Dynamic Characteristics of Particle Size Distribution in Highway Runoff: Implications for Settling Tank Design

Yingxia Li[1]; Sim-Lin Lau[2]; Masoud Kayhanian, M.ASCE[3]; and Michael K. Stenstrom, F.ASCE[4]

Abstract: To understand the characteristics of particle size distribution (PSD) in highway runoff and to facilitate designing best management practices, PSD (2–1,000 μm) was monitored in seven rainfall events in the 2002–2003 rainy season at three highway sites in west Los Angeles. Most of the particles in number were less than 30 μm in diameter and more than 90% were less than 10 μm. Particle number concentration decreased rapidly to 6 mm of accumulated rainfall and then declined more slowly throughout the storm. Particle number concentration was correlated with total suspended solids (TSS) and turbidity. Grab sample particle median diameter increased with increasing TSS. A two-compartment settling tank was evaluated using the measured PSD and was effective in removing both small and large particles. Capturing and retaining the first 20% of the runoff volume on seasonal average can remove 40% of the total particulate load based on calculated particle mass. Using literature data for metal concentrations sorbed to particles, this size holding compartment coupled with a similar size continuous flow clarifier can achieve 65–90% removal for the metals investigated.

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Introduction

Stormwater has become a major pollution source to many urban waters (Characklis and Wiesner 1997; Barrett et al. 1998; Davis et al. 2001; German and Svensson 2002; Vaze and Chiew 2004) and highway runoff has received much attention due to the appearance of heavy metals, hydrocarbons, and fuel additives (Furumai et al. 2002). Particles in highway runoff carry a significant amount of pollutants from highways and most runoff treatment facilities such as ponds, detention basins, and wetlands are evaluated based on particle removal (Oliver et al. 1974; Herrmann 1981; Ongley et al. 1981; Hoffman et al. 1985; Hewitt and Rashed 1992; Andral et al. 1999; Legret and Pagotto 1999; Bäckström 2002; German and Svensson 2002). Therefore particle characteristics are a critical issue for highway runoff treatment (Andral et al. 1999; Furumai et al. 2002; Li et al. 2005).

Research has been performed on particle characteristics in road or highway runoff in recent years. Sediments in channels and detention basins, as well as particles transported in the runoff or collected from street surfaces were investigated. Due to possible aggregation and differential sedimentation, particle size distribution (PSD) and associated pollutant distribution in sediments are not the same as those of the suspended solids in the runoff (Slattery and Burt 1997; Roger et al. 1998). Suspended solids carried by highway runoff are usually smaller in size than sediments recovered from channel or detention basins (Roger et al. 1998). Andral et al. (1999) investigated both groups of particles for the same event and showed that the PSD of suspended solids carried in the runoff could be quite different than the sediments depending on particle diameter and other conditions. The PSD of sediments has been analyzed by sieving after drying (Sansalone and Buchberger 1997a) or before drying (Roger et al. 1998; Andral et al. 1999) and no consensus exists about the superiority of methods. Pollutant distribution across different particle size ranges has also been studied (Sansalone and Buchberger 1997a; Roger et al. 1998). Finally, it has been noted that particles in highway runoff are not stable and the PSD changes with time, which requires analysis to be performed within six hours of sample collection (Li et al. 2005).

Some recent field studies showed that fine to medium particles accounted for most of the total suspended solid (TSS) load and solid pollutant load in highway runoff. Several studies (Vignoles and Herremans 1995; Roger et al. 1998; Andral et al. 1999) demonstrated that particles less than 50 μm in diameter were 70–80% of TSS load carried by runoff by weight. Furumai et al. (2002) showed that particles less than 20 μm accounted for more than 50% of the particulate mass for runoff samples with TSS concentration less than 100 mg/L. In addition, the finest particles in highway runoff had the highest concentration for many pollutants, especially metals (Sansalone and Buchberger 1997a; Roger et al. 1998; Morquecho and Pitt 2003). Vaze and Chiew (2004) showed that most of the particulate total phosphorus (TP) and nitrogen (TN) were sorbed to particles between 11 and 150 μm in diameter with 30–60% of particulate TN associated with

[1]Ph.D. Candidate, Dept. of Civil and Environmental Engineering, Univ. of California, Los Angeles, CA 90095-1593.

[2]Research Engineer, Dept. of Civil and Environmental Engineering, Univ. of California, Los Angeles, CA 90095-1593.

[3]Associate Director, Center for Environmental and Water Resources Engineering, Dept. of Civil and Environmental Engineering, Univ. of California, Davis, CA 95616.

[4]Professor, Dept. of Civil and Environmental Engineering, Univ. of California, Los Angeles, CA 90095-1593.

