Optimization of Settling Tank Design to Remove Particles and Metals

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Abstract: Mass reduction rates of particles and metals were simulated for a two-compartment settling tank composed of a storage compartment and a continuous flow compartment. Particle-size distribution, rainfall, and flow data from 16 storm events measured at three highway sites were used. The volume ratio (i.e., ratio of surface areas for a given depth) between storage and continuous flow compartment was optimized for a given design storm size to maximize total mass reduction rates of particles and heavy metals. Measured settling velocity profiles of runoff samples were used in the simulation. Simulation results showed that in a given total design storm, larger storage compartment fractions (>0.95) enhanced the removal of smaller particles (2–104 μm) and particulate phase metals, and even a small fraction (<0.05) of continuous flow compartment effectively removed larger particles (104–1,000 μm). A volume fraction of 0.75 for the storage compartment is suggested to optimize annual reductions of particles and associated heavy metals.

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CE Database subject headings: Stormwater management; Highways and roads; Runoff; Particle size distribution; Best Management Practice; Settling velocity; Heavy metals; Pollution; Optimization.

Introduction

Nonpoint source pollution has become the leading cause of the deterioration of water bodies in the United States because of continuing urbanization and the reductions from point sources due to wastewater treatment plant construction. Heavy metals, hydrocarbons, and fuel additives in roadway runoff, including highways, can be serious threats to the quality of receiving waters (Colwill et al. 1984; Driscoll et al. 1990; Young et al. 1996; Barrett et al. 1998a). Due to the nondegradable, accumulative, and toxic character of heavy metals, highway runoff treatment has become increasingly important. In addition, because of the episodic nature of storm-water discharges, large variability in pollutant concentrations, and the implementation of more stringent water quality regulations, such as total maximum daily loads, special attention is being given to mitigate pollutants from highway runoff.

Various treatment methods have been utilized to treat storm water, including detention basins (Jacopin et al. 1999), sedimentation tanks (Aldheimer and Bennerstedt 2003), ponds (Hvitved-Jacobsen et al. 1994), wetlands (Birch et al. 2004), biofiltration, such as grassy swales and strips (Barrett et al. 1998b; Bäckström 2003), vortex or swirl concentrators (Lee et al. 2003), and slow sand filters (Barrett 2003). The California Dept. of Transportation (Caltrans) has undertaken pilot studies with a variety of methods, including extended detention basins, infiltration basins and trenches, wet basins, media filters, biofiltration, drain inlet inserts, continuous deflection separators, oil/water separators, multichambered treatment trains, and silt traps (Caltrans 2004). The performance of each treatment method strongly depends on particle size, shape, and density, and associated settling velocity. Several researchers have investigated particle settling velocities in storm water with different methodologies and obtained different results (Aiguier et al. 1996; Michelbach and Weiß 1996; Krishnappan et al. 1999; Bäckström 2002). However, a common finding of these studies was that larger particles are removed more easily than smaller particles as intuitively conjectured.

A number of factors influence treatment efficiency, including influent pollutant concentrations, runoff magnitude, and facility size. As shown in Table 1, removal efficiencies highly vary depending on the pollutant type and treatment and analysis methods, from negative to 98%. The use of simple treatment efficiency as an indicator of performance has been questioned by Strecker et al. (2001), who believe that comparing effluent concentrations is a more robust way of estimating performance.

Some of the treatment systems, such as sedimentation tanks (Sonstrom et al. 2002; Aldheimer and Bennerstedt 2003) and dry detention ponds (Stanley 1996) are designed to capture the first flush of runoff and bypass the following, greater flow. The efficiency calculation is often based only on the treated portion, and bypassed pollutant mass may not be considered, which overestimates pollutant reduction rate. In addition, the dynamic behavior of flow and pollutant concentrations throughout a storm as well as seasonal changes should be considered when evaluating the per-

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Table 1. Removal Efficiency (%) of Different Treatment Methods

BMP types (references)	TSS	Turbidity	COD	Total P	Total N	TKN	Cd	Cu	Cr	Fe	Ni	Pb	Zn	Fecal coliform	TPH	OG[a]
Grassy swales	−85–75	69–78	61–63	34–44		33–44				75–79		17–41	75–91	−477–192		
(Barrett, et al. 1998b; Bäckström 2003)	85–87															
Constructed wetlands and wet ponds	60–80			25–65		20–55							20–60			
(USEPA 1993; Birch et al. 2004)	−98–46			12	16	9		65	64	−84	22	65	52	76		
Sedimentation tank (Aldheimer and Bennerstedt 2003)	66–99			26–95	−26–40		0–92	18–96	37–98		0–94	50–99.8	30–97			−35–87
Sedimentation chamber (Sonstrom, et al. 2002)	77–88			67		18							85	−7	16	
Continuous flow clarifier (Clausen et al. 2002; Waschbusch 1999)	21–34		20	17–29		32	27	25				24	17–60	−15	12	
Oil-grit separator (Clausen et al. 2002; West et al. 2001)	49			74		44							45	99	37	
Swirl concentrator (Lee et al. 2003)	65–70															
Filtration (Papiri et al. 2003)								98				98	98			95

Note: BMP=best management practice; TSS=total suspended solids; COD=chemical oxygen demand; Total P=total phosporous; TKN=total Kjeldahl nitrogen; Cd=cadmium; Cr=chromuim; Fe=iron; Ni=nickel; Pb=lead; Zn=zinc; TPH=total petroleum hydrocarbon.

[a]Oil and grease.

formance of treatment facilities (Whipple and Hunter 1981; Characklis and Wiesner 1997; Lee et al. 2004). Removal efficiency is usually greater for higher influent pollutant concentrations (Strecker et al. 2001; Lau et al. 2001). Because pollutant concentrations tend to decrease as rainfall or runoff progresses (Sansalone and Buchberger 1997; Larsen et al. 1998; Krebs et al. 1999; Li et al. 2005), enhancing initial runoff (i.e., first flush) treatment can improve overall performance of a treatment facility.

Partitioning of metals between dissolved and particulate phases is important to evaluate removal efficiencies because most treatment methods remove particles as opposed to removing soluble species. The partitioning information can be conveyed by the dissolved fraction value, f_d, which is defined as the proportion of dissolved mass of a metal element divided by the total mass of the metal element or the sum of dissolved and particle-bound mass (Sansalone and Buchberger 1997). Large f_d values indicate that the metals are mainly in dissolved form. Table 2 shows selected f_d values reported by different researchers. Although there exists some variation in f_d values from different references, aluminum (Al), chromium (Cr), iron (Fe), and lead (Pb) are mainly in particulate form in highway runoff. Lower pH and higher average pavement residence time are associated with higher dissolved metal fraction (Sansalone and Buchberger 1997). At the same time, metal element dissolution/adsorption kinetics plays an important role in their partitioning. Sample holding time also has a significant influence on the partitioning of some metal elements such as copper (Cu), Pb, and nickel (Ni), with particle-phase concentrations increasing with increasing holding time.

