Protocol Evaluation of the Total Suspended Solids and Suspended Sediment Concentration Methods: Solid Recovery Efficiency and Application for Stormwater Analysis

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ABSTRACT: Total suspended solids (TSS) is routinely measured in water and wastewater treatment plants, and protocols are well-known. The TSS measurement in stormwater is more difficult, because the particle size and density can be much greater, biasing the sample if it is collected from a poorly mixed location or allowed to settle in a quiescent collection container. An alternative method, called *suspended sediment concentration* (SSC), uses a different protocol, which analyzes the entire contents of the sample collection container. The SSC method is not compatible with many monitoring programs, which require several constituents to be analyzed from a single sample container, such as from a flow-weighted composite sample. This paper addresses TSS protocol using glass beads and samples with known particle size distribution and shows that proper mixing, combined with appropriate pipettes, can largely avoid sampling error for typical sediments as large as 250 μm with specific gravity of 2.6. *Water Environ. Res.,* **80,** 796 (2008).

KEYWORDS: stormwater management, highways, runoff, particle size distribution, suspended solids, suspended sediment concentration, best management practice.

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Introduction

Total suspended solids (TSS) in stormwater is frequently used as a surrogate indicator of overall water quality, because TSS is often correlated with other water quality parameters, such as heavy metals, nutrients, polynuclear aromatic hydrocarbons, and chemical oxygen demand (Han et al., 2006; Schorer, 1997). The TSS is easy to measure, requiring no sophisticated instrumentation or special training. Heavy metals are often sorbed to suspended solids, and their analysis requires a metal digestion procedure (Lau and Stenstrom, 2005), requiring more time and expense for monitoring. If metals and TSS are correlated, the simpler, less expensive TSS procedure may serve as a predictive indicator or surrogate for metal concentrations (Furumai et al., 2002; Herngren et al., 2005).

An alternative method for measuring suspended solids content is the suspended sediment concentration procedure (SSC) (ASTM, 1999). This method differs from the TSS method principally in the way the sample is collected. In the SSC method, subsampling using a pipette or volumetric cylinder is not allowed. This direct measurement avoids potential problems of large or dense particles not being correctly sampled as a result of stratification in the sample container. Both the TSS and SSC methods require samples to be collected from representative, well-mixed locations, such as a rapidly flowing stream or a free waterfall, or from stratified flows using some type of sampler that ensures proper depth integration. The SSC method has been frequently used by researchers interested in determining the mass of sediment (bed load) that might accumulate at the mouth of a river or similar areas (Glysson et al., 2004). The TSS method has more frequently been used when analyzing pollutant concentrations.

The purpose of this paper is to investigate the utility of TSS for characterizing stormwater samples, in which the solids might have specific gravities (the ratio of solids density to the density of water) of approximately 2.6, and to show how strictly adhering to the mixing required by the protocol are necessary for obtaining representative results. To illustrate the correct methodology, silicon beads of four different sizes and embedded sediment (solids collected from the bottom of a sedimentation device) were used. Also, various editions of *Standard Methods for the Examination of Water and Wastewater* (APHA et al., 1925–2000) were reviewed to pinpoint when the mixing advisory of the TSS protocol changed. Several editions do not advise analysts to ensure mixing for heavy, large particles, and recommendations to use a wide-bore pipette are inconsistent over the editions from 1981 to 2000.

Background and Literature Review

Solid matter suspended in wastewater has long been quantified by a procedure called *total suspended solids* or *total suspended matter*, and the analytical protocol has been documented in every edition of *Standard Methods* (APHA et al., 1925–2000) since 1925. The primary use of this method has been to characterize the suspended material in drinking waters or wastewaters. This method uses a filter paper to separate the suspended and soluble materials. For this reason, the definition of soluble material is often arbitrarily defined as the pore size (typically 0.45 to 1.5 microns) of the filter paper used in the analysis. Particles smaller than the pore size are generally considered soluble. In drinking waters or wastewaters,

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Table 1—Material, size ranges, and mixing speeds.