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Table 1. Particle Specific Gravity

Size ranges (μm)	Specific gravity	Sampling and experimental methods	References
Stormwater sediments			
<50	2.38–2.65	Manually collected from channel;	Andral et al. 1999, Kérault Region, France
50–100	2.53–2.86		
100–500	2.5–2.82	Wet filtration-oven drying at 105°C	
500–1,000	2.51–2.7		
All sizes	2.20–2.27	Manually collected from traps installed on the bottom of a detention basin	Jacopin et al. 1999, Bordeaux, France
Street sweeping			
<63	2.19–2.56	Manual brushing and vacuuming;	Butler et al. 1992, London
63–150	2.13–2.51		
150–300	2.26–2.83		
300–600	2.02–2.41	Oven drying at 105°C-sieving	
600–1,000	1.99–2.59		
>1,000	1.89–2.53		
All sizes	2.70–3.01	Vacuuming; air drying-sieving	Sansalone and Tribouillard 1999, Cincinnati
<75	2.61	Sweeping	Bäckström 2002, Luleå, Sweden
75–125	2.58		

particles less than 20 μm and 30–50% of particulate TP associated with particles less than 20 μm. These findings suggest that removal of small particles is an important issue in the design of highway runoff treatment facilities (Furumai et al. 2002; Vaze and Chiew 2004).

Settling is effective in removing pollutants and reducing toxicity in runoff (Pitt et al. 1995). In order to evaluate pollutant removal efficiency by sedimentation, knowledge of particle characteristics and pollutant concentration as a function of particle sizes is essential. A number of researchers have investigated the settling characteristics of particles in runoff (Butler et al. 1992; Andral et al. 1999; Jacopin et al. 1999; Bäckström 2002; Furumai et al. 2002; Vaze and Chiew 2004). Tables 1 and 2 summarize literature data on particle characteristics—Table 1 shows particle densities and Table 2 shows metal concentrations as a function of particle sizes with metal concentrations increasing with decreasing particle sizes. For additional metal allocation with different particle size ranges, readers can refer to Biggins and Harrison (1980), Ellis and Revitt (1982), Stone and Marsalek (1996), and Sutherland (2003).

The objective of this study is to characterize PSD in highway runoff and its correlation with other water quality parameters, such as TSS and turbidity. Using this information, a better sedimentation basin design is proposed.

Methodology

Site Description

Three sites in west Los Angeles were monitored in the 2002–2003 rainy season. These three sites were chosen as typical highway sites (0.39–1.69 ha) with heavy traffic load (greater than 260,000 vehicles per day) and within 15 min travel time to the lab at the Univ. of California, Los Angeles (UCLA). Close proximity to UCLA was important to facilitate rapid analysis of the PSD, as well as other parameters. PSD was always measured within 6 h of sample collection. Rainfall and flow rate were recorded by tipping bucket rain gauges and American Sigma (Loveland, Colo.) 950 flow meters installed at each site. Flow meters were calibrated in our lab using a 610 mm (24 in.) wide flume with flow measuring instrumentation before the rainfall season started. More information about sites can be found in Ma et al. (2002) and Li et al. (2005).

Sample Collection Procedures and Particle Size Analysis

Grab samples were manually collected with a polypropylene scoop at a free water fall where runoff exited the drainage pipe. In this way, a representative sample for the whole flow cross sectional area was obtained. The first grab sample was collected at the beginning of runoff, which was usually within a few minutes after the onset of rainfall. Grab samples were taken at 15 min intervals in the first hour of runoff and at 1 h intervals over the next 7 h. PSD was analyzed with a Nicomp (Santa Barbara, Calif.) PSS AccuSizer 780 Optical Particle Sizer module equipped with an auto-dilution system and a light scattering/extinction sensor (Model No. LE1000-2SE). This module has a measurable range of 2–1,000 μm. TSS and turbidity were also measured and reported in this paper. A large suite of other parameters were measured and have been reported elsewhere (Han et al. 2006). For additional information on sample collection and particle size analysis, please refer to Li et al. (2005).

Settling Methods

Various methods have been utilized to remove particles in highway runoff, such as sedimentation basins, ponds, wetlands, grassy swales, and slow sand filters (Nix and Daykin 1992; Hvitved-Jacobsen et al. 1994; German and Svensson 2002). All depend on particle size and the settling velocity associated with each particle size, particle shape, and density. Design of these devices is complicated by site-specific issues, including available space. In order to evaluate the potential impact of particle size on efficiency, a simplified analysis was used and site-specific issues were left for later consideration.

Stormwater runoff volume varies with total rainfall. For this

Table 2. Metal Concentrations for Different Particle Size Ranges

Size ranges (μm)	Heavy metal concentration (μg/g)								Sampling and experimental methods	References
	Al	Cd	Cr	Cu	Fe	Ni	Pb	Zn		
Urban stormwater suspension										
0.45–2				2,894	29,267		199	13,540	Manually collected samples; wet sieving	Morquecho and Pitt 2003, Birmingham and Tuscaloosa, Ala.
2–10				4,668	18,508		868	13,641		
10–45				735	26,221		229	1,559		
45–106				1,312	14,615		226	2,076		
106–250				2,137	21,730		375	3,486		
>250				50	28,604		117	266		
Highway runoff sediments										
25–38		16.8		364			265	1189	Manually collected from trough; drying at 110°C- sieving	Sansalone and Buchberger 1997a, Cincinnati
38–45		17.2		353			236	996		
45–63		17.3		364			266	1,027		
63–75		16.3		333			258	1,057		
75–150		15		312			248	1,014		
150–250		9.2		204			195	574		
250–425		8		78			65	325		
425–850		9.5		48			53	314		
850–2,000		9.7		45			37	259		
<50	60,000		350	420		230	1,570	4,370	Manually collected from collection channel; wet sieving-drying at 105°C	Roger et al. 1998, Hérault region, France
50–100	45,000		400	250		250	1,480	1,700		
100–200	38,000		410	200		220	1,550	1,100		
200–500	35,500		150	100		220	850	930		
500–1,000	37,500		140	50		220	460	930		
Street sweeping										
<75				470				410	Vacuuming; sieving	German and Svensson 2002, Jönköping, Sweden
75–125				270				230		
125–250				340				190		
250–500				200				120		
500–1,000				50				70		
<43		5	46	220		65	350	960	Vacuuming; air drying- sieving	Lau and Stenstrom 2005, Los Angeles
43–100		5	58	230		50	300	805		
100–250		2	38	230		40	210	500		
250–841		na	12	240		5	44	150		
Average		1	28	238		25	142	360		

