Available online at www.sciencedirect.com
ScienceDirect
Chemosphere 71 (2008) 827–833
CHEMOSPHERE
www.elsevier.com/locate/chemosphere

First flush in a combined sewer system

Janet Barco [a], Sergio Papiri [b], Michael K. Stenstrom [a,*]

[a] *Department of Civil and Environmental Engineering, University of California Los Angeles, 5714 Boelter Hall, Los Angeles, CA 90095-1598, USA*
[b] *Department of Hydraulic and Environmental Engineering, University of Pavia, Via Ferrata 1, 27100 Pavia, Italy*

Received 19 June 2007; received in revised form 18 November 2007; accepted 19 November 2007
Available online 8 January 2008

Abstract

Pollutant first flush was examined in an urban catchment with area of 12.7 ha and drained by a combined sewer system located in northern Italy. A total of 23 rainfall-runoff events were monitored and 281 samples were analyzed. The selected quality parameters were biochemical oxygen demand, chemical oxygen demand, suspended solids, settleable solids, total phosphorus, total nitrogen, ammonium nitrogen, lead, and zinc, specific conductivity and hydrocarbons. A subset of representative storms was selected for first flush analysis. The catchment presented a strong first flush for almost all storms and most constituents. The analysis shows that treating the maximum amount of the early part of the runoff is a better strategy than treating a constant flow rate. Best management practices that can treat or store the first runoff are favored in this kind of system for these water quality parameters.

Keywords: Cascina Scala; Urban storm water runoff; Monitoring; Best management practices (BMPs)

1. Introduction

Although characterizing contaminants in storm water is a complex problem due to spatial and temporal variations in climate and weather conditions and the variable precipitation, it has become an increasingly important environmental issue for urban communities. Stormwater runoff typically contains significant amounts of anthropogenic pollutants as well as naturally occurring materials such as sediments from soil erosion (Weibel et al., 1964). The early runoff in a storm event is often more contaminated than the later part of runoff, which may be due to several factors, including the mobilization of material accumulated during antecedent dry periods, a lack of dilution flow and a disproportionate runoff volume from the impervious surfaces, where pollutants may accumulate. Strong first flushes are usually associated with small impervious catchments such as highways and parking lots (Ma et al., 2002), and specific rainfall patterns (Kang et al., 2006). There have been numerous studies to characterize the first flush as a function of site and weather conditions (Cristina and Sansalone, 2003). A quantitative relationship between imperviousness and catchment size and the degree of first flush has been demonstrated using a deterministic model (Kang et al., 2006). Li et al. (2005) measured the particle size distribution from a highway runoff monitoring site and reported a high first flush in particulates. Best management practice (BMP) focusing on treating first flush runoff is being considered as a more economical approach for reducing contaminates from stormwater.

This paper describes the results of a monitoring program for storm water runoff in a 12.7 ha watershed located in Pavia, Italy with a combined sewer system. A total of 23 events were sampled. This study documents the existence of strong first flush for almost all storms and most water quality parameters.

2. Methodologies

2.1. Catchment description

Fig. 1 shows the Cascina Scala urban catchment, which is located in northern Pavia (Lombardia-Italy) and

* Corresponding author. Tel.: +1 310 825 1408; fax: +1 310 206 5476.
E-mail address: stenstro@seas.ucla.edu (M.K. Stenstrom).

0045-6535/$ - see front matter © 2007 Elsevier Ltd. All rights reserved.
doi:10.1016/j.chemosphere.2007.11.049

composed exclusively of residential use, supporting approximately 1500 inhabitants. The total contribution area is 12.7 ha, where 62% of the total area is impervious (22.7% roofs and 39.6% streets and paved surfaces). The catchment is drained by a combined sewer system with 42 pipes with a total length 2045 m; the pipe has average slope of 0.042 and all pipes are constructed of concrete. Papiri (1989) has described the hydrologic and hydraulic behavior of the basin and the physical characteristics of the basin and the drainage system are reported in Ciaponi and Papiri (1994).