In this study, particle and metal removals in a two-compartment settling tank were simulated using measured particle-size distribution (PSD), particle settling velocity profiles, and wet particle specific gravity, complemented with literature data on solid phase concentrations of metals. The settling tank has two compartments—one compartment (storage compartment) to capture and retain the initial runoff (i.e., first flush) and the other compartment (continuous flow compartment) that functions as a continuous flow clarifier for treating the remaining runoff. The optimum fraction between the two compartments for various design storm sizes (DSs) is obtained using the simulation results. The results can be used to optimize settling tank design.

Methodology

Storm Events for Settling Tank Performance Simulation

To simulate performance of the two-compartment settling tank, precipitations, flows, and PSDs of grab samples for 16 storm events (1.5–71.4 mm total event rainfall) measured during 2002–2003 wet season at three highway runoff sites in west Los Angeles were used. PSDs were measured using a Nicomp Particle Sizing Systems AccuSizer 780 optical particle sizer module (Santa Barbara, Calif.), which quantifies the number of particles in 512 intervals over the size range of 2–1,000 μm. The AccuSizer 780 utilizes light scattering or obscuration to detect particles passing through the sensing zone. The detected pulses by the sensor have different pulse height and detect frequency depending on the mean particle diameter and particle numbers, which are directly converted to PSD using a calibration curve previously prepared.

Annual precipitation for the year 2002–2003 was about the average historical annual precipitations in the Los Angeles area,

Table 2. Dissolved Fraction f_d Values for Metals

Al	Cd	Cr	Cu	Fe	Ni	Pb	Zn	Reference
Embedded sediments from highway runoff								
0.04 (0.003–0.31)	0.54 (0.45–0.96)		0.62 (0.31–0.71)	0.03 (0.01–0.13)		0.21 (0.18–0.45)	0.85 (0.54–0.96)	Sansalone and Buchberger 1997
Suspended solids in highway runoff								
0.29	0.008	0.18	0.01			0.05	0.53	Pitt et al. 1995
	0.2 (0.03–0.49)		0.28 (0.07–0.53)			0.03 (0–0.17)	0.25 (0.04–0.56)	Gromaire-Mertz et al. 1999
			0.11–0.44			0.04–0.21	0.11–0.45	Furumai et al. 2002
	0.2 (0.17–0.33)		0.22 (0.13–0.24)		0.12 (0.09–0.2)	0.03 (0–0.03)	0.26 (0.22–0.32)	Westerlund et al. 2003
	0.79	0.21	0.59		0.61	0.07	0.72	Our data, seasonal average
Suspended solids in urban runoff								
	0.78	0.16	0.63	0.03		0.18	0.28	Morquecho and Pitt 2003

Note: Data in parentheses show the range of observation.

which corresponds to approximately 60% probability (i.e., 60% of annual precipitations will be less than the 2002–2003 precipitation). More details on site descriptions, the 16 storm events, and sample collection procedures have been discussed previously (Li et al. 2005).

Wet Particle Specific Gravity

No consensus-based definition and methodology for wet particle specific gravity (WPSG) exist in the literature. Particles are usually dried in an oven to measure specific gravity (SG). However, the drying step may significantly change particles' physicochemical characteristics (i.e., size), modifying settling behavior of particles (Krein and Schorer 2000). The WPSG may be a more reasonable parameter to represent the particle density determining virtual settling velocity in storm water.

Direct Measurement

Stored highway runoff samples were filtered through 0.45 μm membranes. A 10 mL volumetric flask was filled with 9 mL deionized water by a pipette and weighed. Wet solids on the membranes were carefully taken into the flask until the water surface reached the 10 mL line. As the solids were taken from the membranes, minor changes in shape or texture of the wet solids might occur but chemical properties and mixing ratio of solid and water absorbed in the solids are conserved. The flask was weighed immediately after adding wet solids. The weight increase as the unit of 10^{-1} g was defined as the wet particle specific gravity.

Indirect Estimation

As an alternative method for estimating WPSG, total suspended solids (TSS) mass and total particle volume measured in the same runoff sample can be compared (measured within 6 h after collection). Our measurements of highway runoff particles showed that the contribution of particles between 0.5 and 2 μm to the total particle volume concentration is less than 4% and was neglected, and therefore TSS (mg/L) mass can be directly related to total volume concentration ($\mu m^3/mL$) of particles between 2 and 1,000 μm as follows:

$$\text{WPSG} = \frac{\rho_p}{\rho_w} = \frac{V_s\rho_s + (V_p - V_s)\rho_w}{\rho_w V_p} = f\left(\frac{\rho_s}{\rho_w} - 1\right) + 1 \tag{1}$$

$$f \simeq \frac{10^6 \times \text{TSS}}{\rho_s \sum_i n_i \frac{\pi D_{p,i}^3}{6}} \tag{2}$$

where ρ_p=wet particle density (g/cm^3); ρ_s=particle density (g/cm^3); ρ_w=water density (g/cm^3); V_s=solid volume of wet particles (μm^3); V_p=total volume of wet particles (μm^3); f =fraction is fraction of solids volume to total volume of wet particles $(=V_s/V_p)$; TSS=total suspended solids concentration (mg/L); n_i=number concentration of particles in size range i (number/mL); and $D_{p,i}$=diameter of particles in size range i (μm).

Particle Setting Velocity Profile

Sedimentation experiments were conducted using the stored highway runoff samples that had stable particle-size distribution. Li et al. (2005) showed that particles may grow rapidly in the first few hours after collection followed by decreased growth rate. Therefore, in the real situation, particles will grow in a settling basin, increasing their settling velocities. For simple and more conservative calculation of particle settling efficiency, it is assumed that no change in PSD occurs during the settling process and thereby particles settle discretely (Type I settling). Eight settling tests were performed with four different stored samples to obtain settling velocity profiles. First, a highway runoff sample stored in a 1 L plastic column was completely mixed by gently inverting the column five to six times and then a small volume of sample from 0.5 to 5 mL, depending on the particle number concentration, was removed from the 1 L column for initial PSD measurement. Next, the particles were allowed to settle undisturbed over 48 h. During this period, 0.5–5 mL volumes of samples for PSD measurement were removed from 17 cm below the water surface (about 50% of the depth) of the column using a wide bore pipette at various time intervals. Great care was taken to insert the pipette into the water column and remove the fluid very slowly to avoid disturbing the liquid. The sampling height (17 cm) was divided by each sampling time to obtain particle settling velocities. The number of removed particles was calculated by subtracting PSD at each sampling time from the PSD at the initial time. Measured particle settling velocities were compared with settling velocities calculated with Newton's law.