reason, the removal rate is influenced by storm size. Therefore, an average approach must be used, which addresses a portion of the storms based upon their magnitude. Several design criteria have been considered, which include retention time, overflow rate or minimum critical settling velocity, and strategies that collect and hold a fraction of the initial runoff. In this study, we evaluated a two-compartment sedimentation design based upon our PSD measurements. Particle settling velocity was calculated using Stokes' law for particles smaller than 40 μm in diameter and Newton's law for larger particles with the Reynolds number larger than 0.05, as well as the assumption that all particles have a density of 2.6 g/cm^3 and are spherical in shape.

Throughout this paper, the terms "particles" or "particle concentration," means the number of individual particles—not the particle mass or surface area. Particle mass will always be indicated as "particle mass," which is calculated from the measured PSD data by assuming spherical particles and a uniform density of 2.6 g/cm^3. "Particle removal" or "pollutant removal," means the mass of particles or pollutant mass sorbed to particles that is removed, and is calculated using the same assumptions.

Results and Discussion

Statistical Description of PSD

Table 3 summarizes the events. Li et al. (2005) described some events in greater detail, including typical hydrographs and grab

Table 3. Event Summary

Event date	Grab sample amount	Antecedent dry day (days)	Event rainfall (mm)	Runoff volume (m^3)	Max intensity (mm/h)	Rainfall duration (h:min)	Runoff duration (h:min)
Site 1							
November 7, 2002	14	40.1	29.0	210	10.2	47:31	44:09
December 16, 2002	11	16.4	29.7	348	16.3	6:00	21:58
December 19, 2002	13	3.3	36.1	436	20.3	7:16	14:57
February 11, 2003	12	44.3	23.4	235	15.2	10:32	15:04
Site 2							
November 7, 2002	14	41.2	58.7	826	14.2	46:29	46:43
November 29, 2002	5	20.2	1.8	23	3.1	7:44	8:14
December 15, 2002	8	16.1	2.5	30	2.0	3:20	4:38
December 16, 2002	10	1.2	59.9	826	35.6	6:02	10:17
February 11, 2003	12	44.3	24.4	339	10.2	11:57	13:01
April 15, 2003	12	27.8	21.3	311	9.7	15:59	16:14
Site 3							
November 7, 2002	14	40.2	71.4	178	12.2	47:05	47:38
November 29, 2002	6	20.2	1.5	1	2.0	6:52	7:21
December 16, 2002	8	0.3	40.6	125	27.4	3:52	4:45
December 19, 2002	11	3.1	32.5	108	15.2	7:05	7:40
February 11, 2003	12	44.1	20.1	44	10.2	15:38	12:47
April 15, 2003	10	27.8	19.8	53	19.3	15:38	18:26

sample PSD. A total of 172 grab samples were analyzed from the three monitoring sites. Total particle (2–1,000 μm) concentration ranged from 4,100 to 3,742,000 mL^{-1} with a median value of 147,700 mL^{-1}. For the counted particles between 2 and 1,000 μm in diameter, the median particle diameter of all grab samples ranged from 2.72 to 7.15 μm.

To quantitatively describe the PSD, a number fraction was defined as follows:

$$\text{number fraction} = \frac{\text{total number of particles in a certain size range}}{\text{total number of particles } (2-1{,}000\ \mu\text{m})} \quad (1)$$

The fraction can be applied to a single grab sample or an entire event. For an entire event, the total number of particles is calculated in a fashion that is analogous to calculating total pollutant mass (Ma et al. 2002).

Fig. 1 shows the number fraction (top) and calculated mass fraction (bottom) of particles in different size ranges, which were calculated for all events for the entire runoff. The horizontal axis indicates the individual particle diameter ranges. The box plots show the number fraction and mass fraction of particles in individual size ranges for all events at three sites. The continuous lines correspond to the right vertical axes and are the accumulated number fraction (top) and the accumulated mass fraction (bottom) of median values of distinct size ranges. Fig. 1 demonstrates that small particles are large in number but contribute less to calculated mass. From the accumulative lines, more than 90% of particles in number are less than 10 μm whereas their mass contribution is less than 10%. Particles larger than 100 μm contribute more than 60% of the calculated mass.

Particle concentrations decreased with increasing accumulated rainfall, as shown in Fig. 2, which demonstrates the particle concentrations of all grab samples from three monitoring sites for all 16 storms in the 2002–2003 rainy season. There was a sharp falloff in particle concentration at the beginning of the storm, which continued to about 6 mm of accumulated rainfall. After 6 mm, the rate of decline in particle concentration decreased. These results dramatically demonstrate particle first flush.