The catchment has been instrumented in various ways since 1989. During the period of this study, the catchment had two rainfall gauges, a flow gauge at the outlet, a refrigerated automatic grab sampler (ISCO 6700 SR, Genova, Italy) with 24 bottles, and a multi-parameter water quality measuring sonde. The two rainfall gauges (P1 and P2, see Fig. 1) were SIAP tipping bucket rain gauges (SIAP, 40050 Villanova BO – Italy) with 0.2 mm accuracy. The distance between the two rain gauges was 310 m, which allowed the spatial uniformity of the precipitation to be checked and the rainfall volume to be evaluated accurately. Stormwater runoff was measured at the outlet of the sewer system (located at the south-east corner of the catchment area, see Fig. 1) using a venturi tube with an ISCO 4230 bubbler flow meter. Temperature and conductivity were measured on site with a YSI 600 multiparameter sonde. Event mean concentrations were calculated from the grab samples and the measured flow rates. Most of the impervious areas (approximately 70%) in Cascina Scala are concentrated in the north and west of the catchment where there are mainly buildings and condominiums. The south and southeast is predominantly composed of single family dwellings.

Cascina Scala, as a combined sewer catchment, might be expected to retain sediments during dry periods which would contribute to a first flush in wet periods. This might occur because combined sewers need to be larger to accommodate storm flow, which means they are often oversized for the sanitary flow, with low velocities that allow sediments to accumulate. The drain system design has average slope of 0.042, which is high enough to avoid deposition during dry periods. Furthermore most of the sewer sections are egg-shaped that reduce sediment deposition by maintaining higher velocity at low flow rate (Bertrand-Krajewski, 2003). The drainage network has been the object of an accurate inspection and it has not been found an appreciable thickness of sediments. In addition, a continuous simulation in the sewer network using US. EPA storm water management model was carried out to check the behavior during dry periods. The results shows that the sediments deposited during the diurnal low flow period are flushed out during the diurnal maximum flow rate. These measures as well as the observation that the observed

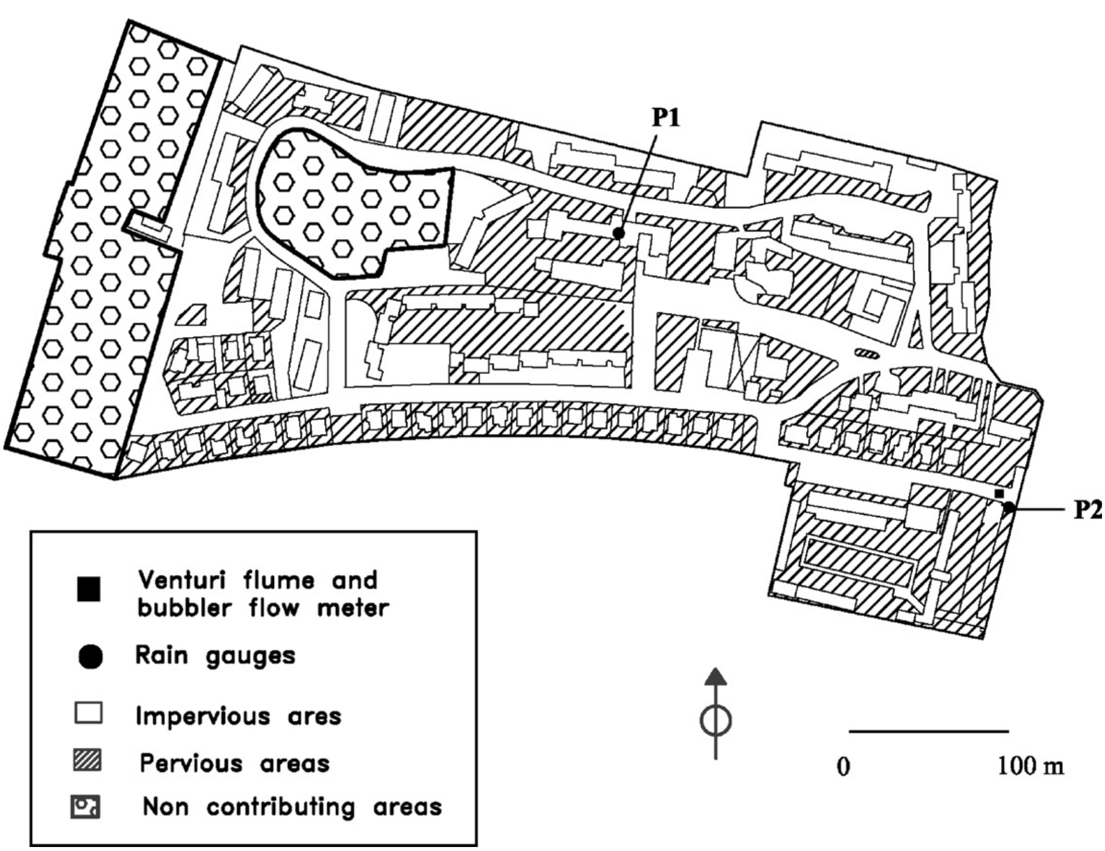

Fig. 1. Cascina Scala experimental urban catchment.