	Silicon beads	Embedded sediments
Specific gravity	2.6	2.2 to 2.4
Size ranges (μm)	45 to 90	<45
	90 to 150	45 to 106
	150 to 250	106 to 250
	250 to 425	250 to 850
Mixing speed (rpm)	200	200
	300	350
	450	550
	600	700
	850	850
	1100	1100

suspended matter is typically organic-rich, which tends to reduce the specific gravity to relatively low values ranging from 1 to 1.1 (Tchobanoglous et al., 2003). Because of their low specific gravity, the concentration of suspended material can be measured using a subsample taken from a sample container, with little bias from sedimentation or poor mixing of solids in the container.

Suspended materials in surface waters or stormwater typically contain a relatively greater portion of minerals, resulting in much higher specific gravities compared with that of wastewater, ranging from 1.5 (soil particles) to 2.6 (silica sand), and, in rare cases, to as much as 4.2 (garnet sand). The size of the particles of interest may be much larger, because, for example, rivers can transport particles larger than 1000 μm in diameter, especially during flooding (Glysson et al., 2004). Additionally, the need for such measurements is not always for pollution monitoring, but sometimes for quantifying sediment accumulation behind dams or in deltas. To properly estimate the concentrations of these larger, denser particles, the SSC method has been used, and the principal difference compared with the TSS method is the prohibition of subsampling. Subsampling from the original sample container using a pipette or similar device may not provide an accurate measurement of suspended solid concentration, because heavy particles settled on the bottom of the container or particles larger than the opening size of the pipette cannot be effectively collected. Therefore, subsampling that is allowed in the TSS method can produce significant error in estimating the amount of solids in surface water, such as river and stormwater runoff. For example, Gray et al. (2000) discussed the differences between the two methods and the effects of the choice of the method on sediment estimates in surface water, suggesting that studies using the TSS method are flawed, underestimating sediment concentration or mass emission rate. Glysson et al. (2004) compared TSS and SSC data from a range of locations and concluded that there was no simple way of reconciling the two measurements.

For stormwater monitoring, the SSC method has disadvantages compared with TSS. The SSC method uses the entire sample volume, which requires a second sample to be collected if other constituents are to be analyzed. A second automatic sampler may be required, which is expensive. Moreover, investigators may be concerned that automatic samplers using tubing pumps may not be able to pump the largest, densest particles into the sample container. Another potential problem in using SSC as a replacement for TSS is that particulate pollutants are typically measured using the residue collected on the filter paper, and, if different methods are used to collect the samples being filtered, the particulate pollutant may no longer be correlated to TSS or SSC.

Experimental Methods

Mixing Tests. To compare the SSC and TSS methods for different types, sizes, and densities of particles; mixing regimes; and pipette sizes, a series of tests were performed in 1-L glass beakers of a synthetic water sample containing known sizes and concentrations of particles. The contents of the beakers were sampled, either by taking a subsample using a pipette for the TSS method or by filtering the entire volume for the SSC method. Spherical silicon beads and embedded sediments were used to simulate suspended solids. Silicon beads were purchased, ranging from 45 to 420 μm in diameter, with a specific gravity of 2.6 (McMaster Carr, Santa Fe Springs, California). Embedded sediments were collected from a highway stormwater runoff detention basin near Los Angeles, California, and sieved into four fractions, as shown in Table 1. The detention basin received pavement runoff and runoff from vegetated shoulders.

In each set of experiments, 6 to 12 beakers were filled with deionized water and 500 mg of test material, such as the 45- to 90-μm silicon beads, to obtain a 500-mg/L solids concentration. One beaker was used for the SSC method, and the others for the TSS method. Each beaker was placed on a magnetic stirrer and mixed at seven different speeds, from 200 to 1100 rpm. The mixer speed was measured using a Pocket Laser Tach 200 (Monarch Instrument, Amherst, New Hampshire). The stirring bar measured 40 mm ×10 mm. The G-factor was calculated using mixer speed and the size of the stirring bar and ranged from 81 seconds^{-1} (200 rpm) to 1041 seconds^{-1} (1100 rpm). The two-paddle turbulent equation parameters were used (Reynolds and Richards, 1995). A gang-mixer (PB-700 Jartester, Phipps & Bird, Richmond, Virginia) typically used in coagulation–flocculation studies was also evaluated for mixing.