The pollutant concentration or number of particles in the runoff from the start of runoff to any point of time can be expressed by a running average, calculated in a fashion similar to the calculation of event mean concentration (EMC) and is termed partial event mean concentration (PEMC) (Sansalone and Buchberger 1997b; Lee et al. 2002). For the number of particles in the runoff, the particle PEMC is the accumulated number of particles at any time divided by the accumulated flow volume at the same point of time, as shown in

$$\text{PEMC} = \frac{n(t)}{v(t)} = \frac{\int_0^t c_1 q_1 dt}{\int_0^t q_1 dt} \quad (2)$$

where $n(t)$=particle number transported up to time t; $v(t)$=flow volume up to time t (m^3); c_t=particle number concentration at time t ($\#/m^3$); q_t=flow rate at time t(m^3/s); and t=time (s).

EMC is also defined by Eq. (2) when it is integrated to the end of the runoff. If the particle number and flow are normalized, the particle number first flush ratio is provided by Eq. (2) (Li et al. 2005).

Fig. 3 shows the runoff, accumulated runoff, rainfall intensity, and particle PEMC of a typical storm event. The particle PEMC peaked just a few minutes after the beginning of runoff and then decreased rapidly to an asymptotic value (EMC). The PEMC declined to 120% of the EMC after 55% of the total runoff occurred. For the storms shown in Table 3, on average, the PEMC decreased to 150% of the EMC after half of the event rainfall. This implies that treating the initial portion of runoff would be more efficient than treating the later runoff, which is of critical importance for best management practice (BMP) design.

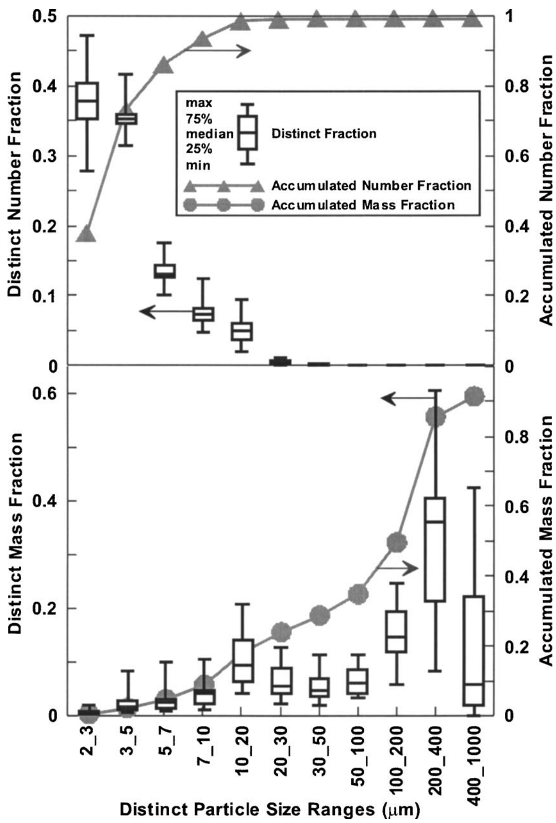

Fig. 1. Particle number fraction of all events at three sites in 2002–2003 rainy season

Correlation among Particle Concentration, Total Suspended Solids, and Turbidity

TSS and turbidity concentrations increased with increasing particle concentrations, as shown in Fig. 4. The log of particle concentration was linearly correlated to the log of TSS and turbidity with R^2 values of 0.689 and 0.692 and significance p value of less than 0.001. The log of TSS and turbidity were also correlated with R^2 of 0.485 and p value less than 0.001. The correlation among TSS, turbidity, and particle concentration suggests that these parameters might be useful surrogates for each other. Possible pitfalls for using the correlation exist when applying it to different land uses where the PSD or correlations might be different.

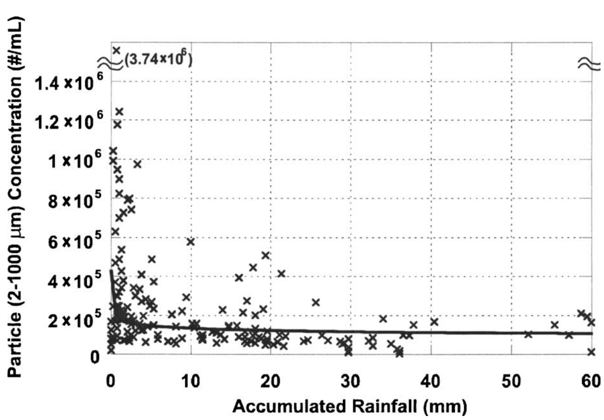

Fig. 2. Particle (2–1,000 μm) concentration of grab samples versus accumulated rainfall

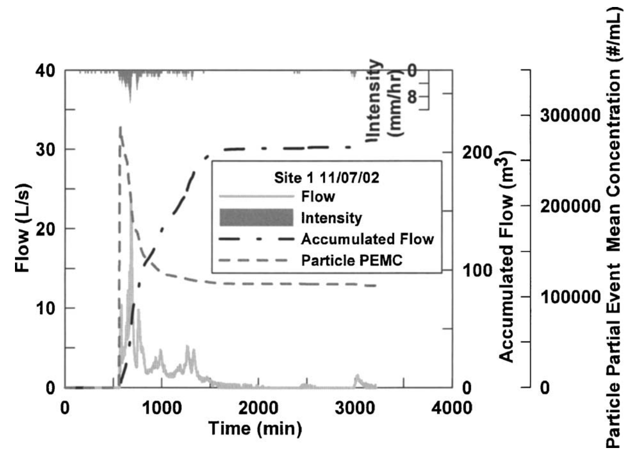

Fig. 3. Hydrograph, accumulated runoff, and particle partial event mean concentration of event November 7, 2002, Site 1