Table 1
Main characteristics of monitoring storms

Event no.	Date [d/m/y]	Rainfall length [min]	Rainfall depth [mm]	Observed volume[a] [m^3]	Max flow rate[a] [$L\ s^{-1}$]	Runoff coeff.	Dry period [d]	Collected samples
1	10/06/2000	11	12.8	634[b]	969[b]	0.44	4.2	1
2	11/06/2000	423	35.4	1655[b]	939[b]	0.41	0.4	5
3	11/06/2000	197	11.8	529	255	0.39	0.5	3
4	13/06/2000	30	2.0	28	36	0.12	0.8	1
5	23/06/2000	108	16.4	764	551	0.41	10.8	18
6	28/06/2000	23	15.6	752	850	0.42	4.8	12
7	08/07/2000	50	7.0	231	326	0.29	10.0	8
8	10/07/2000	64	11.0	455	376	0.36	1.8	12
9	11/07/2000	215	10.6	464	190	0.39	0.9	4
10	13/03/2001	247	3.8	131	33	0.30	0.3	12
11	17/03/2001	478	26.2	1416	281	0.48	3.9	24
12	28/03/2001	443	18.6	935	263	0.44	11.0	24
13	10/04/2001	111	8.4	444	157	0.47	3.3	16
14	20/04/2001	380	15.8	861	257	0.48	0.0	22
15	02/03/2003	100	4.8	223	117	0.37	0.6	7
16	09/04/2003	862	18.0	579	39	0.25	5.7	5
17	11/04/2003	964	23.4	1078	139	0.36	1.2	19
18	28/06/2003	162	38.8	2600[b]	1050[b]	0.53	29.9	20
19	24/07/2003	248	12.6	480	234	0.30	25.9	12
20	31/07/2003	231	16.2	1000	245	0.49	6.8	20
21	24/09/2003	286	7.0	186	60	0.21	14.2	9
22	26/10/2003	666	10.4	453	34	0.34	1.6	5
23	31/10/2003	1133	39.8	2702	149	0.54	1.6	22

[a] The value was estimated by numerical simulation because the sewer operated under pressure flow conditions (surcharge) for this storm.
[b] Refers to wet weather flow.

first flush magnitudes are not related to the antecedent dry periods (Table 1) suggest that Cascina Scala catchment is typical of a well designed combined sewer catchment and does not accumulate solids due to any site-specific design shortcomings.

2.2. Data collection

The rainfall-runoff data were collected from June 2000 to October 2003 with some interrupted periods due to instrumentation failures. Water quality data were collected for 23 storm events and 281 samples were analyzed in a commercial laboratory (Analytica SRL, Pavia, Italy). The data recorded by rain gages P1 and P2 (see Fig. 1) were analyzed to check the spatial distribution of the precipitation. Because of the small differences in rainfall depth and duration, only the data from gage P1 were needed. The differences between gage readings were within the expected precision of the modeling efforts, which is not surprising due to the small catchment size. Table 1 shows the characteristics of rainfall and runoff and the number of collected samples for the 23 monitored storms. The storms had rainfall depths ranging from 2 to 39.9 mm and the duration ranged from 11 to 1133 min. The dataset includes a wide range of storms with different intensities and depths. The antecedent dry days ranged from less than one day to 30 d. Thirteen of the storms were successfully sampled with 10 or more grab samples. Equipment failures or insufficient rainfall limited sampling from ten storms.