Total Suspended Solids and Suspended Sediment Concentration Standard Methods. The TSS method was performed according to *Standard Methods* (APHA et al., 1925–2000). The TSS discussion has been simplified since 1971, removing or reducing the discussion requiring a wide-bore or cut pipette and adequate mixing of the sample. These two points received special emphasis in the editions of *Standard Methods* published before 1971. However, all the editions of *Standard Methods* published between 1925 and 2000 suggest the use of a 100-mL pipette and a single 47-mm circle of Wathman 934-AH filter paper (1.5-μm cutoff) for sample collection and separation of suspended solids, respectively. The following three types of pipettes were used to examine the effect of pipette type on the TSS measurement:

(1) An original or unmodified pipette,
(2) A pipette that had been cut off in the middle of the tip contraction and fire polished, and
(3) An open pipette that had been cut off just above the tip contraction.

The diameters of the pipette openings were 1420 μm (original), 1840 μm (cut), and 3950 μm (open). The modified pipettes were calibrated to compensate for the delivery volume change by comparing with unmodified pipettes and placing a new "full mark" using tape. Generally, the change in volume for the cut and open pipettes were 0.08 and 0.65 mL, respectively.

The SSC method was performed using the ASTM procedure D3977-97 (ASTM, 1999). The procedure is similar to the TSS

method, except that the entire volume of the beaker was filtered through the same type of filter paper. Solids remaining in the beaker were washed into the filter flask with distilled water. For both methods, the filter papers were carefully removed, avoiding any loss of solids, and oven dried at 103 to 105°C for 1 hour. One hour was sufficient time to ensure that the residue was dried to constant weight, changing less than 0.5 mg, and was established early in the experimental program.

The value of TSS or SSC was reported as follows:

$$SS = \frac{(W_1 - W_0)}{V} \quad (1)$$

Where

SS = concentration of TSS or SSC (kg/m^3),
V = volume of the filtered mixture (0.01 m^3 for TSS and 0.1 m^3 for SSC), and
W_0 and W_1 = weights of the filter paper and filter paper plus filtered material (kg), respectively.

Sediments and Sieving Methods. Sediments were collected by our laboratory from two sedimentation basins receiving highway and grassy shoulder runoff from a major freeway in the area of Los Angeles, California, having average daily traffic of approximately 200,000 vehicles. Embedded sediments were collected from site 4, and water column suspended solids entering the sedimentation basin were collected from site 5. Embedded sediments were allowed to dry to a stable, fixed weight at room temperature and humidity. These sediments were then sieved using standard Tyler sieves into the four size fractions shown in Table 1, and the individual size fractions were later used in settling tests. Silicon beads were purchased in four different size fractions, as shown in Table 1. Small portions of beads in each size range were sieved to verify the sizes. In each size fraction of beads, less than 10% of the beads, by mass, were smaller than the indicated minimum size (i.e., less than 10% of the beads in the 250 to 425 μm sizes were smaller than 250 μm). The silicon beads are spherical, and settling velocity should closely follow Newton's law. The embedded sediments are not spherical, but of arbitrary shape (Sansalone et al., 1998), and should settle at lower rates than the beads, for the same mean diameter and density. Particle size distribution (PSD) was measured on samples from site 5.

Particle Size Distribution Analysis. A Nicomp Particle Sizing Systems (Santa Barbara, California) AccuSizer 780 optical particle sizer module equipped with an autodilution system and a light scattering/extinction sensor (model LE1000-2SE) was used for particle size analysis. This instrument was selected for its wide size range of detectable particles (0.5 to 500 μm), speed (2 minutes per sample analysis), and auto dilution capability. Analysis was performed by collecting a representative sample (0.5 mL) from the well-mixed original sample using a wide-bore glass pipette and then injecting it to the AccuSizer. Between samples, the system was flushed with deionized water at least three times, which reduced background particle concentrations to less than 3 particles/mL. Li et al. (2005) previously described the technique to ensure that a representative sample is collected.

Experimental Results

Silicon Beads. Figure 1 shows the TSS recovery rate (fraction by weight of the added particles measured by the TSS analysis), as a function of mixing speed for three types of pipettes, for the silicon beads. For the smallest size fraction (45 to 90 μm), the TSS recovery was almost 100% at 600 rpm and higher. For all of the four different size beads, the recovery rate generally increased as the mixing speed increased and reached its maximum at approximately 600 to 800 rpm and, in some cases, slightly declined after 800 rpm. The recovery rate decline at the highest mixing speed might be related to cavitation around the stirring bar or may have occurred because the momentum of moving beads was too high for the beads to change their horizontal trajectory to an upward direction into the pipette. The recovery of the 150- to 250-μm beads was only 85% using the cut pipette at 800 to 1100 rpm and only 65% for the largest beads (250 to 420 μm).

