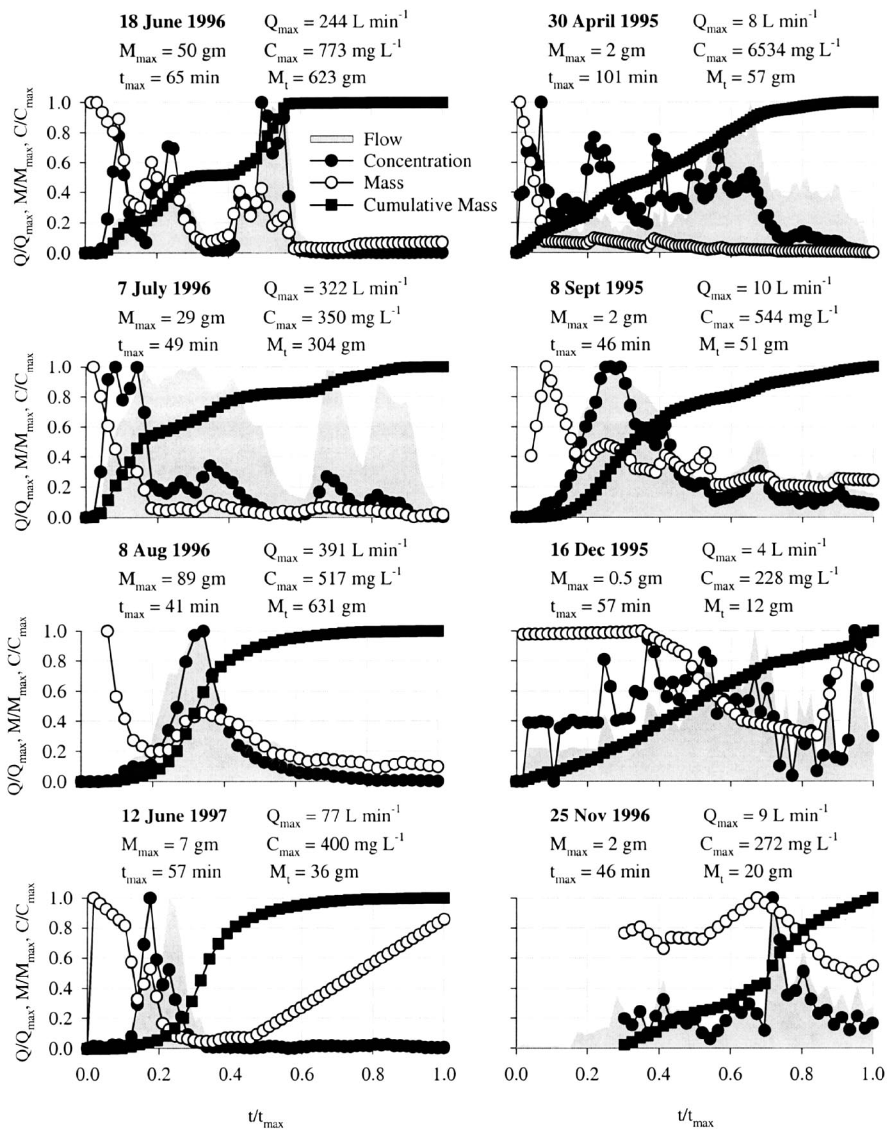

Fig. 1. Normalized flow, concentration, and cumulative particulate mass as suspended sediment concentration for eight rainfall runoff events in Cincinnati, Ohio. Mass-limited high runoff volumes are located on left hand side of plot and flow-limited events are located on left hand side of plot.

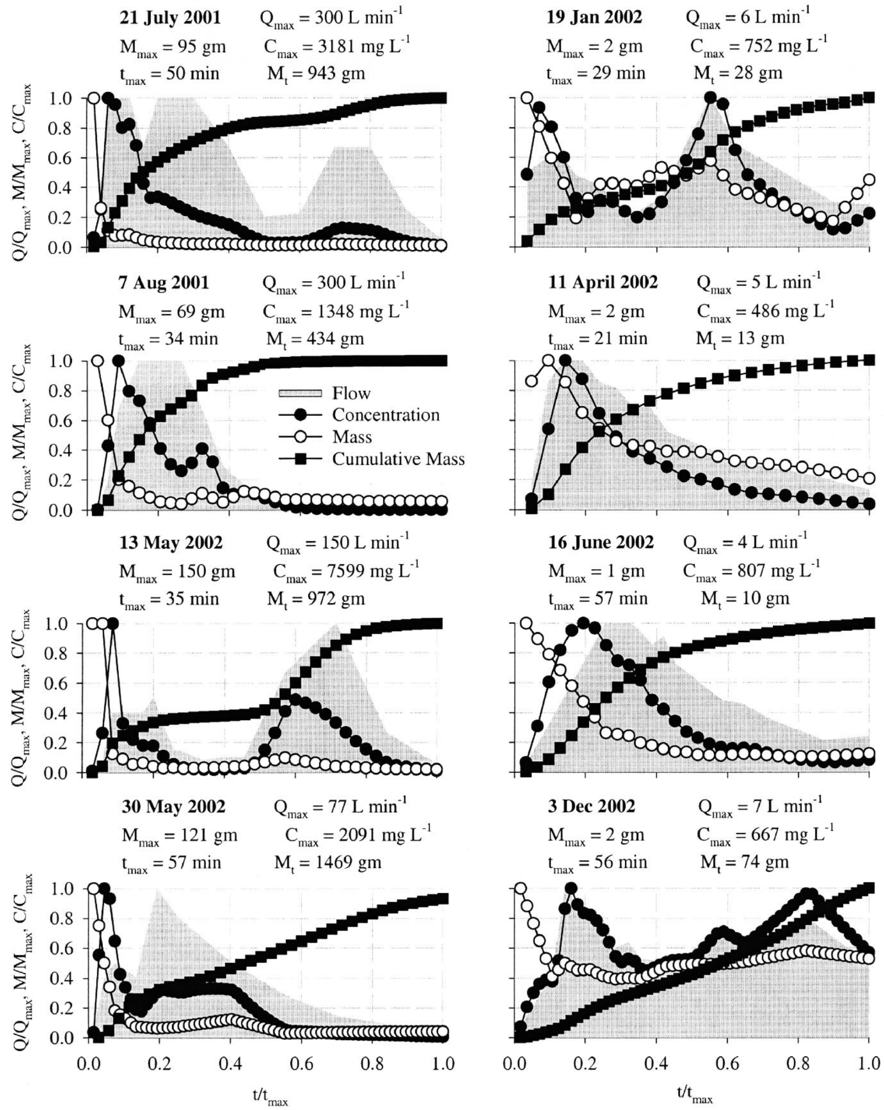

Fig. 2. Normalized flow, concentration, and cumulative particulate mass as suspended sediment concentration for eight rainfall runoff events in Baton Rouge, La. Mass-limited high runoff volumes are located on left hand side of plot and flow-limited events are located on left hand side of plot.