The selected quality parameters were biochemical oxygen demand (BOD), chemical oxygen demand (COD), suspended solids (SS), settleable solids (SetS), total phosphorus (TP), total nitrogen (TN), NH_3–N, Pb, and Zn, specific conductivity (SC) and hydrocarbons (HC). These parameters were analyzed in accordance with UNI EN ISO 9002 procedures and were chosen to characterize the level of organic and inorganic pollution, heavy metals and nutrients in the runoff (see Barco et al., 2004 for more detail). Table 2 shows the mean and median values, standard deviation and range of the water quality parameters for the samples collected during the 23 storms. The range in concentrations on many occasions far exceeded what might normally be expected of raw wastewater, which implies that treatment of this flow is an important goal. Table 3 compares Cascina Scala with other catchments and literature data and with urban waste water treatment directive 91/271 EEC and 91/676 prescriptions for treatment plant outlets.

A subset of representative storms was selected for first flush analysis. The selection was based upon the following criteria: (1) regular operation of rain gages and flow meter. The events, operating under pressure flow conditions were excluded; (2) total rain depth equal to or larger than 5 mm; (3) maximum rainfall intensity at least 0.1 mm min^{-1}; (4) maximum rainfall depth of at least 2 mm over a minimum of 15 min. Low intensity events were not selected because events with low rainfall intensity were too small and infrequent to be representative; and (5) completeness of the

Table 2
Basic statistics of all storm events

	SC ($\mu S\ cm^{-1}$)	COD ($mg\ l^{-1}$)	BOD ($mg\ l^{-1}$)	HC ($mg\ l^{-1}$)	SS ($mg\ l^{-1}$)	Set S ($mg\ l^{-1}$)	TN ($mg\ l^{-1}$)	NH_3–N ($mg\ l^{-1}$)	P ($mg\ l^{-1}$)	Pb ($mg\ l^{-1}$)	Zn ($mg\ l^{-1}$)
Mean	226	563	276	4.59	507	17.8	21.7	7.79	3.03	0.26	0.62
Median	205	330	160	2.10	335	10	18.0	6.28	2.18	0.08	0.41
Standard deviation	124	648	317	8.89	512	21.1	17.5	6.44	3.08	1.12	0.91
Maximum	1144	5080	2120	96.0	3880	115	128.6	39.60	26.9	13.1	9.73
Minimum	70	28	8	0.10	20	0.14	1.51	0.45	0.22	0.001	0.001

Table 3
EMC statistics for Cascina Scala compared with other databases (after Milano et al., 2002)

Pollutant	Statistics	Cascina Scala	Picchianti	NURP	QASTOR	91/271 EEC
SS	Range	242–1428	26–568	22–412	160–460	–
	Mean	499	217	91	329	<35
	Median	389	174	69	–	–
	CV	0.77	0.74	0.85	0.94	–
COD	Range	248–1143	27–267	40–184	80–320	–
	Mean	469	128	61	216	<125
	Median	415	107	57	–	–
	CV	0.63	0.65	0.39	0.89	–

Units are in $mg\ l^{-1}$.

water quality data (no missing samples or laboratory errors). After applying these conditions, eight storms with samples covering the entire experimental hydrograph, and large enough to be practical interest, remained. Table 4 shows total mass of SS, BOD and COD and the event mean concentration (EMC) for the selected storms. The EMC was calculated as a flow weighted average of the individual grab samples. Table 3 shows the range, mean, median and coefficient of variation for EMC for SS and COD for Cascina Scala compared to catchments: the Picchianti sewer catchment draining light industrial and commercial land uses (Milano et al., 2002); the nationwide urban runoff program (USEPA, 1983) from the United States for commercial land uses, and the French QASTOR database describing separate sewer stormwater systems (Saget, 1994). The urban waste water treatment directive 91/271 EEC and 91/676 requirements for treatment plant discharges are also presented. The EMC statistics from Cascina Scala are larger then the other polluted sources, and the TSS is more than ten times greater than the EEC requirement. Combined sewer catchments such as Cascina Scala can be significant sources and must be managed.

2.3. First flush background

In general the term first flush has been used to indicate that the mass emission rate is higher during the initial portions of runoff than during the last portion of the runoff. The concept of the first flush phenomenon was first advanced in the early 1970s and it continues to be debated by many researchers. Thornton and Saul (1987) defined the first flush as the initial period of storm water runoff during which the concentration of pollutants is substantially higher than those observed during the later stages of the storm event. Geiger (1987) defined the phenomenon as occurring when the slope of normalized cumulative mass emission plotted against normalized cumulative volume is greater than 45°. Saget et al. (1995) and