The effect of pipette type on recovery rate was greater for the larger beads. Contrary to expectation, the open pipette had poorer recovery for the larger beads than the cut pipette. Close observation of the pipette revealed that large particles were transported into the pipette, but some portion of the particles settled out of the pipette during the brief time between the end of filling and transfer of the pipette to the filter funnel. For the cut and standard pipettes, settling also occurred, but the taper at the pipette tip reduced the settling rate, preventing the particles from exiting the pipette. To reduce the effect of the gravity settling of captured beads inside the pipette, quicker pipetting was attempted, but the improvement was insignificant. Figure 1 clearly demonstrates the superiority of a cut pipette and the wisdom of the explicit recommendations in the 1971 and earlier editions of *Standard Methods.* The diameter of the pipette mouth obviously has an effect, even though it is much larger than the particle diameter (i.e., 1840 μm versus 850 μm for the largest particle diameter).

One method of suspending particles while subsampling is to swirl the liquid while pouring (*Standard Methods* editions 10, 12, and 13). Li et al. (2005) was able to recover stormwater particles from highway runoff, with consistent results, from 4-L capped bottles using a repeated inverting and shaking technique. Such mixing cannot be used with open beakers, and simple swirling was able to recover only 40, 32, 25, and 18% of the silicon beads for the 45-to-90, 90-to-150, 150-to-250, and 250-to-420 μm fractions, respectively. Additionally, mixing with a gang-stirrer with 76 mm × 25 mm paddles at 50 to 300 rpm did not improve recovery compared with the results using the magnetic stirrer. Larger magnetic stirring bars (50 mm and 63 mm ×10 mm in diameter) and square containers were also evaluated, but they did not improve the recovery. Although square containers reduced the vortex at high mixing speeds, particles settled in the stagnant zones at the corners.

Embedded Sediments. The solids recovery results using embedded sediments (sediments that are recovered from a sedimentation basin or other sedimentation device) are shown in Figure 2 and are more consistent than those observed with silicon beads. At mixing speeds of 600 rpm or greater, the TSS method accurately measured the suspended solids concentration for particles less than 106 μm, with all three pipette types. For particles in the 106-to-250 μm range, the TSS method accurately measured suspended solids when the mixing speed was 700 rpm or greater, using the cut and open pipettes, but the recovery rate for the original pipette began to decrease as the mixing rate increased from 700 rpm. For the largest fraction (250 to 850 μm), at the maximum speed of 1100 rpm, the TSS method recovered approximately 80% of the embedded sediments, and the original pipette was inferior to the cut and open pipettes. The TSS method was more accurate for the embedded sediments than for the silicon beads, for the same mixing speeds and pipette type. This probably results because of the lower settling velocity resulting from their lower specific gravities (2.3 versus 2.6) and irregular shape.