$$V(t)=\frac{\int_0^k Q(t)dt}{\int_0^n Q(t)dt} \tag{1}$$

$$M(t)=\frac{\int_0^k Q(t)C(t)dt}{\int_0^n Q(t)C(t)dt} \tag{2}$$

In these expressions $V(t)$=dimensionless ratio of the total volume of runoff observed at any time k to the total volume of runoff observed for the event; k=any time between the initiation of runoff (t_0) and the time coinciding with the cessation of runoff (n), and $Q(t)$=function denoting the measured hydrograph of a rainfall runoff event. $M(t)$ is similarly defined as a dimensionless ratio of constituent mass delivered at any time k to the total mass delivered throughout an event and $C(t)$=function denoting measured constituent concentration graph as a function of time.

Since continuous functional relationships describing $Q(t)$ and $C(t)$ are rarely, if ever, available for a given site, and there is always a limited number of flow measurements, limited number of samples and aqueous/solid-phase sample analyses for a given event, Eqs. (1) and (2) are typically discretized and evaluated in the following expressions:

$$V(t)=\frac{\sum_{i=0}^{k}\overline{Q}(t_i)\Delta t}{\sum_{i=0}^{n}\overline{Q}(t_i)\Delta t} \tag{3}$$

$$M(t)=\frac{\sum_{i=0}^{k}\overline{Q}(t_i)\overline{C}(t_i)\Delta t}{\sum_{i=0}^{n}\overline{Q}(t_i)\overline{C}(t_i)\Delta t} \tag{4}$$

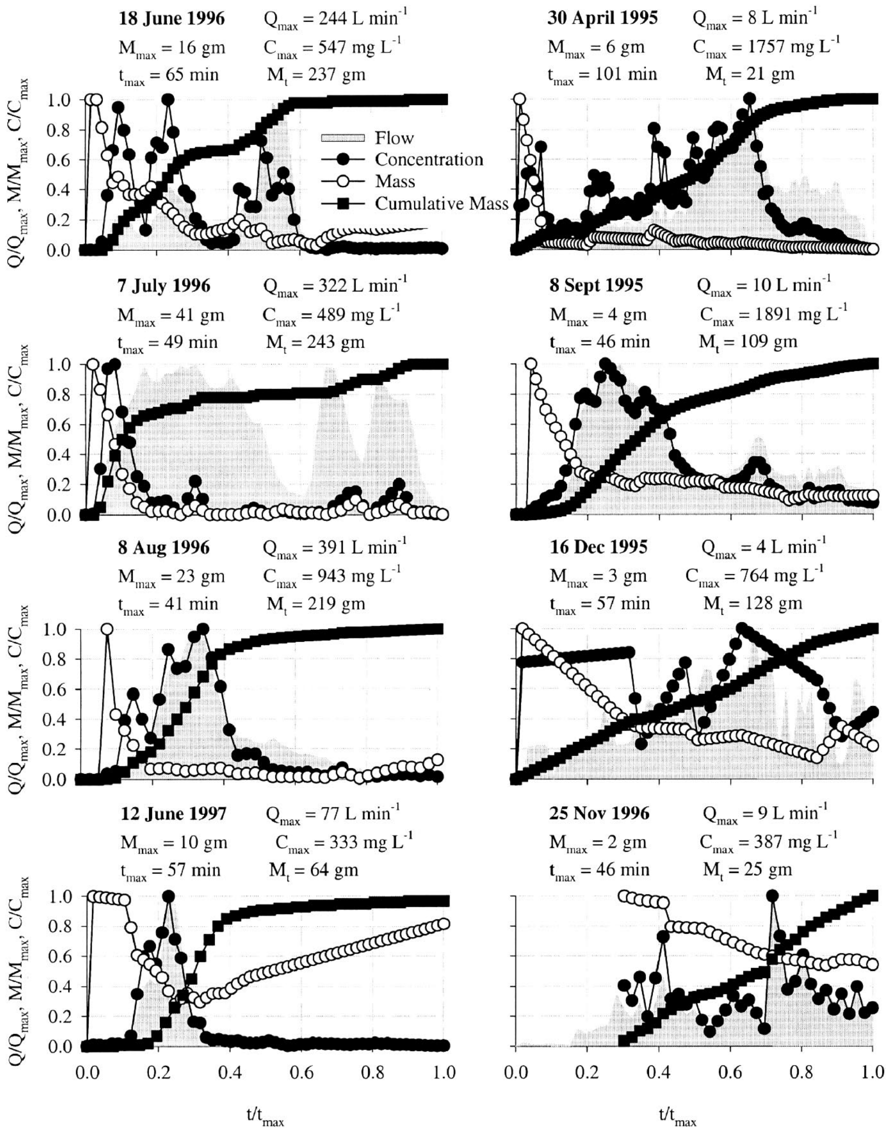

Fig. 3. Normalized flow, concentration, and cumulative dissolved mass as total dissolved solids for eight rainfall runoff events in Cincinnati, Ohio. Mass-limited high runoff volumes are located on left hand side of plot and flow-limited events are located on left hand side of plot.

In these expressions $\overline{Q}(t)$=average volumetric flow rate between successive measured flow rates ($L^3\,T^{-1}$); $\overline{C}(t)$=mean concentration of pollutant between successive measured concentrations ($M\,L^{-3}$); and Δt=time increment between successive measurements in units of T.

The MBFF is indicated by a disproportionately high delivery of constituent mass during the rising limb of the runoff hydrograph or the early portion of the runoff hydrograph. With the aid of Eqs. (1) and (2) the MBFF can be generally defined as

$$M(t) > V(t) \tag{5}$$

There are three methodologies commonly found in the literature to quantify a mass or concentration first flush and are conceptually and mathematically equivalent. Irrespective of the methodology used to describe a first flush, the absence of a CBFF or MBFF indicates that mass delivery and concentration tends to be proportional to the runoff hydrograph intensity.