Table 4
Total mass and EMC of SS, BOD and COD for the selected storms

Event no.	Date [d/m/y]	Total mass (SS) [kg]	Total mass (BOD) [kg]	Total mass (COD) [kg]	EMC (SS) [$mg\ l^{-1}$]	EMC (BOD) [$mg\ l^{-1}$]	EMC (COD) [$mg\ l^{-1}$]
5	23/06/2000	311	142	307	393	180	387
7	08/07/2000	352	83	282	1428	336	1143
8	10/07/2000	187	41	121	383	84	248
13	10/04/2001	200	117	261	417	243	544
14	20/04/2001	367	197	423	384	207	443
17	11/04/2003	264	109	257	257	106	250
19	24/07/2003	247	98	242	486	192	475
20	31/07/2003	248	129	266	242	126	259

Bertrand-Krajewski et al. (1998) defined the first flush as occurring when at least 80% of the pollutant mass is discharged in the first 30% of the runoff volume.

The existence of a first flush depends on the type of pollutant, size of the catchment as well as the surfaces. Forster (1996) and He et al. (2001) observed a first flush of heavy metals from rooftops surfaces. Fam et al. (1987) and Ma et al. (2002) observed the first flush in oil, grease, TSS, COD and total organic carbon from highways surfaces. Artina et al. (2006) observed the first flush in a commercial-industrial site near Bologna Italy. In order to create a general of first flush from the various definitions and notions of first flush, a quantitative, continuous definition has been offered by Han et al. (2006), described as the mass first flush ratio or MFF. Kang et al. (2006) has shown that the magnitude of the first flush, using he MFF ratio, can be calculated as a function of surface slope, antecedent dry day ands and storm duration.

2.4. Mass first flush ratio

The magnitude of the first flush can be quantified for each storm and for each water quality parameter using a mass first flush ratio, MFF (Ma et al., 2002; Han et al., 2006). The MFF describes the fractional mass of pollutants emitted as a function of the storm progress. It can be calculated for any point in a storm and is defined as follows:

$$\mathrm{MFF}_n = \frac{\frac{\int_0^{T_1} c(t)q(t)\mathrm{d}t}{M}}{\frac{\int_0^{T_1} q(t)\mathrm{d}t}{V}} \quad (1)$$

where n is the index or point in the storm, and corresponds to the percentage of the runoff, ranging from 0% to 100%. M is the total mass of emitted pollutant, V is the total runoff volume, $c(t)$ and $q(t)$ are the pollutant concentration and runoff volume as functions of time. By definition, the MFF is equal to zero at the storm beginning and always equals 1.0 at the end of the storm. Values greater than 1 indicate first flush. For example, an MFF_{20} equal to 2.5 means that 50% of the pollutant mass is contained in the first 20% of the runoff volume. The MFF ratio is a useful tool for quantifying first flush and can be statistically characterized or used in regressions or other investigations to understand the magnitude of a first flush and storm or catchment characteristics.

3. Results and discussion

3.1. Quantification of first flush using MFF ratios

The normalized mass was plotted against the normalized runoff volume for each storm event and each water quality parameter. Fig. 2a shows the normalized mass of SS as a function of normalized flow for the eight events presented in Table 4. The slope of the mass emission line exceeds the diagonal of 45°, in almost all events, fitting Geiner's definition of first flush. The first flush is greatest for events 13 and 20 but fall short of fitting either Saget et al. (1995) or Bertrand-Krajewski et al. (1998) definitions of first flush (only 73% of the mass, as opposed to 80% of the mass is discharged in the first 30% of the runoff volume). The lack of consensus is motivation to use quantitative, continuous first flush definition such as the MFF ratio. Clearly Fig. 2a shows that the suspended solids exhibit a first flush, and two of the proposed definitions exclude this conclusion.

The same problems exist with mixed definitions for other storms and pollutants. Fig. 2b shows the first flush for SS, COD, BOD, TN, TP, lead and zinc for event no. 5. TN, COD and TP had a larger first flush than the other