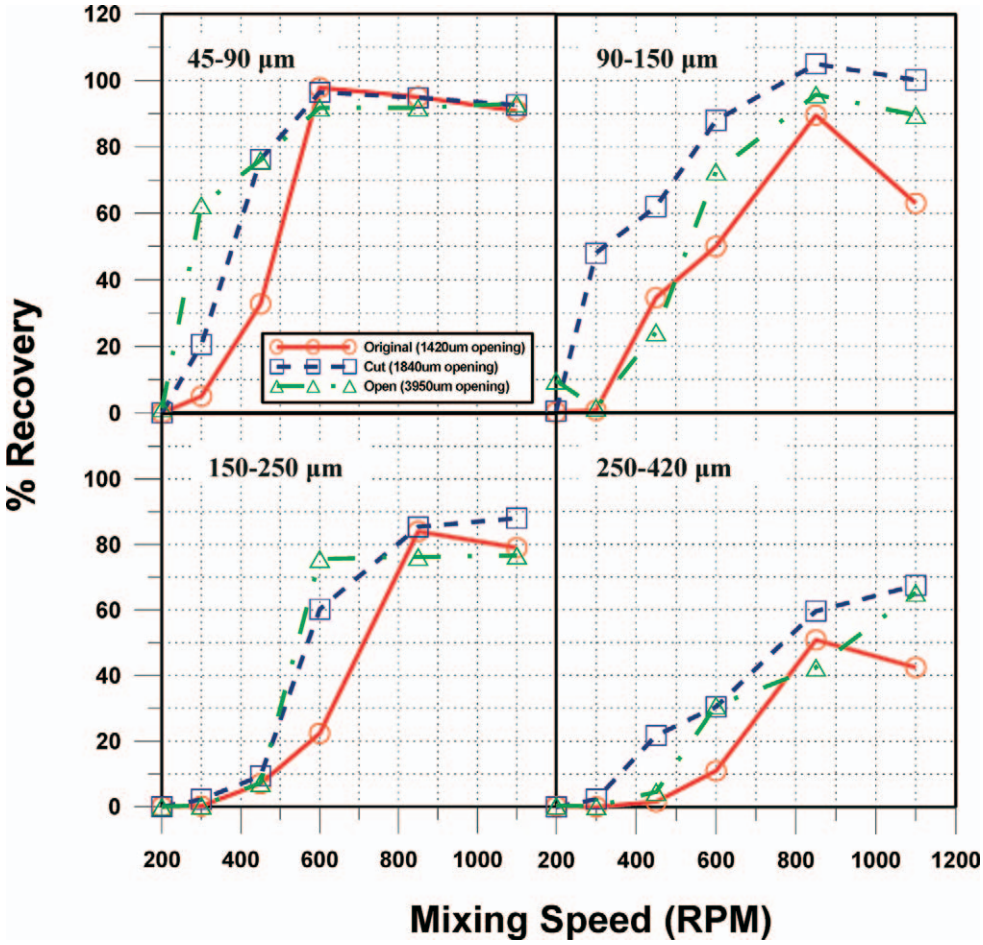

Figure 1—Silicon bead recovery during TSS analysis versus mixing speed; size fractions are as follows: upper left = 45 to 90 µm; upper right = 90 to 150 µm; lower left = 150 to 250 µm; and lower right = 250 to 420 µm.

Results and Comparison. Table 2 summarizes the results of the experiments. The recovery of the cut-tip pipette was 13 to 18% more accurate than that of the original pipette. Moreover, mixing the sample well was essential. The experiments showed that the TSS method results approached those of the SSC method at 1100 rpm mixing speed for silicon beads and embedded sediments than are 250 µm or smaller. For particles larger than these upper limits, the TSS method underestimated the solids concentration.

Mixing Time and Effect on Particle Size Distribution. For many analytical procedures, it is desirable to measure not only the TSS concentration, but also PSD. Therefore, it is important to know if the increased mixing intensity associated with improved TSS analysis will change measured PSD. To determine whether this can occur, a series of experiments was performed with embedded sediments.

Embedded sediments were added to a 1000-mL beaker to create a suspended solids concentration of 500 mg/L, as before. Samples were collected using the cut pipette for PSD analysis at various mixing times and speeds. Figure 3 shows the results for four different combinations of mixing times and speeds. The line indicated by the "+" symbols with error bars is the PSD for mixing speeds from 200 to 1100 rpm after 2 minutes of mixing. Mixing for 2 minutes had had no measurable effect on the measured PSD, and mixing as low as 200 rpm was able to keep the smaller particles (<20 µm) in suspension. The other three graph lines show the PSD measured after 30 minutes of mixing. At 200 rpm, only the number of particles smaller than 0.6 µm in diameter increased. The PSD changed at higher mixing speeds (350 and 800 rpm), resulting in a greater number of the smaller particles. The number of particles smaller than 10 µm generally increased, with the number of smallest particles (0.5 to 1 µm) increasing 1.5 to 2 times. The pattern indicates that larger particles tend to break into finer particles during prolonged mixing. These results show that the increased mixing used to improve the accuracy of the TSS method does not change PSD, as long as the mixing time is less than 2 minutes.