Event Removal Efficiency and Total Reduction Rate of Particles

Using data from each storm event and the settling velocity profile of different size particles obtained from the sedimentation experiments, PSD in the water column after settling were obtained for specific size fractions corresponding to the compartments in the two-compartment settling tank simulation. The particle numbers for each particle size range were converted to the particle masses and summed to obtain total particle mass, assuming spherical shape and uniform density of particles within each size fraction. The removal efficiencies calculated for each of the 16 storm events were used to calculate the total particle mass reduction and was always based on the total particle mass generated by the 16 storm events (i.e., sum of particle mass entering settling tank and bypassed particle mass). Throughout this paper, the terms "particle removal (or reduction)" or "metal removal (or reduction)" refer to the calculated mass of particles or metal mass sorbed to the particles that are removed.

Event Removal Efficiency in the Storage Compartment

To simplify the particle removal calculation, particle removal that might occur in the storage compartment during filling time was ignored; this is reasonable because there will be turbulence during filling and as the storage compartment is capturing the first flush, the filling time will be short. Particle removal rate is a function of critical settling velocity, v_c (m/day), which was a single value of 3 m/day, assuming a tank depth of 3 m and holding time of 24 h (v_c=3 m/24 h) in this study. The removal efficiency of particle can be calculated using the classic relationship developed for ideal discrete settling (Metcalf and Eddy Inc. 2003)

$$E = 1 - f_c + \frac{1}{v_c}\int_0^{f_c} v_p df \tag{3}$$

where E=particle removal efficiency; f_c=fraction of particles with settling velocity v_c or less; and v_p=settling velocities of specific size particles.

Event Removal Efficiency in the Continuous Flow Compartment

Practically, the continuous flow compartment should be operated through three steps: fill, flow through, and drain. The time for tank filling was ignored to simplify the calculation. Because particle removal in an ideal continuous settling is only a function of overflow rate (v_c), which is the ratio of flow rate to tank surface area, removal efficiency is independent of tank volume or retention time. Tank depth or volume will determine tank filling and draining time when the initial operation is based on initially dry tank, which is assumed here. That is, as the tank depth or volume decreases, tank filling and draining times decrease and vice versa. With these assumptions, Eq. (3) can be utilized to calculate the removal efficiency of particles in the continuous flow compartment. The overflow rate of the continuous flow compartment changes over time and, therefore, time-varying values of v_c were used (i.e., instant flow rate/tank surface area). The use of time-varying flow and PSD during the storm measured by grab samples, the particle removal efficiency for the two-compartment settling tank can be calculated.

Metal Removal Efficiency

Particulate metal removal efficiency was calculated by Eq. (4) using the concentrations for different particle size ranges shown in Table 2. Assuming no dissolved metal removal by sedimentation, total metals removal efficiencies were calculated from particulate metal removal efficiencies using Eq. (5). Table 2 shows the dissolved metal fractions measured by different researchers and our observations from the 16 storm events

$$\text{particulate metal removal efficiency} = \frac{\sum_i c_i m_i^r}{\sum_i c_i m_i} \tag{4}$$

$$\text{total metal removal efficiency} = \frac{\sum_i c_i m_i^r}{\sum_i c_i m_i} f_p = \frac{\sum_i c_i m_i^r}{\sum_i c_i m_i}(1 - f_d) \tag{5}$$

where c_i=particulate metal concentration in particle size range i; m_i^r=removed particle mass in size range i; m_i=initial particle mass in size range i; f_p=particulate metal fraction; and f_d=dissolved metal fraction. Our averaged 2002–2003 dissolved metal fraction f_d values were used to calculate total metal removal efficiency for individual metal species, except for Fe, for which we used the average value in Table 2 (i.e., f_d=0.03 for Fe).

Optimum Tank Design to Maximize Total Reduction Rate

Our preliminary finding (Li et al. 2006) is that a two-compartment settling tank effectively removes both large and small particles with one compartment dedicated to storing the first flush and the other compartment as continuous flow clarifier to treat the later part of runoff. Due to the long holding period (24 h), the storage compartment is more efficient in removing the small particles. Depending on storm size, the continuous flow compartment is primarily responsible for removing large particles.

The following analysis investigates the relative size of the two compartments for a fixed total tank size (storage+continuous flow compartment). Assume a fixed total tank size is realistic because the total budget and site availability for treatment facilities is limited, especially in urban areas. The optimum volume fraction (i.e., surface area fraction given a fixed depth of 3 m) of storage and continuous volumes in the two-compartment settling tank was determined by maximizing the total reduction rate of particles or metals for the 16 storm events using

$$\text{total reduction rate} = \frac{\sum_{i=1}^{16} M_{\text{rem}}(\text{PSD}, \text{flow}, \Psi, V_T, r)_i}{\sum_{i=1}^{16} M_{\text{runoff}}(\text{PSD}, \text{flow})_i} \tag{6}$$

where $M_{\text{rem},i}$=total mass removed for the ith storm event; $M_{\text{runoff},i}$=total mass generated in the ith storm event; PSD=particle-size distributions; flow=runoff flow rate; ψ=particle settling velocity profile; V_T=total volume of the two-compartment settling tank; and r=fraction of storage compartment in a given V_T. The V_T value can be calculated by multiplying the design storm size (1.6–52 mm) by the catchment area (0.39, 1.69, and 1.28 ha for the three sites, respectively) and runoff coefficient (0.95). The maximum total reduction rate can be esti-

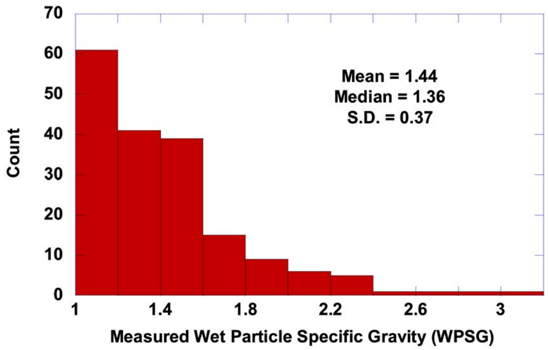

Fig. 1. Frequency histogram of wet particle specific gravity (180 grab samples from the 16 storm events during the 2002–2003 wet season)

mated by evaluating Eq. (6) using small, incremental values of r from 0 to 1.0.

Results and Discussion

Wet Particle Specific Gravity

Wet particle specific gravity measurements were conducted three times with stored runoff samples. The WPSG ranged from 1.30 to 1.42 with an average of 1.35. Fig. 1 shows the frequency histogram of WPSGs calculated by Eqs. (1) and (2) using a total 180 grab samples from the 16 storm events. Approximately 75% of total grab samples have WPSGs less than 1.6. Variation in WPSGs among grab samples is relatively small (SD=0.38). Mean and median of WPSGs are 1.36 and 1.44, respectively, which are close to the measured range of WPSGs (1.30–1.42).