Fig. 5 shows particle median diameter of grab samples as a function of TSS concentration for all sites. The correlation is better for lower TSS concentrations and is more scattered at higher TSS concentrations. This occurs because larger particles contribute more to TSS load than smaller particles and the number of larger particles is much more variable than the number of small particles (please refer to Li et al. 2005 for the accuracy of the instrument for the larger particles). For example, for TSS concentrations greater than 200 mg/L, the contribution of particles larger than 30 μm was more than 60% by mass (assuming spherical particles with uniform density in all size ranges).

Application of PSD to BMP Design

Knowledge of the PSD provides an opportunity to evaluate and suggest better BMP design. More important, if the solid phase

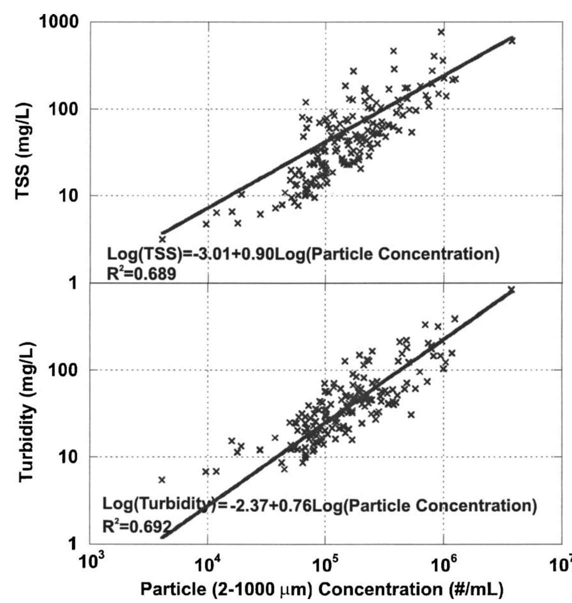

Fig. 4. Particle (2–1,000 μm) concentration of grab samples versus TSS and turbidity

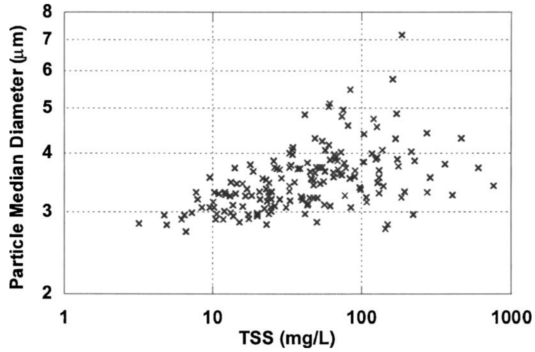

Fig. 5. Particle median diameter of grab samples versus TSS

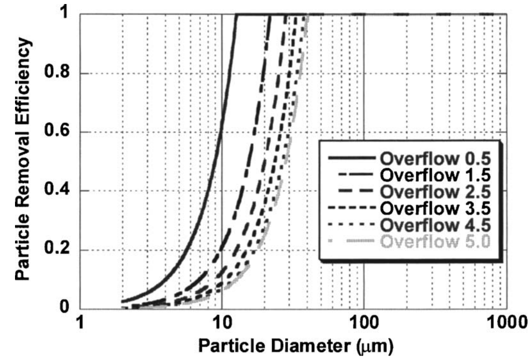

Fig. 7. Particle removal efficiency at different overflow rates (assuming spherical particles; uniform specific gravity 2.6; discrete settling with Newton's and Stokes' settling velocities; overflow 0.5 refers to overflow rate of 0.5 m/h)

concentration (i.e., pollutant mass per unit mass of particles) is known as a function of particle size, overall pollutant removal rates can be calculated.

Measured PSD data were used to perform particle and pollutant removal simulation for the 2002–2003 rainy season and is described in the following paragraphs. The total rainfall for this season and location was 280 mm (11 in.) and was slightly less than the long-term average of 380 mm (15 in.). There were 12 storms compared to the average of 16 storms (Wong et al. 1997). The 2002–2003 season characteristics are within one standard deviation of the average storm and are considered typical and useful for simulation. Years with very different rainfall characteristics would have different particle and pollutant removal results.

We propose a two-compartment sedimentation design after evaluating several settling tank design criteria, such as retention time, overflow rate or minimum critical settling velocity, and strategies that collect and hold some fraction of the initial runoff (Fig. 6). The first compartment is designed to capture and retain the initial runoff for a defined period (24 h in our example case). The extended holding time allows a greater fraction of the smaller particles to settle. This compartment removes most of the particles and associated pollutants contained in the initial part of runoff or the particle first flush (Li et al. 2005). The second compartment is a continuous flow sedimentation tank or clarifier, which treats the later runoff that bypasses the first compartment. The continuous flow clarifier mainly removes the larger particles. The size of the tanks can be optimized to remove the most particles for a given total volume or construction cost. The optimization will depend on the particle size distribution for each site, the target pollutant, and its concentration as a function of particle size.