Method I

The first variation on the MBFF definition includes a comparison of $M(t)$ versus $V(t)$ as a function of the elapsed time of the storm (Sansalone and Buchberger 1997; Sansalone et al. 1998; Cristina and Sansalone 2003). This method is typically expressed graphically by plotting $V(t)$ and $M(t)$ on the dependent axis and normalized time on the independent axis. An MBFF occurs for any period during which the $M(t)$ plot resides above the $V(t)$ plot indicating that a disproportionately high percentage of mass has been delivered by a given volume of flow.

Method II

The next variation replaces the independent variable t in Method I with $V(t)$. In this method, a line L with a slope of 1:1 is drawn from the origin and $M(t)$ is plotted on the dependent axis. An MBFF occurs for any period during which $M(t)$ exceeds L (Deletic 1998; Bertrand-Krajewski et al. 1998; Larsen et al. 1998).

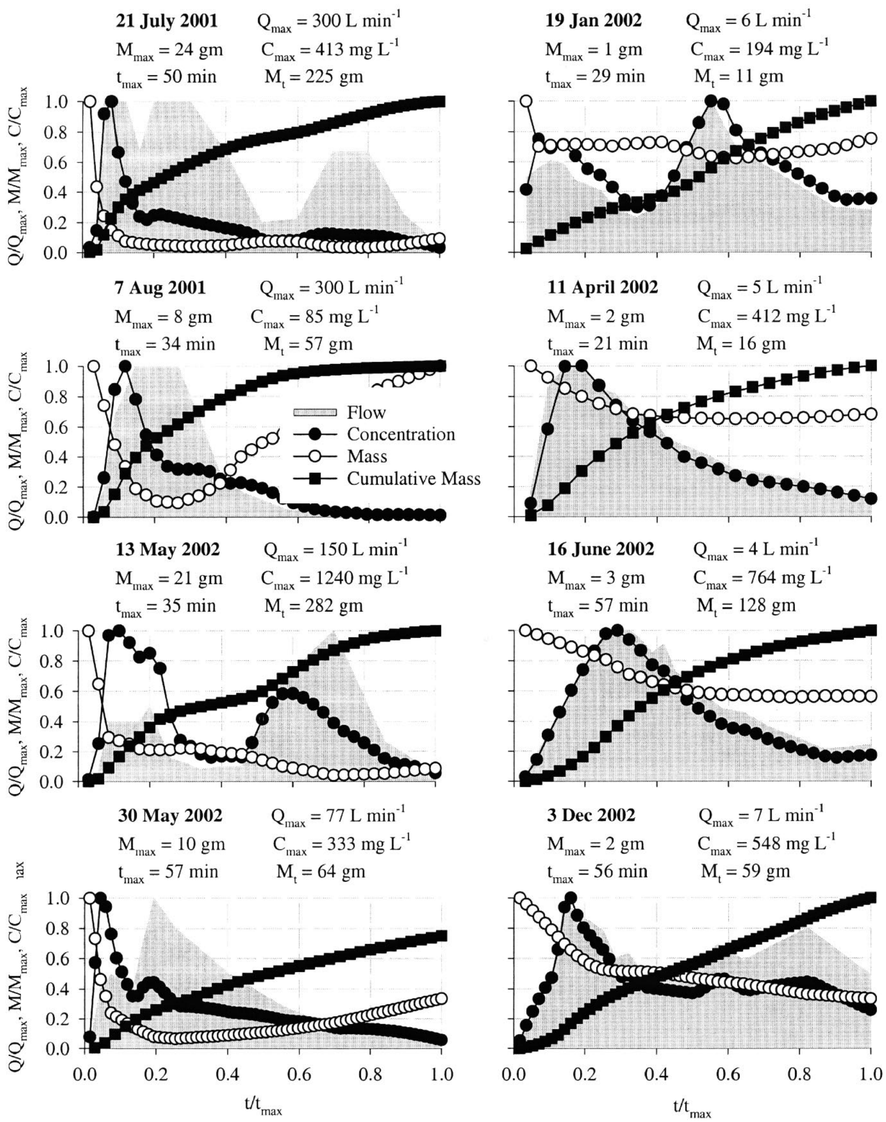

Fig. 4. Normalized flow, concentration, and cumulative dissolved mass as total dissolved solids for eight rainfall runoff events in Baton Rouge, La. Mass-limited high runoff volumes are located on left hand side of plot and flow-limited events are located on left hand side of plot.

Method III

In this variation, $M(t)$ is related to $V(t)$ through the following expression:

$$M(t) = [V(t)]^b \tag{6}$$

In this expression b=fitted exponential parameter. Values of b less than 1 indicate the occurrence of an MBFF, i.e., a disproportionately high mass delivery of mass. Values of b greater than 1 indicate that an MBFF is absent (Saget et al. 1996; Bertrand-Krajewski et al. 1998).

In addition to the methods delineated above, a number of other methods to define the first flush exist that do not fall neatly into the above two categories. The first method includes multiple linear regressions based on a number of parameters including, but not limited to, rainfall intensity, rainfall duration, and antecedent dry weather (Gupta and Saul 1996). Alternatively, common first flush criteria have been defined as the first 20 L of runoff from elevated bridge scuppers (Drapper et al. 2000), the first 1.27 cm (0.5 in.) of runoff per contributing area (Grisham 1995), the first 1.27 cm (0.5 in.) runoff per contributing impervious acre (first 3.14 cm per contributing hectare) or the volume of runoff produced by a 1 in. storm (Schueler 1987) the volume of water obtained by a 1.9 cm (0.75 in.) rainfall event (State of California 2001). Recently, the term "water quality volume" (WQV) has been used to represent the volume of runoff constituting the first flush (City of Boise 1998; Barrett 1999; State of Idaho 2001). The methods utilized in many reported investigations of the first flush are summarized in Table 1.