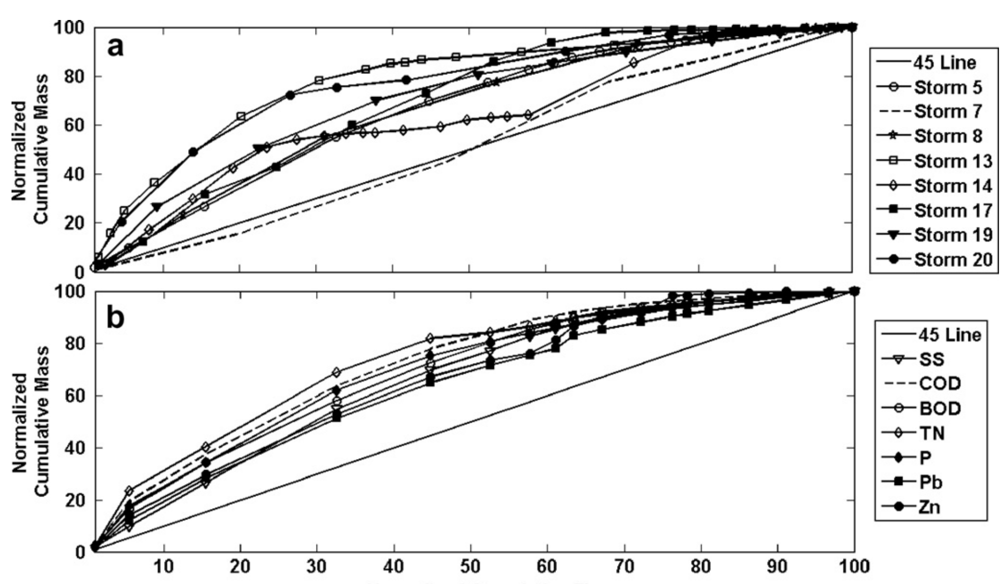

Fig. 2. Normalized mass first flush relative to normalized runoff flow. (a) Suspended solids (top). (b) Different constituents in the event no. 5 (23/6/2000) (bottom).

Table 5
MFF_{20} for selected events and parameters

Event no.	SS	COD	BOD	TN	P	Pb	Zn
5	1.7	2.2	2.0	2.4	2.1	1.7	1.8
7	0.8	0.8	1.2	0.9	1.0	3.2	1.1
8	1.8	1.8	2.2	2.0	1.8	1.8	1.4
13	3.1	1.9	1.8	1.5	1.8	4.4	1.4
14	2.2	3.2	3.2	1.5	2.3	3.0	1.7
17	1.9	1.7	1.5	0.9	1.7	1.3	1.3
19	2.3	2.1	2.1	2.2	2.1	2.0	1.8
20	3.0	3.1	3.2	2.0	–	–	–
Average	2.1	2.1	2.2	1.7	1.8	2.5	1.5

(–) No data available.

Table 6
MFF_n for event no. 5

Constituent	MFF_{10}	MFF_{20}	MFF_{30}	MFF_{40}	MFF_{50}
SS	1.7	1.7	1.7	1.6	1.5
COD	2.8	2.2	2.0	1.8	1.6
BOD	2.5	2.0	1.8	1.7	1.6
TN	3.1	2.4	2.2	1.9	1.7
P	2.5	2.1	1.9	1.8	1.6
Pb	1.9	1.7	1.6	1.5	1.4
Zn	2.1	1.8	1.7	1.5	1.4
Average	2.4	2.0	1.8	1.7	1.5

pollutants. Again, there is an obvious first flush, but it falls short of the most stringent definitions of first flush.

Table 5 shows the MFF_{20} for all events and parameters. The range of MFF_{20} is from 0.8 to 4.4. Event 7 has the lowest values of MFF_{20} for all the pollutants observed. This is probably due to the small rainfall depth (7.0 mm) and short rainfall duration (50 min) of the event. Kang et al. (2006) provided an explanation for these situations. Small intensity rainfall such as event seven typically shows weak first flush because the runoff flow does not have time to develop sufficient energy to scour and mobilize the pollutants, and short rainfall events may not have sufficient time to wash out the pollutants so that a decline in concentration can be observed near the end of the storm. The lack of a first flush for a small storm is not a disadvantage when using BMPs optimized for treating the first flush, since the entire runoff volume of a small storm may be less than the first flush volume of a large storm.