To evaluate the pollutant removal efficiency of the proposed two-compartment sedimentation tank, it was necessary to calculate particle removal efficiency, as well as pollutant removal efficiency. The literature data presented in Tables 1 and 2 were used. We assumed the particles to have homogenous density of

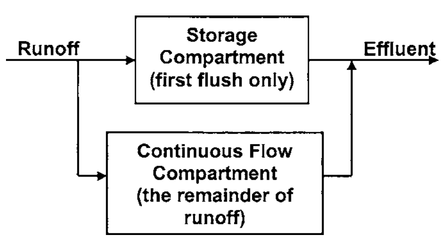

Fig. 6. Two-compartment sedimentation design

2.6 g/cm^3 and to be spherical in shape in calculating particle settling velocity and mass based particle and pollutant removal efficiency. The actual shape of the particles is probably not spherical (Sansalone et al. 1998), but this assumption is considered sufficient for this demonstration.

Impact of Particle Settling Velocity

Discrete (Type I) settling analysis was used to analyze the performance of the proposed two-compartment tank. The particles observed in our samples were not flocculent and were too low in concentration to create hindered or zone settling (Types II, III, and IV). The discrete particle terminal settling velocity was calculated using Newton's law or Stokes' law (Tchobanoglous et al. 2003). The overflow rate ($Q/A, m^3/m^2\,s$) was used to determine which particle was removed; particles with greater settling velocities were removed completely.

In an ideal situation, for a continuous flow settling tank, particles with settling velocities equal to or larger than the overflow rate are totally removed and particles with settling velocities smaller than the overflow rate are removed at a rate equal to particle settling velocity divided by overflow rate. Fig. 7 shows the calculated particle removal efficiency as a function of diameter for different overflow rates. Particles with diameters larger than 40 μm are totally removed at overflow rates as high as 5 m/h, whereas particles with diameters smaller than 10 μm are difficult to remove even at very low overflow rates. In addition, the error introduced by our assumptions (specific gravity 2.6 g/cm^3, spherical shape, and discrete particle settling) will be larger at smaller diameters and the expected removal for smaller particles will be even less—Bäckström (2002) has noted this phenomenon. Applying his recommendations, the particle removal efficiency decreases by up to 95% for the smallest particles. For example, Fig. 7 shows a removal efficiency of 47% for 15 μm diameter particles at overflow rate 1.5 m/h. By using Bäckström's suggestions, the removal efficiency decreases to 10%.

For the holding compartment, removal efficiencies are also calculated using Stokes' and Newton's laws. In this case, the particles must settle from their initial height in the tank to the bottom of the holding compartment. Again, Bäckström's suggestion can be evaluated. With his suggestion, total particle (2–1,000 μm) removal reduces by less than 6%, whereas associated pollutant

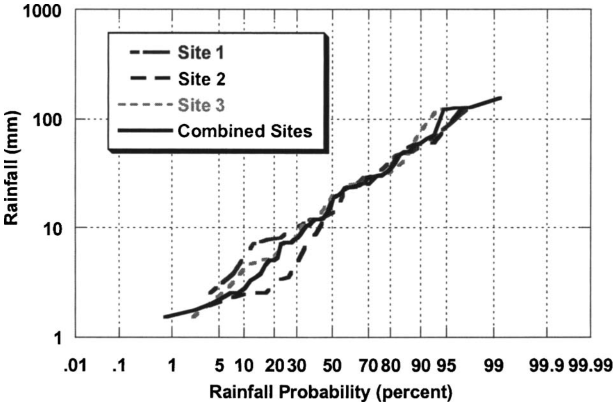

Fig. 8. Rainfall probability for three sites monitored in 2000–2003 rainy seasons

removal decreases up to 32% in our sample calculation. The reason for this is that small particles have much higher associated pollutant concentration than large particles, as shown in Table 2, and most of the removal efficiency decrease is due to the reduced settling velocity of small particles.

Impact of Flow Variability-Design Storm

Rainfall is highly variable and a probabilistic basis must be used for tank design. We chose to use rainfall probability based on total event rainfall. Fig. 8 shows the probability of total rainfall for our 2000–2003 monitored events for the three sites taken separately and combined. For different rainfall probability, the corresponding rainfall amount is termed the "design storm" which can be design storm of storage compartment (DSs) or design storm of continuous flow compartment (DSc), as shown in Fig. 9. For example, the 50% rainfall corresponds to a design storm of