Particle Settling Velocity Distribution

Fig. 2 shows the averaged particle settling efficiency from eight settling tests compared with several cases of ideal discrete settling with different particle densities and shapes. The horizontal axis represents settling velocity and the vertical axis represents the remaining particle mass fraction (2–400 μm), which is the remaining suspended particle mass divided by initial mass. Particle mass in the sedimentation experiment was calculated from several

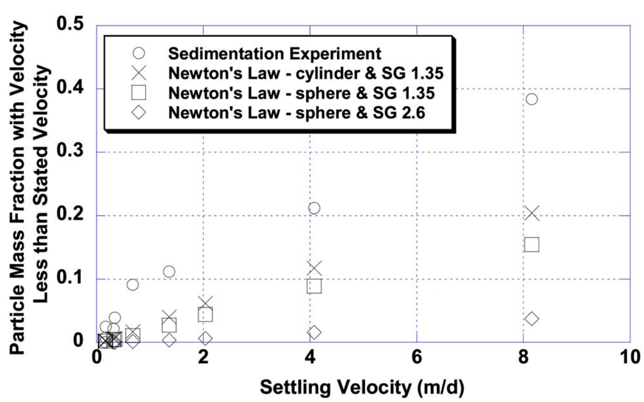

Fig. 2. Comparison of experimental and calculated particle (2–400 μm) settling characteristics

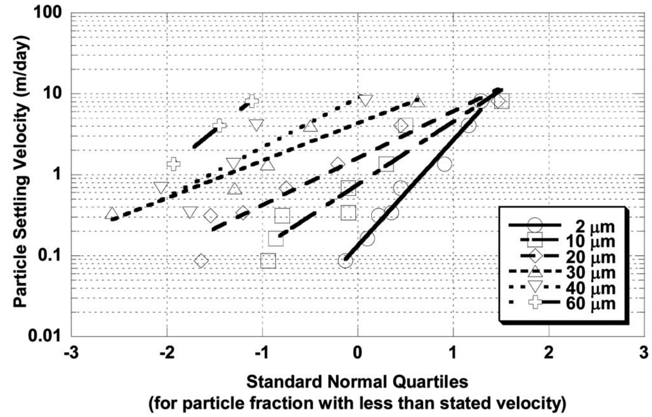

Fig. 3. Log-normal probability plot showing frequency distribution of particle settling velocity

PSD measurements at different settling times assuming spherical particles and uniform density for all particle size ranges (i.e., particle volume removal fraction=particle mass removal fraction). The number for individual particle size ranges were converted to volumes assuming spherical shape of particles and then integrated to obtain the total mass of the remaining particles and normalized by initial masses to obtain remaining mass fraction. As shown in Fig. 2, the sedimentation experiment revealed much lower settling efficiency than calculated with Newton's law. The assumption of uniform particle density and spherical shape overestimated particle settling efficiency. For example, from the sedimentation experiment, 21% of the particle mass had settling velocity less than 4.1 m/day. When applying Newton's law and assuming cylindrical shape and 1.35 of SG for the particles, only 12% of the particle mass had settling velocities of less than 4.1 m/day. The difference in settling velocity between calculated and measured values may be caused by nonuniform specific gravities, irregular shapes, runoff characteristics, and total suspended solid concentrations in the runoff (Aiguier et al. 1996).

Fig. 3 shows the probability of settling velocity for different particle diameters (D_p) from the sedimentation experiments. The horizontal axis is the standard normal quartile for the particle fraction with less than stated settling velocity and the vertical axis is settling velocity using a log scale. Because the data plots are well correlated with linear regression as displayed in Fig. 3, settling velocity of particles with a certain value of D_p can be assumed log-normally distributed. Log-normal probability distribution of settling velocity for each value of D_p is a function of the corresponding mean and standard deviation, which can be obtained from the regression lines in Fig. 3. Therefore, settling velocity analysis curves for each particle size can be obtained from cumulative density function (cdf) of log-normal distribution as follows:

$$\mathrm{cdf}(v_p) = \frac{1}{2} + \frac{1}{2}\,\mathrm{erf}\left[\frac{\ln(v_p) - \mu}{\sigma\sqrt{2}}\right], \quad v_p > 0 \qquad (7)$$

where μ=mean of log-transformed particle settling velocity and σ=standard deviation of log-transformed particle settling velocity. The cumulative density functions fitted with measured settling velocity profiles for several different values of D_p are illustrated in Fig. 4. Fig. 5 shows μ and σ as functions of D_p. As shown, the value of μ is proportionally related to the value of D_p in the range of 0–60 μm. The linear relationship between μ and D_p was used to obtain cdf for a given D_p. The relationship between σ and D_p

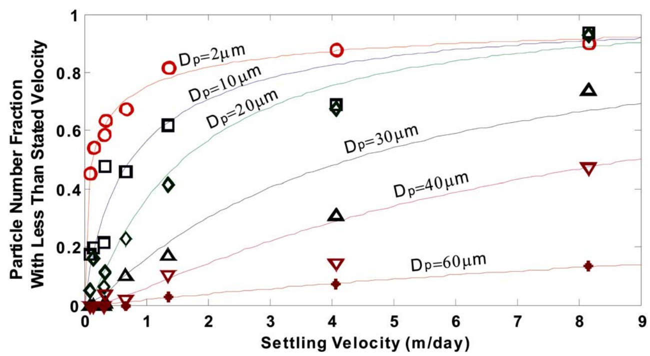

Fig. 4. Log-normal cumulative distribution function fitted with experimental settling velocity profile for different particle sizes

was curvilinear within 1.4–3.0 SG, which may be due to the difficulty in experimentally observing values of μ and σ for the particles larger than 60 μm. Most particles larger than 60 μm ($D_p > 60$ μm) were completely removed before the first or second measurement, providing too few data points to obtain a reliable regression line of log-normal distribution.

Maximum Removal Efficiency and Optimum Tank Design

Particle Removal Efficiency

The removal efficiency of each particle size range was calculated using the corresponding cdf, which is a function of μ and σ. The values of μ and σ for the particle size ranges between 2 and 60 μm were obtained using the regression line for μ and interpolated line for σ in Fig. 4. For the particles larger than 60 μm, values of μ were obtained by extrapolating the regression line, whereas values of σ were assumed to be 2.2, which is the value at $D_p = 60$ μm.