Objectives

There were three objectives for this study examining the delivery of common aggregate parameters of the suspended sediment fraction as SSC (mass based $d_{50} \sim 10-25\ \mu m$) and operationally dissolved fraction ($\leqslant 1\ \mu m$) as TDS from two representative small paved urban watershed sites impacted by transportation activities. This study did not focus on the delivery of the larger (gravimetrically and dimensionally) settleable and sediment (bed-load) fractions. The first objective was to review and compare common

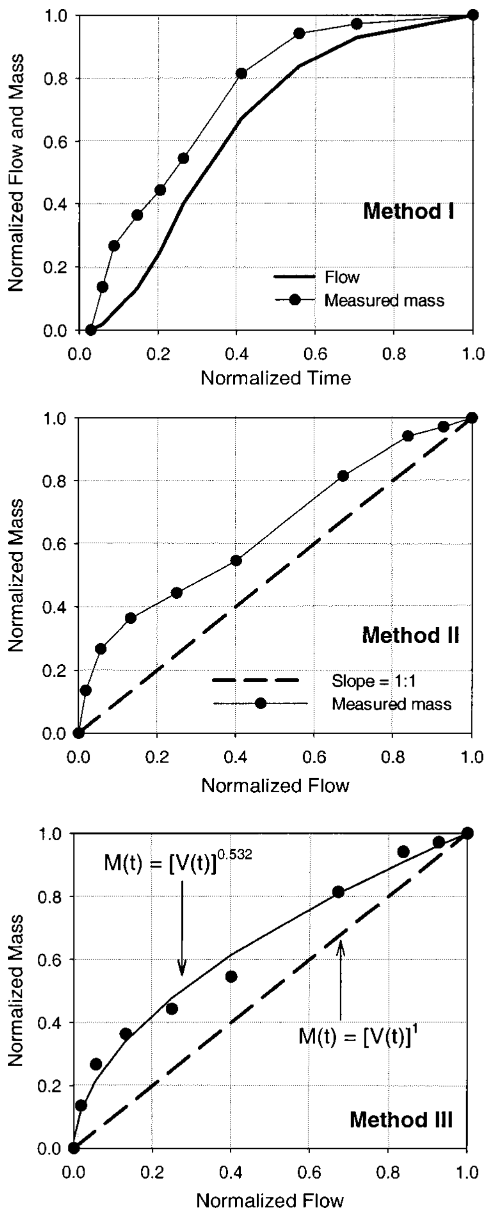

Fig. 5. Comparison of three methods to calculate mass-based first flush for 30 May 2002 event. Methods to determine mass-based first flush: method I: $M(t)$ plot resides above $V(t)$, method II: $M(t)$ exceeds 1:1 sloped line for any time, method III: exponent b of power law <1.

methodologies published of a first flush and examine common concepts and definitions of the first flush from the literature in order to arrive at a framework of interpretation for the first flush based on the delivery of SSC and TDS. The second objective was to examine whether the delivery of SSC and TDS mass and concentration was disproportionate or proportionate to the runoff hydrograph for two instrumented sites of similar land use, area, geometry, residence times, loadings, and surface conditions. As part of this objective, requirements for first-flush analysis and monitoring were considered. The third objective was to examine a number of literature estimates of the water quality volume and apply such estimates to these two urban experimental sites in order to determine the potential for concentration and mass bypass for in situ control strategies or best management practices (BMP) designed only to capture and treat the WQV in small urban watersheds.

Methodology

Site, Sampling, and Dimensionless Plot Descriptions

Eight rainfall runoff events were analyzed from each of two separate experimental sites that were hydrologically well defined. The first site is located in urban Cincinnati, Ohio along an asphalt-paved section of Interstate 75. The watershed dimensions of this segment of I 75 are 15 m long by 20 m wide (lateral pavement sheet flow length is 20 m). A full description of the Cincinnati site, sampling, and analysis methodology can be found elsewhere (Sansalone and Buchberger 1997; Sansalone et al. 1998; Cristina and Sansalone 2003). The second site is located along an elevated section of Portland cement concrete paved Interstate 10 in urban Baton Rouge, La with a drainage area of 544 m^2. A full description of the Baton Rouge site can be found elsewhere.

Water quality samples were collected at consistent 1–2 min intervals throughout each event. All samples were taken manually as discrete samples. All samples for all events were separated into SSC and TDS fractions. The SSC (TSS) and TDS were determined using Standard Methods 2540 (APHA 1992). Towards the end of each event, sampling intervals varied depending on the duration of each event. In order to facilitate the comparison of storms with different characteristics, dimensionless plots were created for each event. In each plot, the instantaneous flow rate Q was normalized to the maximum observed flow rate Q_{max}, the instantaneous concentration C was normalized to the maximum measured concentration C_{max}, the mass M transported during each measured time interval was normalized to the maximum mass M_{max} transported during any measured interval, the cumulative mass was normalized to the total mass M_T transported throughout the duration of the event, and the independent variable time was normalized to the duration of runoff.

First Flush Framework

In this study, procedures were utilized to examine a MBFF for each of the three MBFF methods. Method I is typically expressed graphically by plotting $V(t)$ and $M(t)$ on the dependent axis and normalized time on the independent axis. By definition, an MBFF occurs for any period during which the $M(t)$ plot resides above the $V(t)$ plot indicating that a disproportionately high percentage of mass has been delivered by a given volume of flow. The next variation (Method II) eliminates time as the independent variable and instead plots $V(t)$ as the independent variable. A line L with a slope of 1:1 is drawn from the origin and $M(t)$ is plotted on the dependent axis. An MBFF occurs for any period during which $M(t)$ exceeds L, which is equivalent to the conclusion reached through the use of Method I. Since L is equivalent to plotting $V(t)$ versus $V(t)$, $M(t)$ greater than L indicates that a disproportionately high mass delivery has occurred. In Method III, $M(t)$ is related to $V(t)$ through the power law Eq. (4). In this method, $b=1$ is equivalent to the line L in Method II. Values of b less than 1 indicate the occurrence of an MBFF, i.e., a disproportionately high mass delivery has occurred. Values of b less than 1 indicate that an MBFF is absent since $M(t)$ would fall below L in Method II or below $V(t)$ in Method I.