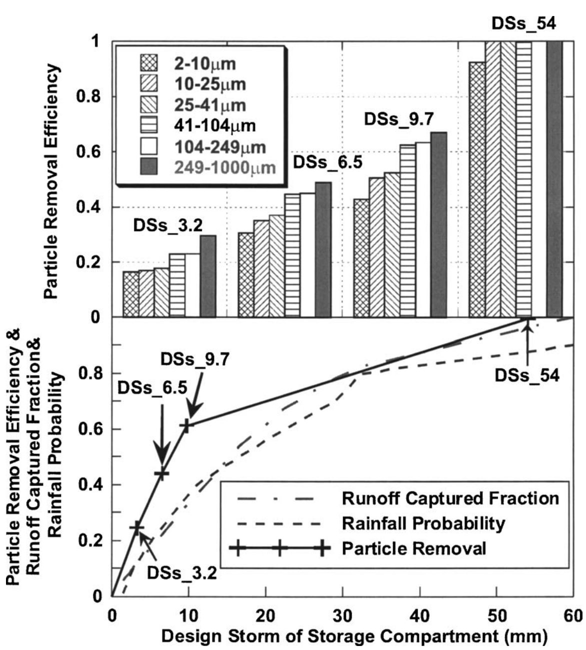

Fig. 9. Simulated seasonal (2002–2003) particle removal efficiency with only storage compartment (e.g., DS_3.2 refer to design storm of storage compartment 3.2 mm)

18 mm. For this design storm, assuming the runoff coefficient to be 0.95, the total runoff volume for Sites 1, 2, and 3 (catchment area 0.39, 1.28, and 1.69 ha, respectively) are computed to be 219, 289, and 67 m^3, respectively.

Particle and Pollutant Removal Efficiency

Measured PSD data were used, which divided particle concentrations into 512 size ranges, log evenly distributed between 2 and 1,000 μm. Particle settling velocity was calculated for each range using the average diameter of the particles in that range. Removal by the holding tank was assumed if the settling velocity was greater than the critical velocity. Removal by the continuous flow clarifier was assumed if the particle settling velocity was greater than the overflow rate and the overflow rate was calculated as the instantaneous runoff flow divided by the clarifier surface area. Removal based upon particle number was calculated in this fashion, and by assuming spherical geometry and a specific gravity of 2.6, mass removal was calculated. Sorbed pollutant mass removal was calculated using the literature data in Table 2. Removal for larger size intervals was calculated by combining the data of the smaller included intervals. In this respect, the intervals used by previous investigators were matched.

The design procedure we propose is to set the storage compartment volume equal to the runoff for the DSs. The depth of the storage compartment is assumed to be 3 m, which also determines its area since the volume is fixed. All storms less than or equal to the design storm are completely captured and retained. We ignore the possibility of two storms occurring within 24 h, which did not occur in our study. For larger storms, the excess is treated only by the second compartment continuous flow clarifier. The method used to determine surface area of the continuous flow compartment is similar to that used for the storage compartment.

Fig. 9 shows the simulated removal of particle with only the storage compartment for the entire 2002–2003 season. The bottom panel shows the overall particle removal efficiency and the top panel shows the particle removal efficiency for particles within the defined size ranges for different DSs. The horizontal axis shows the design storm of storage compartment. The vertical axis shows the overall particle removal efficiency, the seasonal runoff captured fraction, the design storm's probability (bottom), and the removal efficiency for individual particle size range (top). The impact of the first flush is shown, for example, at a design storm of 5.1 mm or 20% probability, storage compartment removes 35% of the particle mass, while capturing only 17% of the runoff volume. The simulation shows that the storage compartment with 24 h retention time will remove most of the particles less than 10 μm in diameter and all the particles larger than 10 μm that were captured. Larger particles show higher removal efficiency than smaller particles, which is due to larger particles' greater settling velocity and stronger first flush than smaller particles (Li et al. 2005).

Figs. 10 and 11 are similar to Fig. 9. Fig. 10 shows the simulated seasonal particle removal efficiency with only the continuous flow compartment. For the same size storage and continuous flow compartments, the storage compartment is better for removing particles smaller than 10 μm (e.g., 17% in Fig. 9 for DSs of 3.2 mm versus 7% in Fig. 10 for DSc of 3.2 mm) and is poorer for removing particles larger than 10 μm, especially for particles larger than 25 μm due to the limited

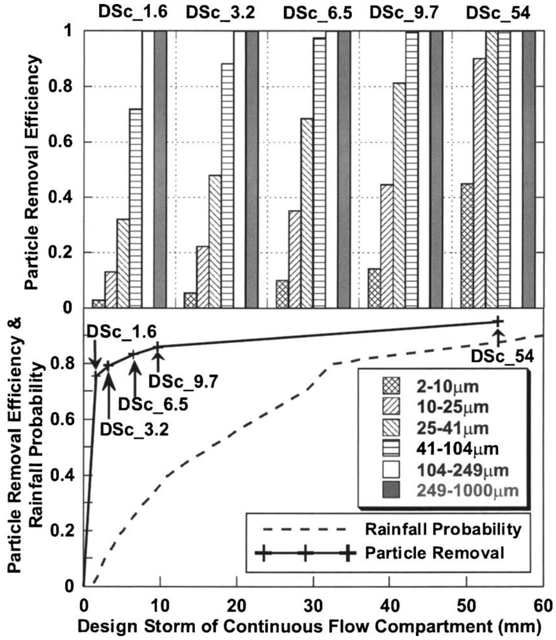

Fig. 10. Simulated seasonal particle removal efficiency with only continuous flow compartment (e.g., DSc_3.2 refer to design storm of continuous flow compartment 3.2 mm)

holding capacity. All of the particles larger than 100 μm can easily be removed by the continuous flow compartment. Fig. 11 shows the particle removal efficiency with both compartments. The top of Fig. 11 shows total particle removal within defined size ranges by two compartments—various storage compartment volumes with a fixed size continuous flow compartment with DSc of 3.2 mm. The bottom of Fig. 11 shows total particle removal by two compartments—various storage compartment