For the storage compartment or the continuous flow compartment with critical settling velocity or overflow rate v_c (m/day), the removal efficiency of each particle size range can be calculated by substituting Eq. (7) into Eq. (3), which becomes

$$E = 1 - \frac{1}{v_c}\int_0^{v_c} \text{cdf}(v_p)dv_p \quad (8)$$

Eq. (8) can be solved numerically or analytically. The analytical solution of Eq. (8) is obtained by solving the integration term on the right-hand side of Eq. (8), resulting in

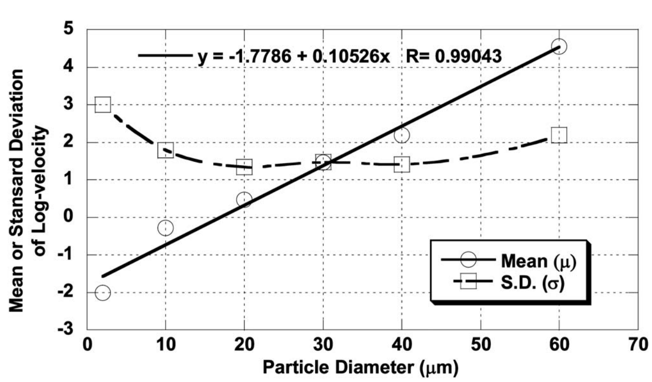

Fig. 5. Mean and standard deviation of log-transformed velocity for different particle sizes

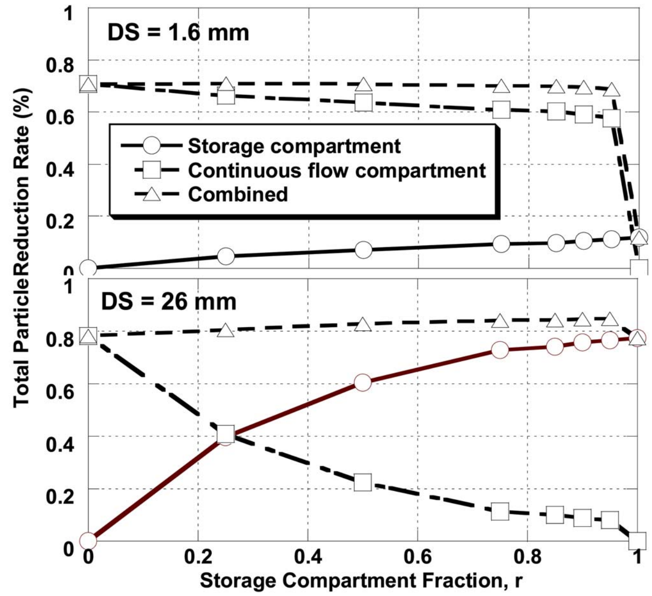

Fig. 6. Total particle reduction rate in individual compartments at design storm size=1.6 and 26 mm

$$E = \frac{1}{2} - \frac{e^{\mu}}{2v_c}\left[e^{z}\,\text{erf}\left(\frac{\ln(v_c) - \mu}{\sigma\sqrt{2}}\right) + e^{\sigma^2/2}\left\{\text{erf}\left(\frac{\sigma}{\sqrt{2}} - \frac{\ln(v_c) - \mu}{\sigma\sqrt{2}}\right) - 1\right\}\right] \quad (9)$$

Using Eq. (9) along with flow and PSD information for the 16 storm events, particle reduction rates were calculated for two-compartment settling tank. Fig. 6 shows the total particle reduction rate in the individual and combined compartments for two different DSs as a function of the fraction of storage compartment (r). For example, $r=0$ indicates that the storage compartment volume is zero and the entire volume is used for the continuous flow compartment. The vertical axis represents total particle reduction rate calculated using the 16 storm events. Fig. 6 demonstrates that when the DS is 1.6 mm (i.e., a small settling tank), total particle reduction rate changes little as r increases. This is because most of the particle removal occurs in the continuous flow compartment and the storage compartment is too small to capture a measurable fraction of total runoff volume. At DS=26 mm, total particle removal increases slightly (5%) as r increases from 0 to 0.95. The storage compartment removes more particles than the continuous flow compartment when r is larger than 0.25. For large storage compartment volume such as DS=26 mm, the entire flow from smaller storms is captured in the storage compartment and the continuous flow compartment functions only for storms larger than 26 mm. Fig. 6 suggests that only a small volume of continuous flow compartment is needed to maintain high efficiency, especially when the design storm size is small.

Fig. 7 shows the total particle reduction rates of the two-compartment settling tank as the DS size is increased. The total particle reduction rate always increases with increasing r as long as a small fraction of continuous flow compartment exists. Fig. 8 shows the changes in particle reduction rate for particles in six different size ranges from 2–10 to 249–1,000 μm. Larger storage compartments provide greater removal of smaller particles, whereas even a small volume of continuous flow compartment completely removes particles larger than 104 μm. To maximize

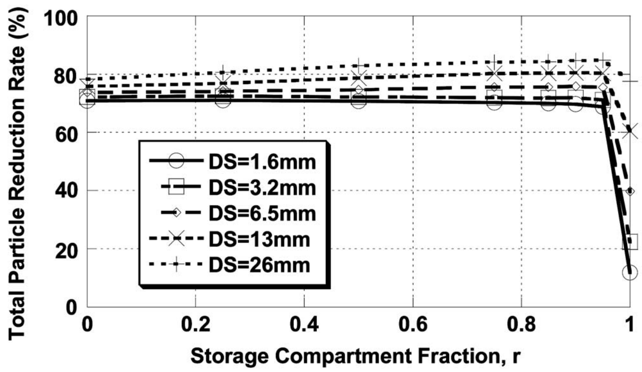

Fig. 7. Total particle reduction rate for different design storm size

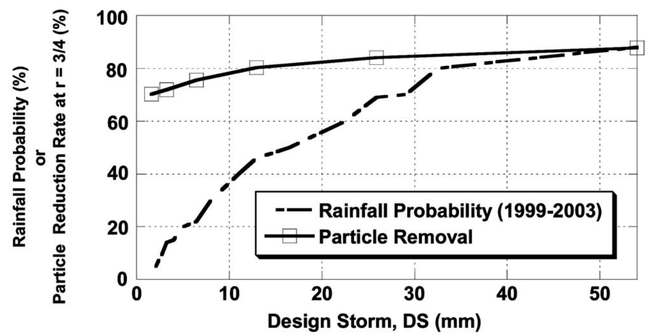

Fig. 9. Optimized particle reduction rate and rainfall probability with respect to design storm (rainfall probability means the probability of an event rainfall to be less than a stated design storm)

overall particle reduction in a given DS, a designer can allocate minimum surface area for the continuous flow compartment targeting large particle removal (>60–100 μm) and use the remaining surface area (or volume) for storage compartment to remove small particles. The simulations show that only a small continuous flow compartment can provide essentially complete removal of particles larger than 104 μm. We suggest a fraction of 0.25 (i.e., r=0.75) for the optimum size of the continuous compartment because the enhancement in particle removal by increasing r from 0.75 to upper value (e.g., 0.95) is very small for a given DS. Volume and depth of the continuous flow compartment should be large enough to mitigate turbulence and prevent short-circuiting. In this paper, the reduction rate at r=0.75 will be referred to as the optimized reduction rate.