By comparing the MFF values for Pb and Zn it is possible to observe the effects of particulate or soluble phases on the first flush. Pb is known to associate primarily in stormwater runoff with particulates while Zn maybe most present in the dissolved phase (Characklis and Wiesner, 1997; Han et al., 2006). The MFF for Pb varied for different storm events resulting from different rainfall-runoff characteristics, and generally has similar trend with the MFF for SS. This is likely because of the affinity of Pb for particulate matter, resulting in similar washoff behavior with that of SS. In contrast, the Zn MFF_{20} changes only slightly for different events. This can be explained by the affinity of Zn for liquid phase. Dissolved pollutants have higher mobility and their washoff is relatively less influenced by flow energy variation resulting from different rainfall characteristics. Event 13 had the largest MFF_{20} for SS ($MFF_{20} = 3.1$) and Pb ($MFF_{20} = 4.4$). Zn and TN, both more associated with the soluble phase, had the lowest values of MFF_{20}. Table 6 shows MFF_n for storm no. 5 with n ranging from 10% to 50%. Using the MFF_{20} ratio definition, all events except storm 7 showed a mass first flush.

3.2. Implications for treatment

The treatment of stormwater to reduce receiving water impacts is an important issue facing urban managers. The reason for developing the MFF parameter was not only to provide a quantitative measure of first flush, but also to quantify the possible benefits of the first flush when developing BMP technology. Certain BMPs, such as infiltration basins, can be operated as a "first flush friendly" BMP, in that the first runoff is preferentially treated over the later runoff. For example, an infiltration basin is usually allowed to fill until the maximum capacity is reached. At this point, it must be bypassed or it changes operation to a flow through basin, becoming a clarifier. The MFF ratio provides a quantitative measure of the value of treating the early runoff compared to the remaining runoff. For example, if the MFF_{20} is 3.0, the first 20% of the runoff will contain 60% of the pollutant and each unit volume of runoff will have, on average, three times the concentration of the remaining runoff. If the cost of BMPs is proportional to volume treated, then parameters and storms with the highest MFF ratios will be most economical to treat. This concept may be used to prioritize BMPs for selection.

The higher initial pollutant concentrations early in runoff that are associated with a first flush have another important interaction with BMP-removal efficiency. It has been noted (CASQA, 2003) that many BMPs, such as sedimentation devices and filters, operate at greater efficiency when the concentrations are higher. It has also been shown that roadway runoff early in storm events contains the greatest numbers of smaller particles (Li et al., 2005). Since many metals and organic pollutants are adsorbed to particles and exist in higher concentrations on smaller particles, treating the first flush provides improved opportunity to remove particulate phase metals (Li et al., 2005, 2006). Managing BMPs so that they can treat the highest concentrations during the storm will increase efficiency. This effect can be large for Cascina Scala, since 40% of the impervious area is composed of streets and other paved surfaces.

4. Conclusions

Major conclusions drawn from this study are as follows:

- Cascina Scala, a 12.7 ha watershed using combined sewers, showed a strong first flush for 7 pollutants for 8 storms with one single exception, for suspended solids for storm 7.

- The magnitude of the first flush was large with 40% of the masses, on average, contained in the first 20% of the runoff ($MFF_{20} = 2.0$).
- The existence of a first flush presents opportunities to select BMPs that favor treatment of the early runoff, when the pollutant concentrations are highest.

The net result of selecting BMPs to take advantage of the first flush will be cost savings, since more treatment can be affected with the same investment in BMPs. In regions were combined sewers are predominately used, the large first flush should be considered with designing combined sewer overflows or storage systems, and every effort should be made to treat as much as possible of the first flush.

References

Artina, S., Bolognesi, A., Liserra, T., Maglionico, M., Salmoiraghi, G., 2006. Experimental analysis of first foul flush in an industrial area. Water Pollut. VIII: Model. Monitor. Manage. 95, 423–432.

Barco, J., Ciaponi, C., Papiri, S., 2004. Inquinamento delle acque meteoriche di dilavamento. Il caso del bacino urbano residenziale di Cascina Scala (Pavia). In: Proceedings of the XXIX Convegno di Idraulica e Costruzioni Idrauliche. Trento, Italy, September 7–10.

Bertrand-Krajewski, J.L., 2003. Sewer sediment management: some historical aspects of egg-shaped sewers and flushing tanks. Water Sci. Technol. 47 (4), 109–122.

Bertrand-Krajewski, J., Chebbo, G., Saget, A., 1998. Distribution of pollutant mass vs volume in stormwater discharges and the first flush phenomenon. Water Res. 32, 2341–2356.

California Stormwater Quality Association – CASQA, 2003. California Stormwater Best Management Practice Handbook – New Development and Redevelopment. California Stormwater Quality Association, Menlo Park, California.