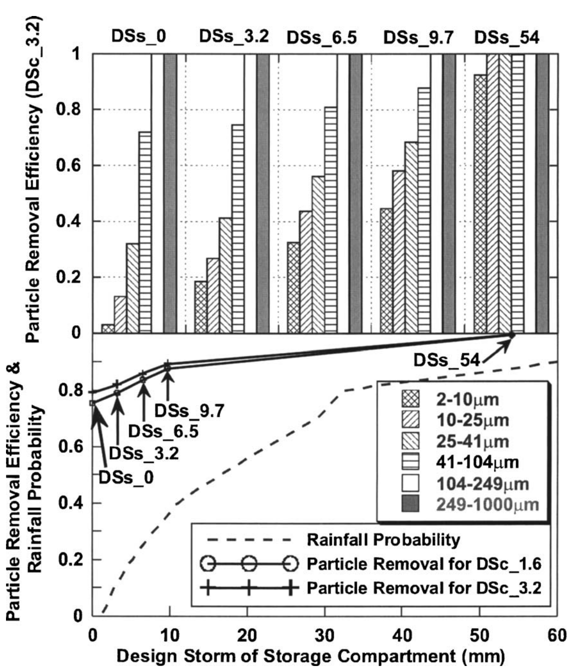

Fig. 11. Simulated seasonal particle removal efficiency with two-compartment settling tank (e.g., DS_3.2 refer to design storm 3.2 mm)

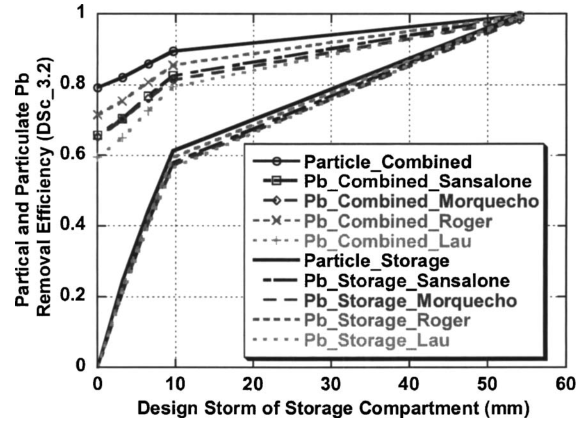

Fig. 12. Seasonal particle and particulate Pb removal efficiency when design storm of continuous flow compartment is 3.2 mm

volumes with a continuous flow compartment with DSc of 1.6 mm or 3.2 mm. Although total particle removal only increased from 80 to 89% with DSc of 3.2 mm when DSs increased from 0 to 9.7 mm, removal of particles between 2 and 10 μm in diameter increases from 3 to 45%. By using both compartments, better removal efficiency for both small particles and large particles is achieved.

To determine pollutant removal efficiency from particle removal efficiency, the pollutant concentrations on the particles as a function of size must be known. The two-compartment design will show the greatest advantage over a single continuous clarifier when the pollutants are more concentrated on the smaller particles. We evaluated removal of eight metals including aluminum (Al), cadmium (Cd), chromium (Cr), copper (Cu), iron (Fe), nickel (Ni), lead (Pb), and zinc (Zn) using five different sets of concentration vs. size data, as shown in Table 2. Fig. 12 is an example of the particulate Pb removal efficiency. The lower group of lines in Fig. 12 shows the removal efficiency of particles and particulate Pb by the storage compartment and the upper group of lines demonstrates removal efficiency by both compartments. The removal by the storage compartment calculated using different researchers' Pb concentration data are similar. This occurs because nearly all of the captured particles are removed in the storage compartment. The combined removals of both compartments are different for different researchers' Pb data. For example, the overall removal of particulate Pb is 76% for the concentration of Roger (1998) and 65% for the concentration of Lau (2005) when both DSs and DSc are all 3.2 mm. In general, when pollutant concentrations are higher on large particles the removal efficiency will be higher because the larger particles are removed more efficiently. In the two-compartment settling tank design, when the targeted pollutant is more associated with small particles, a larger storage tank will be preferred. Conversely, when the targeted pollutant is more associated with larger particles, a larger continuous flow compartment should be used.

Conclusions

Some previous studies have shown that small particles accounted for most of the particulate pollutant load carried by stormwater runoff for certain pollutants, such as total phosphorus and nitrogen. In this study, particle size distribution was measured during individual storm events over the 2002–2003 rainy season. More than 90% of the particles in number were less than 10 μm in diameter. Particle number concentrations declined with accumulating rainfall. Log transformed particle number concentrations were linearly correlated with TSS and turbidity. Grab sample median particle diameter increased with increasing TSS concentration.

A two-compartment settling tank demonstrated improved mass removal efficiency for both small and large particles. Pollutant removal efficiency was evaluated using several researchers' published solid phase pollutant concentrations. When the targeted pollutant was more associated with smaller particles, a larger storage compartment resulted in higher removal efficiency. When the targeted pollutant was more associated with larger particles, a larger continuous flow compartment produced better removal efficiency. The observed particle first flush more than doubled the removed particle mass as compared to hypothetical runoff that had no particle first flush.

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