Fig. 9 shows the optimized total particle reduction rate as a function of design storm size. Rainfall probability is also shown for reference. Rainfall probability is calculated from the event rainfall data obtained from the three highway runoff sites during the 1999–2003 monitoring seasons. Optimized particle reduction rate increases rapidly as DS increases up to 13 mm. At DS = 13 mm, 80% of the particle mass from the entire season of 2002–2003 can be removed by the two-compartment tank. When the tank size is doubled (i.e., DS=26 mm), the total particle reduction rate increases by only 5%.

Metal Removal Efficiency

Pollutant distribution on different size particles is one of the key factors that determine pollutant removal efficiency. Fig. 10 illustrates the particulate zinc (Zn) reduction rate. The simulation used

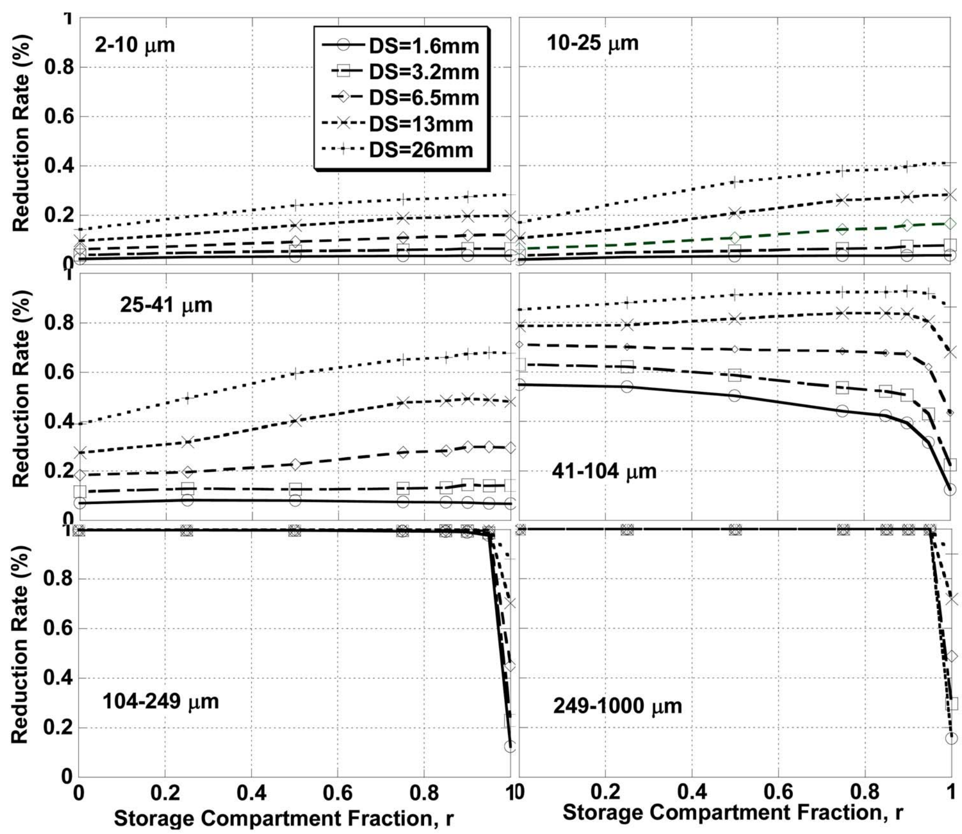

Fig. 8. Particle reduction rates for different size particles under different design storm sizes

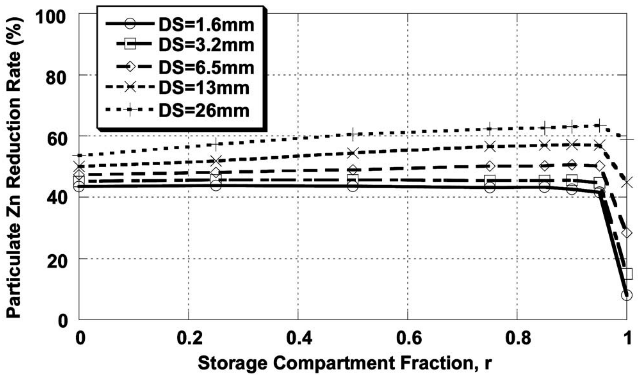

Fig. 10. Particulate zinc reduction rate at different design storm size using Morquecho's zinc concentration distribution on different particle sizes

the Zn concentrations for different particle size ranges reported by Morquecho and Pitt (2003) as shown in Table 3. Particulate Zn reduction rate showed a similar pattern with particle reduction rate (Fig. 7) but the particulate Zn reduction rate is consistently lower than the particle removal efficiency. This occurs because the smaller particles with higher Zn concentrations are removed less efficiently than larger particles with lower Zn concentrations. Larger storage compartments provide greater particle removal and metal removal, with proportionally larger increases in metal removal, as the storage compartment improves removal of small particles. For example, at DS=13 mm, particulate Zn reduction rate increases from 50 to 57% (7% increase), whereas particle reduction rate increases from 76 to 80% (4% increase) with increasing r from 0 to 0.75. This results because the Zn concentration on smaller particles (13,641 $\mu g/g$ for particles 2–10 μm) is much greater than on larger particles (266 $\mu g/g$ for particles larger than 250 μm).

Fig. 11 shows the optimized total metal reduction rates ($r=0.75$) for different values of DS using the metal concentration data reported by different researchers (Table 3). No dissolved metal removal is assumed and the difference in removal rates among metals is a function of the dissolved metal fraction, f_d, with lower values of f_d providing greater efficiency. Fig. 11 shows that reduction rates of Cr, Fe, and Pb (f_d values of Cr, Fe, and Pb are 0.21, 0.03, and 0.07, respectively) may approach 50–70%, whereas Cd and Zn are less, closer to 20%. Each reference found different metal concentrations on particles, resulting in different removal efficiencies for the same metals. Improved metal removal will occur when the particulate phase concentrations are greater.