Characklis, W.G., Wiesner, M.R., 1997. Particle, metals, and water quality in runoff from large urban watershed. J. Environ. Eng. – ASCE 123, 753–759.

Ciaponi, C., Papiri, S., 1994. Bacino di Cascina Scala – Codice IT04. Le Misure di Pioggia e di Portata nei Bacini Sperimentali Urbani in Italia. Publication of Centro Studi Deflussi Urbani, Milan, Italy, 1–127.

Cristina, C.M., Sansalone, J.J., 2003. First flush, power law and particle separation diagrams for urban storm-water suspended particulates. J. Environ. Eng. – ASCE 129, 298–307.

Fam, S., Stenstrom, M.K., Silverman, G.S., 1987. Hydrocarbons in urban runoff. J. Environ. Eng. – ASCE 113, 1032–1046.

Forster, J., 1996. Patterns of roof runoff contamination and their potential implications on practice and regulation of treatment and local infiltration. Water Sci. Technol. 33 (6), 39–48.

Geiger, W., 1987. Flushing effects in combined sewer systems. In: Proceedings of the 4th International Conference Urban Drainage, Lausanne, Switzerland, pp. 40–46.

Han, Y.-H., Lau, S.-L., Kayhanian, M., Stenstrom, M.K., 2006. Correlation analysis among highway stormwater pollutants and characteristics. Water Sci. Technol. 53 (2), 235–243.

He, W., Wallinder, I.O., Leygraf, C., 2001. A laboratory study of copper and zinc runoff during first flush and steady-state conditions. Corros. Sci. 43, 127–146.

Kang, J.-H., Kayhanian, M., Stenstrom, M.K., 2006. Implications of a kinematic wave model for first flush treatment design. Water Res. 40, 3820–3830.

Li, Y.X., Lau, S.-L., Kayhanian, M., Stenstrom, M.K., 2005. Particle size distribution in highway runoff. J. Environ. Eng. – ASCE 131, 1267–1276.

Li, Y.X., Lau, S.-L., Kayhanian, M., Stenstrom, M.K., 2006. Dynamic characteristics of particles size distribution in highway runoff: implications for settling tank design. J. Environ. Eng. – ASCE. 132, 852–861.

Ma, J.S., Khan, S., Li, Y. X., Kim, L.H., Ha, S., Lau, S.-L., Kayhanian, M., Stenstrom, M.K., 2002. First flush phenomena for highways: how it can be meaningfully defined. In: Proceedings of the 9th International Conference on Urban Drainage (ICUD). Portland, Oregon.

Milano, V., Pagliara, S., Dellacasa, F., 2002. Urban stormwater quantity and quality in the experimental urban catchment of Picchianti. In: Proceedings of the 2nd International Conference on New Trends in Water and Environmental Engineering for Safety and Life: Eco-compatible Solutions for Aquatic Environments. Capri, Italy.

Papiri, S., 1989. Precipitazioni e Deflussi nel Bacino Urbano Sperimentale di Cascina Scala (Pavia). Publication of Dipartimento di Ingegneria Idraulica e Ambientale, University of Pavia, Italy, p. 166.

Saget, A., 1994. Base de Données sur la Qualité des Rejets Urbains de Temps de Pluie: Distribution de la Pollution Rejetée, Dimensions des Ouvrages d'Interception. Ph.D. Thesis, Ecole Nationale des Ponts et Chaussées.

Saget, A., Chebbo, G., Bertrand-Krajewski, J., 1995. The first flush in sewer system. In: Proceedings of the 4th International Conference Sewer Solids-Characteristics, Movement, Effects and Control, Dundee, UK, pp. 58–65.

Thornton, R.C., Saul, A.J., 1987. Temporal variation of pollutants in two combined sewer systems. In: Proceedings of the 4th International Conference Urban Drainage. Lausanne, Switzerland, pp. 51–52.

USEPA., 1983. Results of the Nationwide Urban Runoff Program: Volume 1 – Final Report. United States Environmental Protection Agency, NTIS Assession Number: PB84-185552, National Technical Information Service, US Department of Commerce, Springfield, Virginia 22161.

Weibel, S.R., Anderson, R.J., Woodward, H.L., 1964. Urban land runoff as a factor in stream pollution. J. Water Pollut. Contr. Federat. 36, 914–924.