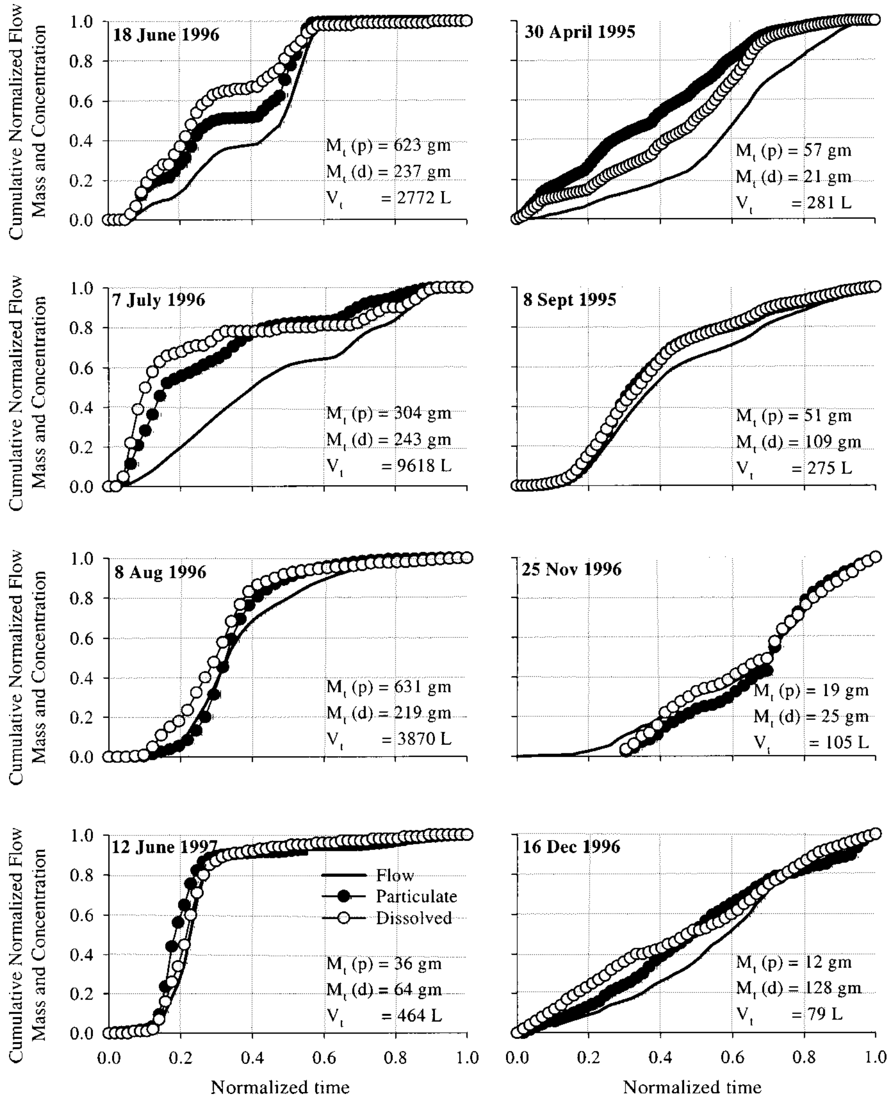

Fig. 6. Mass-based first flush plots for four high intensity events and four low intensity events in Cincinnati, Ohio

Event Mean Concentration and Partial Event Mean Concentration

Due to the high variability in pollutant concentrations throughout a given rainfall-runoff event, a single parameter known as the event mean concentration (EMC) is often used as an event-based characterization of pollutant concentration. The EMC is expressed as

$$\text{EMC} = \overline{C} = \frac{M}{V} = \frac{\int_0^{t_r} q(t)c(t)dt}{\int_0^{t_r} q(t)dt} \tag{7}$$

where EMC = event mean concentration (M L^{-3}); $\overline{C}$ = average concentration of contaminant (M L^{-3}); M = total mass transported throughout the duration of the event in M; V = total volume of runoff (L^3); $q(t)$ = functional relationship expressing runoff as a function of time (L^3 T^{-1}); $c(t)$ = pollutant concentration as a function of time (M L^{-3}); and the limits of integration refer to time 0 (the initiation of runoff) and time t_r (the time at which runoff ceases) both in units of T.

If an aggregate concentration is desired for a period of time less than the duration of runoff, a similar calculation to Eq. (1) can be employed. However, since the entire event is not considered in the calculation, the resulting concentration is referred to as a partial event mean concentration (PEMC) (Sansalone and Buchberger 1997)

$$\text{PEMC} = \frac{m(t)}{v(t)} = \frac{\int_{t_{\text{WQV}}}^{t_r} q(t)c(t)dt}{\int_{t_{\text{WQV}}}^{t_r} q(t)dt} \tag{8}$$

In this expression t_{WQV} = time at which the WQV has been satisfied and under the assumption that the BMP or control strategy is designed to capture and treat only the WQV the remainder of the runoff is bypassed from the treatment system. Therefore the limits of integration begin at an intermediate time within the runoff event and end at the time corresponding to the cessation of runoff.