Effect of First Flush on Settling Tank Performance

Particles showed a first flush and the particle number first flush ratio ($PNFF_{20}$) at 20% of total runoff volume averaged 2.0 (Li et al. 2005). This means that 40% of the particle numbers were contained in the first 20% of the runoff volume. The particle first flush increases the removal efficiency because the storage tank always captures at least a portion of the first flush, even for the largest storms. To investigate the difference between particle reduction rates with and without first flush phenomena, simulations

Table 3. Metal Concentrations for Different Particle Size Ranges

Size ranges (μm)	Heavy metal concentration ($\mu g/g$)								Remarks	References
	Al	Cd	Cr	Cu	Fe	Ni	Pb	Zn		
0.45–2				2,894	29,267		199	13,540	Urban storm-water suspension	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		
25–38		16.8		364			265	1,189	Highway runoff, embedded sediment	Sansalone and Buchberger 1997, 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	Highway runoff, embedded sediment	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		
<43		5	46	220		65	350	960	Street vacuuming	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		

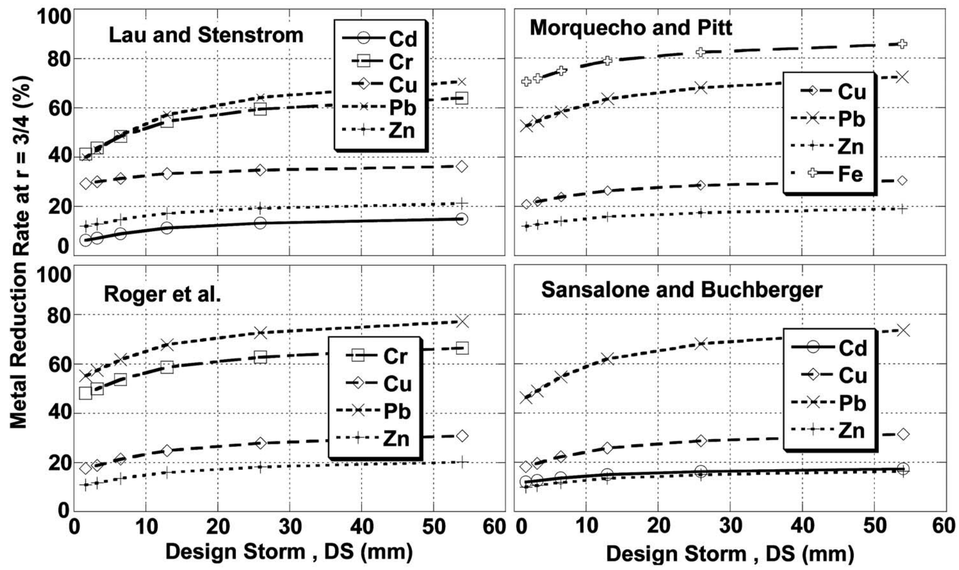

Fig. 11. Optimized reduction rate for total metal species using difference data sources for metal concentration on different particle sizes

using the actual PSD and the event mean PSD for the entire storm were compared. The simulation showed that at DS = 13 mm, the existence of the first flush increased the optimized particle mass reduction by 5, 9, and 16% for the particle size ranges of 2–10, 10–25, and 25–41 μm, respectively. Larger particles ($D_p > 60$ μm) are removed well regardless of the first flush because larger particles are efficiently removed by even a small continuous flow compartment. The overall increase in particle removal due to the existence of first flush was approximately 5%.

Conclusions

Particles in highway runoff from three sites with high annual average daily traffic (~300,000 vehicles/day) were characterized by particle size, density, and settling velocity. Particles with the same diameter exhibited a range of settling velocities and the overall particle settling efficiency was much lower than calculated with Newton's law.

Simulations using data from 16 storm events from three highway sites were used to estimate particle mass reductions for a two-compartment settling tank. One compartment was used to store the initial runoff to prolong the period of settling and the second compartment was used as a continuous flow clarifier. Particle reduction rate was optimized by adjusting the fraction of storage compartment over a range of design storm sizes, ranging from 1.6 to 26 mm total rainfall. Generally a 3:1 ratio of storage to continuous flow compartment surface areas optimized removals. Overall particle mass removal increased from 70 to 80% as the design storm increased from 1.6 to 13 mm. Larger storage compartment surface areas increased removals of particles with diameters 25–41 μm by as much as 26% depending on the design storm size. Particles larger than 100 μm were generally well removed regardless of compartment volumes. The existence of a particle first flush increased small particle reduction rate from 5 to 16% for particles ranging from 2 to 41 μm. Total chromium, iron, and lead, which are more associated with particles (f_d=0.21, 0.03, and 0.07, respectively), had removals of 50–70%, depending on specific conditions, whereas cadmium and zinc (f_d=0.79, 0.72 respectively) had less than 20% removals.

This paper has used scientific and quantitative methods to estimate particle and particulate phase metal removals by sedimentation using Type I sedimentation analysis. It is an example of how unit operations and processes principles can be applied to best management practice analysis to improve their evaluation beyond simple rules of thumb, such as detention time. The simulated removals likely represent the maximum achievable removals using sedimentation, and if greater removals are needed, then filtration or chemical coagulation/flocculation (Kang et al. 2007) will likely be needed.

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References

Aiguier, E., Chebbo, G., Bertrand-Krajewski, J.-L., Hedges, P., and Tyack, N. (1996). "Methods for determining the settling velocity profiles of solids in storm sewage." *Water Sci. Technol.*, 33(9), 117–125.

Aldheimer, G., and Bennerstedt, K. (2003). "Facilities for treatment of stormwater runoff from highways." *Water Sci. Technol.*, 48(9), 113–121.

Bäckström, M. (2002). "Sediment transport in grassed swales during simulated runoff events." *Water Sci. Technol.*, 45(7), 41–49.

Bäckström, M. (2003). "Grassed swales for stormwater pollution control during rain and snowmelt." *Water Sci. Technol.*, 48(9), 123–132.

Barrett, M. E. (2003). "Performance, cost, and maintenance requirements of Austin sand filters." *J. Hydrol. Eng.*, 129(3), 234–242.

Barrett, M. E., Irish, L. B., Jr., Malina, J. F., Jr., and Charbeneau, R. J. (1998a). "Characterization of highway runoff in Austin, Texas area." *J. Environ. Eng.*, 124(2), 131–137.

Barrett, M. E., Walsh, P. M., Malina, J. F., Jr., and Charbeneau, R. J. (1998b). "Performance of vegetative controls for treating highway