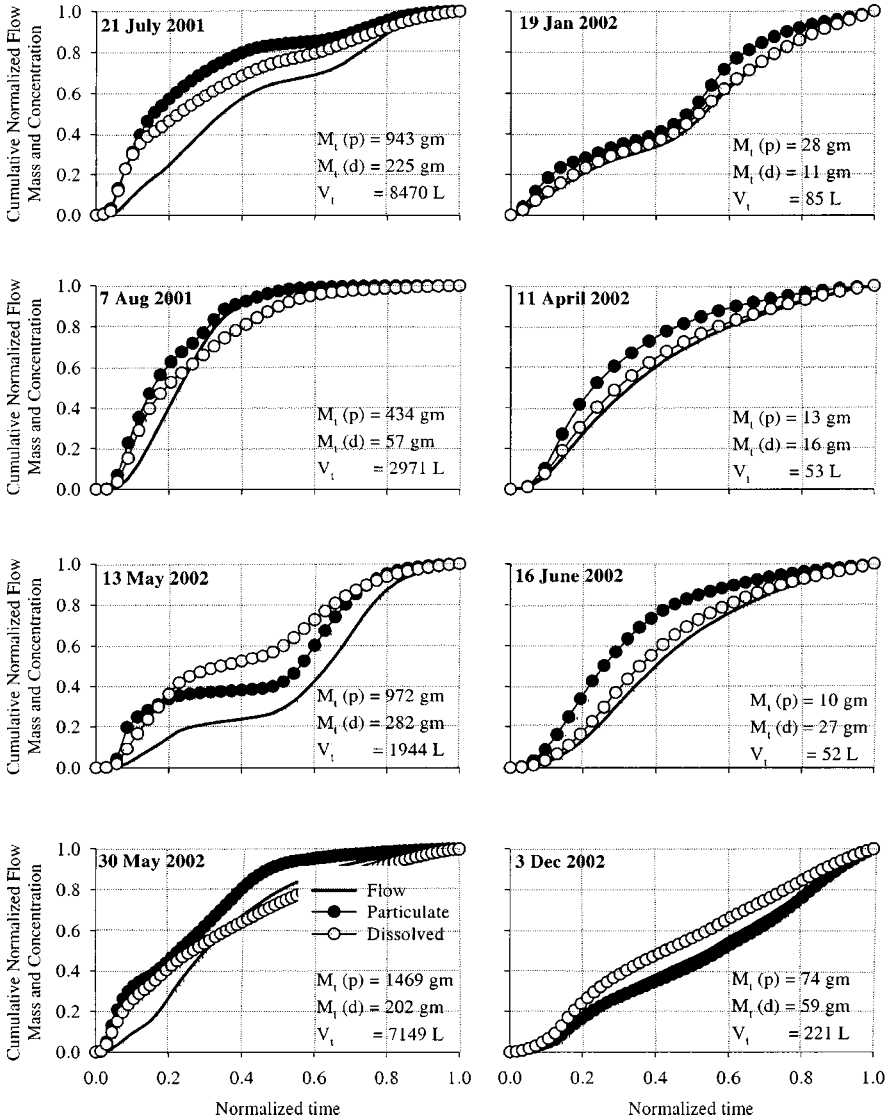

Fig. 7. Mass-based first flush plots for four high-intensity events and four low-intensity events in Baton Rouge, La.

Results

First Flush Behavior

This study examined 16 rainfall-runoff events for first flush behavior based on the CBFF, MBFF, WQV, and flow-limited or mass-limited event designations for the aggregate parameters of SSC and TDS. Each event was further classified as a mass-limited high runoff volume event or a flow-limited low runoff volume event based on the mean flow per unit width of drainage area (Cristina and Sansalone 2003). Descriptive statistics and designations of each event can be found in Tables 2 and 3. Mass-limited events were characterized by high runoff volumes, disproportionately high delivery of mass early in the event (during the rising limb of the first runoff hydrograph), and low vehicle per runoff volume ratios, while flow-limited events were characterized by low runoff volumes, mass delivery that was more proportionate to the time series of runoff hydrographs across the event, and high vehicle per runoff volume ratios (Sansalone et al. 1998; Cristina and Sansalone 2003).

The first analyses involved the investigation of the CBFF for both SSC and TDS. The plots for SSC for the Cincinnatiand Baton Rouge sites storms can be found in Figs. 1 and 2, respectively, with mass-limited events in the left hand column and flow-limited events in the right hand column for both figures. The plots for TDS can be found in Figs. 3 and 4.

Five out of the eight measured mass-limited events in Figs. 1–4 exhibit a strong, nearly first order, decline in the concentration of SSC indicative of a CBFF in which the concentration rapidly falls below 20% of the maximum concentration during the rising limb of the hydrograph for single-peak events or during the first hydrograph peak for multiple-peak events. The exceptions to this observation all occur at the Cincinnati site for the events occurring on 18 June 1996, 8 August 1996, and 12 June 1997. The first exception occurs for the 18 June 1996 event where the concentration initially falls and then alternates between increasing and decreasing trends for the duration of the event. The 8 August 1996 event for SSC exhibits a short increase in concentration during the peak of the hydrograph after which the concentration rapidly declines as expected for mass-limited high runoff volume events. The final exception is the 12 June 1997 event where the

Table 4. First Flush Analysis Based on Definition that First 20% of Flow Volume Should Transport 80% of Pollutant Load (Columns 3 and 4) and Maximum Strength of First Flush Measured for Each Event (Columns 5 and 6)

Event	Classification	$M(t)$ when $V(t)=0.2$ (total dissolved solids)	$M(t)$ when $V(t)=0.2$ (suspended sediment concentration)	Maximum $M(t)-V(t)$ (total dissolved solids)	Maximum $M(t)-V(t)$ (suspended sediment concentration)
18 June 1996	Mass limited	0.48	0.36	0.31	0.20
7 July 1996	Mass limited	0.68	0.55	0.52	0.38
8 Aug 1996	Mass limited	0.32	0.13	0.16	0.11
12 June 1997	Mass limited	0.26	0.44	0.10	0.31
21 July 2001	Mass limited	0.30	0.31	0.23	0.33
7 Aug 2001	Mass limited	0.39	0.47	0.18	0.25
13 May 2002	Mass limited	0.47	0.37	0.31	0.20
30 May 2002	Mass limited	0.37	0.41	0.18	0.23
30 Apr 1995	Flow limited	0.39	0.55	0.23	0.39
8 Sept 1995	Flow limited	0.29	0.27	0.10	0.11
25 Nov 1996	Flow limited	0.16	0.11	0.04	0.05
16 Dec 1996	Flow limited	0.40	0.32	0.21	0.15
19 Jan 2002	Flow limited	0.23	0.28	0.03	0.11
11 Apr 2002	Flow limited	0.23	0.34	0.05	0.18
16 June 2002	Flow limited	0.27	0.47	0.08	0.27
3 Dec 2002	Flow limited	0.29	0.21	0.10	0.01

concentration profile behaves similar to that of the 8 August 1996 event with the exception that the concentration increases at the end of the event.

The CBFF tends to occur less often in flow-limited events than in mass-limited events. The flow-limited events measured for this study had concentrations that were more proportional to the hydrograph. In flow-limited events, the concentration typically fell from a maximum value to a value that was 20–70% of the maximum concentration and remained in this range throughout the duration of the event. The differences between mass-limited events and flow-limited event behavior can be made somewhat clearer by noting the mass transported during each measured interval. For mass-limited events with a mean flow rate greater than 1 L $\text{min}^{-1}\,\text{m}^{-1}$ of pavement, the original supply of particulate matter appears to be rapidly diminished, nearly exhausted by the highly energetic flow of the mass-limited event. The opposite appears to be true for flow-limited events with mean flow rates less than 1 L $\text{min}^{-1}\,\text{m}^{-1}$ of roadway length. For flow-limited events, mass transport typically followed the hydrograph for the duration of the event.

Table 5. Common Water Quality Volume Criteria (A–D) from Four Literature Sources Applied to Pavement Drainage Areas for Cincinnati and Baton Rouge Experimental Sites

Method	First flush runoff volumes to be treated (L) Cincinnati (300 m^2 drainage area)	Baton Rouge (544 m^2 drainage area)
A	282	500
B	3,810	6,756
C	5,715	10,172
D	7,620	13,512

Note: A = first 1.27 cm (0.5 in.) of runoff per contributing impervious acre (Schueler 1987); B = first 1.27 cm (0.5 in.) of runoff per contributing area (Grisham 1995); C = volume of runoff produced by a 1.9 cm (0.75 in.) rainfall event (State of California 2001); and D = volume produced by a 2.54 cm (1 in.) rainfall event (Schueler 1987).