runoff." *J. Environ. Eng.*, 124(11), 1121–1128.
Birch, G. F., Matthai, C., Fazeli, M. S., and Suh, J. Y. (2004). "Efficiency of a constructed wetland in removing contaminants from stormwater." *Wetlands*, 24(2), 459–466.
Caltrans. (2004). "Storm water monitoring and BMP development status report." *Final rep. SW-04-069.04.01*, California Dept. of Transportation, Division of Environmental Analysis, Sacramento, Calif.
Characklis, G. W., and Wiesner, M. R. (1997). "Particles, metals, and water quality in runoff from large urban watershed." *J. Environ. Eng.*, 123(8), 753–759.
Clausen, J. C., et al. (2002). "Stormwater treatment devices section 319 project." *Final Rep.*, Connecticut Dept. of Environmental Protection, Hartford, Conn.
Colwill, D. M., Peters, C. J., and Perry, R. (1984). "Water quality of motorway runoff." *TRRL Supplemental Rep. No. 823*, Transport and Road Research Lavoratory, Crowthorne, Bershire, U.K.
Driscoll, E., Shelley, P., and Strecker, E. (1990). "Pollutant loadings and impacts from highway stormwater runoff. IV: Research data appendix." *FHWA-RD-88-009*, Federal Highway Administration, DOT, Washington, D.C., 1–139.
Furumai, H., Balmer, H., and Boller, M. (2002). "Dynamic behavior of suspended pollutants and particle size distribution in highway runoff." *Water Sci. Technol.*, 46(11–12), 413–418.
Gromaire-Mertz, M. C., Garnaud, S., Gonzalez, A., and Chebbo, G. (1999). "Characterization of urban runoff pollution in Paris." *Water Sci. Technol.*, 39(2), 1–8.
Hvitved-Jacobsen, T., Johansen, N. B., and Yousef, Y. A. (1994). "Treatment system for urban and highway run-off in Denmark." *Tech. Dig. Ser.-Opt. Soc. Am.*, 146/147, 499–506.
Jacopin, Ch., Bertrand-Krajewski, J. L., and Desbordes, M. (1999). "Characterization and settling of solids in an open, grassed, stormwater sewer network detention basin." *Water Sci. Technol.*, 39(2), 135–144.
Kang, J.-H., Li, Y., Lau, S.-L., Kayhanian, M., and Stenstrom, M. K. (2007). "Particle destabilization in highway runoff to optimize pollutant removal." *J. Environ. Eng.*, 133(4), 426–434.
Krebs, P., Holzer, P., Huisman, J. L., and Rauch, W. (1999). "First flush of dissolved compounds." *Water Sci. Technol.*, 39(9), 55–62.
Krein, A., and Schorer, M. (2000). "Road runoff pollution by polycyclic aromatic hydrocarbons and its contribution to river sediments." *Water Resour.*, 34(16), 4110–4115.
Krishnappan, B. G., Marsalek, J., Watt, W. E., and Anderson, B. C. (1999). "Seasonal size distributions of suspended solids in a stormwater management pond." *Water Sci. Technol.*, 39(2), 127–134.
Larsen, T., Broch, K., and Andersen, M. R. (1998). "First flush effects in urban catchment area in Aalborg." *Water Sci. Technol.*, 37(1), 251–257.
Lau, S.-L., Khan, E., and Stenstrom, M. K. (2001). "Catch basin inserts to reduce pollution from stormwater." *Water Sci. Technol.*, 44(7), 23–34.
Lau, S.-L., and Stenstrom, M. K. (2005). "Metals and PAHs adsorbed to street particles." *Water Res.*, 39(17), 4083–4092.
Lee, H., Lau, S.-L., Kayhanian, M., and Stenstrom, M. K. (2004). "Seasonal first flush phenomenon of urban stormwater discharges." *Water Res.*, 38(19), 4153–4163.
Lee, J., Bang, K., Choi, J., Ketchum, L. H., Jr., and Cho, Y. (2003). "The vortex concentrator for suspended solids treatment." *Water Sci. Technol.*, 47(9), 335–341.
Li, Y., Lau, S.-L., Kayhanian, M., and Stenstrom, M. K. (2005). "Particle size distribution in highway runoff." *J. Environ. Eng.*, 131(9), 1267–1276.
Li, Y., Lau, S.-L., Kayhanian, M., and Stenstrom, M. K. (2006). "Dynamic characteristics of particles size distribution in highway runoff: Implications for settling tank design." *J. Environ. Eng.*, 132(8), 852–861.
Metcalf & Eddy, Inc. (2003). *Wastewater engineering: Treatment, disposal, and reuse*, 4th Ed., McGraw-Hill, New York.
Michelbach, S., and Weiß, G. J. (1996). "Settleable sewer solids at stormwater tanks with clarifier for combined sewage." *Water Sci. Technol.*, 33(9), 261–267.
Morquecho, R., and Pitt, R. (2003). "Stormwater heavy metal particulate associations." *Proc., Water Environment Federation's Annual Exhibition and Conf. (WEFTEC)*, Los Angeles, Calif., Water Environment Federation, Alexandria, Va.
Papiri, S., et al. (2003). "Field monitoring and evaluation of innovative solutions for cleaning storm water runoff." *Water Sci. Technol.*, 47(7–8), 327–334.
Pitt, R., Field, R., Lalor, M., and Brown, M. (1995). "Urban stormwater toxic pollutants: Assessment, sources, and treatability." *Water Environ. Res.*, 67(3), 260–275.
Roger, S., Montréjaud-Vignoles, M., Andral, M. C., Herremans, L., and Fortuné, J. P. (1998). "Mineral, physical and chemical analysis of the solid matter carried by motorway runoff water." *Water Res.*, 32(4), 1119–1125.
Sansalone, J. J., and Buchberger, S. G. (1997). "Partitioning and first flush of metals in urban roadway storm water." *J. Environ. Eng.*, 123(2), 134–143.
Sonstrom, R. S., Clausen, J. C., and Askew, D. R. (2002). "Treatment of parking lot stormwater using a StormTreat system." *Environ. Sci. Technol.*, 36(20), 4441–4446.
Stanley, D. W. (1996). "Pollutant removal by a stormwater dry detention pond." *Water Environ. Res.*, 68(6), 1076–1083.
Strecker, E. W., Quigley, M. M., Urbonas, B. R., Jones, J. E., and Clary, J. K. (2001). "Determining urban storm water BMP effectiveness." *J. Hydrol. Eng.*, 127(3), 144–149.
USEPA. (1993). "Guidance specifying management measures for sources of nonpoint pollution in coastal waters." *EPA 840-B-92-002*, Government Printing Office, Washington, D.C.
Waschbusch, R. J. (1999). "Evaluation of the effectiveness of an urban stormwater treatment unit in Madison, Wisconsin, 1996–1997." *USGS Water Resources Investigations Rep. No. 99–4195*, USGS, Middleton, Wis.
West, T. A., Sutherland, J. W., Bloomfield, J. A., and Lake, D. W., Jr. (2001). "A study of the effectiveness of a Vortechs stormwater treatment system for removal of total suspended solids and other pollutants in the Marine Village watershed, Village of Lake George, New York." N.Y. State Dept. of Environmental Conservation, Division of Water, Albany, N.Y.
Westerlund, C., Viklander, M., and Bäckström, M. (2003). "Seasonal variations in road runoff quality in Luleä, Sweden." *Water Sci. Technol.*, 48(9), 93–101.
Whipple, W., and Hunter, J. V. (1981). "Settleability of urban runoff pollution." *J. Alloys Compd.*, 53(12), 1726–1731.
Young, G. K., et al. (1996). "Evaluation and management of highway runoff water quality." *FHWA-PD-96–032*, Office of Environment of Planning, Federal Highway Administration, Washington, D.C.