The procedure for the evaluation of the MBFF appears to be less straightforward than for that of the CBFF. However, it was found that the differences among Methods I, II, and III for an MBFF were only minor and that each method lead to the same conclusion. Fig. 5 evaluates the MBFF evaluation using each of the three described methods.

Since it was determined that the three different methods of calculating the MBFF were equivalent, Eq. (3) of Method I was chosen to evaluate the MBFF. Figs. 6 and 7 contain MBFF plots using Method I for the Cincinnati and Baton Rouge sites, respectively. Again, mass-limited events are in the left column while flow-limited events are in the right column. Fig. 6 illustrates that an MBFF based on the aggregate parameter SSC occurs for all mass-limited events with the exception of the initial portion of the 8 August event for the Cincinnati site. The Baton Rouge site had two exceptions, both occurred for the analysis of TDS including the 7 August 2001 and 30 May 2002 event shown in Fig. 7. The flow-limited events exhibit an MBFF for six of the eight examined events. The exceptions include the 25 November 1996 event for both SSC and TDS and the 3 December 2002 event for SSC only.

The final definition of the first flush investigated in this study dictates that 80% of the total pollutant load be transported by the first 20% of the flow volume (Stahre and Urbonas 1990). Table 4 contains values of $M(t)$ when $V(t)=0.2$ for each of the events in this study. By this definition, a first flush occurs for any event only if the value in Columns 3 (TDS) and 4 (TSS) have a value of 0.8. None of the events measured for this study were found to exhibit first-flush behavior according to this definition. The 7 July 1996 event came the closest to satisfying the definition with $M(t)=0.68$ when $V(t)=0.2$ for TDS and $M(t)=0.55$ when $V(t)=0.2$ for SSC. However the mean value of $M(t)$ when $V(t)=0.2$ for both TDS and SSC was found to be 0.35. In other words, an average of 15% more normalized mass was transported than nor-

Table 6. Bypassed Suspended Sediment Concentration Mass and Event Mean Concentrations (EMC) of Untreated Storm Water Bypass for Best Management Practices or Structural Control Designed to Capture and Treat Only Water Quality Volume Determined in Table 4 for Four Common Criteria of First Flush. No-Bypass (NB)

	Bypassed mass (mg) as % of influent mass First flush criterion				EMC (mg L^{-1}) of bypassed volume as a % of influent EMC First flush criterion			
Event Date	A	B	C	D	A	B	C	D
Cincinnati site (300 m^2 asphalt pavement drainage area)								
30 April 1995	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
8 Sept. 1995	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
18 June 1996	489,157	NB	NB	NB	196	NB	NB	NB
(mass limited)	79	0	0	0	87	0	0	0
7 July 96	248,866	99,708	55,637	22,022	27	17	14	11
(mass limited)	82	33	18	7	84	54	45	35
8 Aug. 96	594,275	3,160	NB	NB	166	52	NB	NB
(mass limited)	94	1	0	0	102	32	0	0
25 Nov. 1996	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
16 Dec. 1996	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
12 June 1997	7,297	NB	NB	NB	41.23	NB	NB	NB
(mass limited)	20	0	0	0	53	0	0	0
Baton Rouge site (544 m^2 concrete pavement drainage area)								
21 July 01	719,548	82,016	NB	NB	91	51	NB	NB
(mass limited)	76	9	0	0	81	45	0	0
7 Aug. 2001	257,855	NB	NB	NB	104	NB	NB	NB
(mass limited)	59	0	0	0	71	0	0	0
19 Jan. 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
11 April 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
13 May 2002	590,539	NB	NB	NB	409	NB	NB	NB
(mass limited)	61	0	0	0	82	0	0	0
30 May 2002	1,052,780	31,705	NB	NB	158	81	NB	NB
(mass limited)	72	2	0	0	77	39	0	0
16 June 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
3 Dec. 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0

malized flow volume when 20% of the total runoff volume was collected. Since no storm investigated herein was found to satisfy the definition of $M(t)=0.8$ when $V(t)=0.2$ [a first flush strength of $M(t)-V(t)=0.6$], the maximum strength of the first flush was computed for each event and can be found in Columns 5 and 6 of Table 4.

Application to In Situ Best Management Practices Capture and Bypass

For stakeholders involved in rainfall-runoff control, the MBFF and the CBFF are useful concepts. For example, there are a wide variety of control strategies or treatment BMPs that have been suggested or applied to capture either the entire rainfall-runoff event or some portion of the event such as the first flush or the WQV. These BMPs include partial exfiltration reactors (Li et al. 1999), vegetated swales (Yu et al. 2001), and wetlands (Yu et al. 1998), and emerging technologies such as hydrodynamic separators and filters. However, the design of such BMP and structural treatment controls requires an estimate of the amount of runoff requiring treatment. It is hypothesized that BMP design based on volumetric capture can have a significant impact on the overall effectiveness of the BMP for mass and concentration control even if the BMP is a highly effective unit operation and/or process. Four common methods of estimating WQV runoff bypass were investigated.

Table 5 contains treatment volume requirements using four estimates of the WQV found in the technical literature or as regulatory guidance. The focus of the last set of analyses in this study was on the mass and concentration in the runoff that bypassed a BMP utilizing these common treatment volume criteria. This runoff volume bypass was generated based on the BMP having a

Table 7. Bypassed Total Dissolved Solids Mass and Event Mean Concentrations (EMC) of Untreated Storm Water Bypass for Best Management Practice or Structural Control Designed to Capture and Treat only Water Quality Volume Depicted in Table 4 for Four Common Criteria (A–D) of First Flush. No-Bypass (NB)

	Bypassed mass (mg) as % of influent mass First flush criterion				EMC (mg L^{-1}) of bypassed volume as % of influent EMC First flush criterion			
Event date	A	B	C	D	A	B	C	D
Cincinnati site (300 m^2 asphalt pavement drainage area)								
30 April 1995	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
8 Sept. 1995	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
18 June 1996	169,294	NB	NB	NB	68	NB	NB	NB
(mass limited)	72	0	0	0	80	0	0	0
7 July-96	161,204	53,401	49,788	34,130	17	9	13	17
(mass limited)	66	22	20	14	68	36	50	68
8 Aug. 96	178,150	4,254	NB	NB	50	70	NB	NB
(mass limited)	81	2	0	0	88	124	0	0
25 Nov. 1996	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
16 Dec. 1996	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
12 June 1997	21,297	NB	NB	NB	120	NB	NB	NB
(mass limited)	34	0	0	0	87	0	0	0
Baton Rouge site (544 m^2 concrete pavement drainage area)								
21 July-01	172,196	27,600	NB	NB	22	17	NB	NB
(mass limited)	77	12	0	0	81	64	0	0
7 Aug. 2001	37,774	NB	NB	NB	15	NB	NB	NB
(mass limited)	66	0	0	0	80	0	0	0
19 Jan. 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
11 April 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
13 May 2002	125,161	NB	NB	NB	87	NB	NB	NB
(mass limited)	44	0	0	0	60	0	0	0
30 May 2002	157,555	21,188	NB	NB	24	54	NB	NB
(mass limited)	78	10	0	0	84	191	0	0
16 June 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0
3 Dec. 2002	NB	NB	NB	NB	NB	NB	NB	NB
(flow limited)	0	0	0	0	0	0	0	0

volumetric treatment capacity equal to the criteria of the WQV from the literature and applied to each of the eight rainfall-runoff events examined at each site. It was assumed that flow volumes in excess of the WQV would be bypassed from the BMP and would receive no treatment. Utilizing the cumulative measured flow and concentration data for SSC and TDS and resulting mass calculations it was possible to calculate the total mass bypassing the system during each of the events as well as the PEMC of the bypassed storm water. The values of bypassed mass, bypassed PEMC [Eq. (8)] and the percent of these quantities with respect to the BMP influent can be found in Tables 6 and 7 for SSC and TDS, respectively. No flow-limited event was found to have a volume of flow in excess of the WQV regardless of the criterion (A–D) applied. In contrast, mass-limited events illustrated varying degrees of bypass for both mass and bypass EMC. For SSC mass and concentration, criterion A always exhibited the highest percent bypass. This same result was consistent for TDS mass but criterion B resulted in a higher PEMC bypass for TDS for several mass limited events.

Summary and Conclusions

Sixteen rainfall-runoff events at two separate yet similar paved urban sites were examined in an attempt to distill the multiple definitions of the first flush phenomenon into a consistent framework. It was determined that two separate definitions of a first flush must be employed. The first definition is a CBFF and the second is a MBFF. The CBFF is defined by a high initial SSC or TDS concentration in the early portions of the storm event followed by a rapid decline (often exponential decline) in concentration throughout the event. While the CBFF has been used fairly consistently in terms of definition, the MBFF has had several forms in the literature that have been shown to be conceptually and mathematically equivalent herein and can be expressed generally as in Eq. (5).

In general, the CBFF and MBFF are both valid approaches to different goals. Many discharge permits are based on concentration indicating the need for the CBFF analysis. However, TMDLs are mass based, suggesting the relevance of the MBFF analysis. The answer as to which definition is applicable is based on control and receiving system objectives.

Many of the storm events in this study were found to exhibit both a CBFF and an MBFF based on the aggregate parameter of SSC for some portion of each event. However, exceptions to these rules do exist. The exceptions serve as reminders that the transport of particulate and dissolved mass as measured by aggregate parameters such as SSC and TDS in the rainfall-runoff process is both deterministic and stochastic and there will be combinations of hydrologic, transport, partitioning/dissolution mechanisms, and anthropogenic activities such as traffic that result in first flush behaviors that do not always neatly fall into absolute categories.

This conclusion has implications for sampling of suspended and dissolved fractions. If control of high concentrations is the goal, the sampling design for the early portion of the event is critical. However, if mass is targeted, the frequency of measurements should be based on the hydrograph shape. For instance, measuring SSC at widely spaced intervals across the hydrograph using automated sampling will not give accurate determinations of mass transport throughout the event. Rather, regular measurements throughout the duration of the event will be more representative of the event as a whole. Alternately, if automated sampling is utilized for only the suspended or dissolved fraction, sampling frequency can be variable and flow-based, thereby allowing sampling frequency to be programmed to follow the hydrograph(s). Consequently, conventional automated sampling protocols that do not account for the variable hydrology or provide a complete sampling of a storm event can generate results that are misleading.

This study also investigated four literature estimates of the water quality volume. Results indicate that treating greater volumes of runoff resulted in greater reductions in both mass and concentration as would be expected. The criterion of the first 1.9 cm (0.75 in.) of runoff (using the entire drainage area to compute the corresponding volume) appears to be an appropriate initial estimate of a water quality storm for both the Cincinnati and Baton Rouge sites. This definition would eliminate system bypass in seven of the eight events for the Cincinnati site and eliminate system bypass for each of the eight events recorded in Baton Rouge, La. While these criteria are appropriate for the sites examined in this study, sites that are representative of small urban and small transportation land use sites, application of this criterion in other climates and for larger watersheds requires separate examination.

The dilemma that is faced when considering the annual performance of structural control strategies or structural BMPs is that the mass or flow-limited behavior or a rainfall-runoff event is never known a priori. As illustrated in Tables 6 and 7 for two small paved urban sites delivering SSC and TDS, in situ BMP designs based on a fixed WQV criterion and BMP performance for the treated capture volume can result in significant misinterpretation of overall BMP benefits. Such results indicate that this misinterpretation can occur not only on an event basis (as illustrated in these tables) but also over the historical record of loading for a site. Since it appears that the determination of the WQV may be site specific, a risk based methodology incorporating both the acceptable risk of bypass and the acceptable mass of bypass may prove beneficial in the design of more effective in situ BMP.

While it was found in this study that the first flush can be detected in small watersheds, it has been previously shown that the first flush is often not evident for complex watershed with a multitude of subwatersheds each possessing unique travel times to the outlet (Wanielista and Yousef 1993). Therefore, if WQV or first flush concepts are to be utilized properly in design of watershed controls, design based on such first-flush concepts such as WQV need to be located in the upper end of the urban watershed prior to the combination of flows from variable sources and travel times.

Although the location of the BMP is important, the tenet upon which the WQV is based is the existence of the first-flush phenomenon. While it has been shown in this study that the first flush exists by some definitions both the analysis of bypass and the results of Table 4 indicate that the first flush is not significant enough to base design criteria only on an initial portion of the event if the goal of treatment is the amelioration of pollutant load. Therefore, in the absence of site-specific data that conclusively show a strong first-flush phenomenon does exist for a site, site conditions, hydrology, and loadings, BMP effectiveness criteria based on mass may require treatment of the entire runoff volume, not some initial fraction thereof.

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