Using Total Suspended Solids and Suspended Sediment Concentration to Estimate Pollutant Removal Efficiency for Stormwater Best Management Practices

Often, the TSS or SSC concentration is used as a surrogate parameter to estimate the concentrations of the pollutants associated with the solids, such as particulate-phase metals. Also, best management practice (BMP) removal efficiencies for solid-phase pollutants are often correlated to solids removal efficiency. The following sections investigate the potential effect of poor solids recovery in the TSS procedure on solids and particulate-phase pollutants removal. Ideally, there should be no difference in

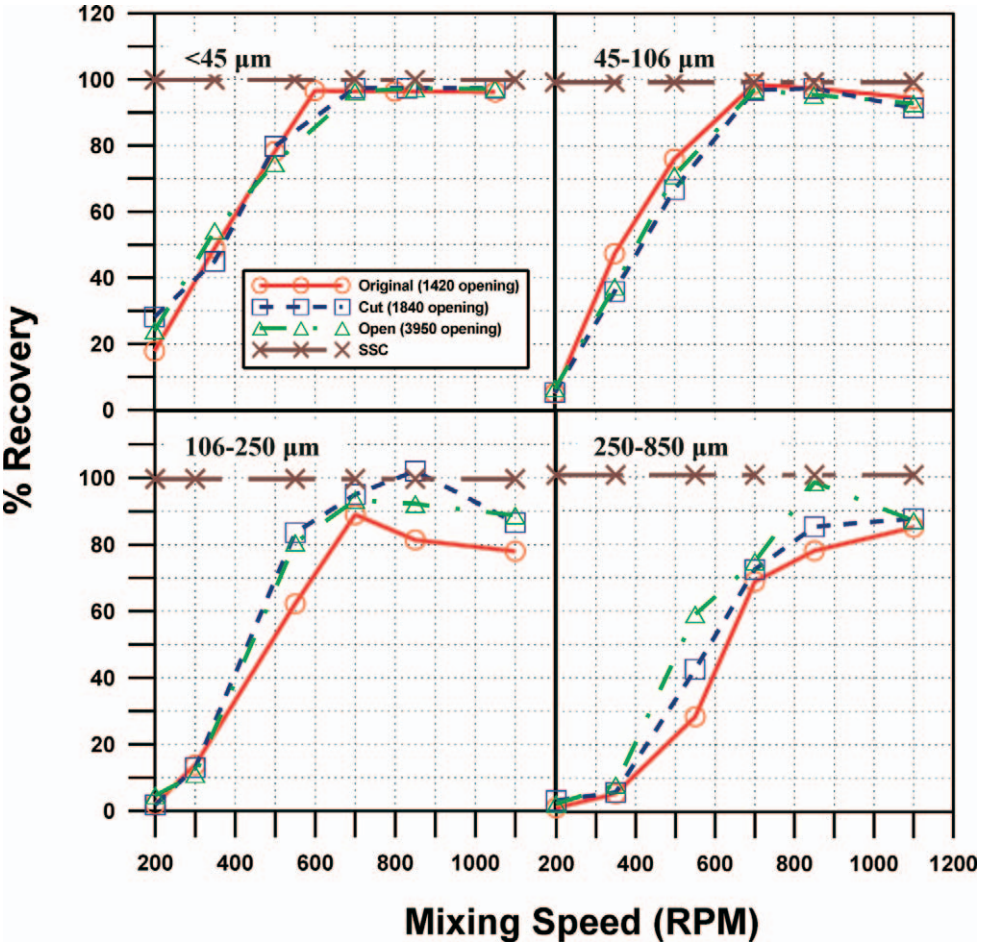

Figure 2—Embedded sediment concentration versus mixing speed; size fractions are as follows: upper left = <45 µm; upper right = 45 to 106 µm; lower left = 106 to 250 µm; and lower right = 250 to 850 µm.

observed removal rate, irrespective of the TSS or SSC method, for quantifying solids.

The recovery efficiencies shown in Figure 2 can be used to evaluate the utility of using TSS or SSC to estimate the removal of particulate pollutants. To determine the differences between the two methods, empirical functions were used to quantify the recovery, solid-phase concentrations, PSD, and removal efficiencies of hypothetical BMPs between the discrete observations. Continuous recovery functions, with respect to mixing speed (Figure 2), and literature data on particulate pollutants concentration were used to estimate recovery of suspended solids or removal efficiency of particulate pollutants in a stormwater BMP.

The total concentration of a particulate-phase pollutant in a water sample can be calculated by summating the concentrations of the individual size fractions, which can be calculated as the product of particulate pollutant concentration, measured suspended solids concentration, and the recovery rate of TSS method, as follows:

$$C_p = \sum_i M_i \cdot SS_i \cdot R_i \quad (2)$$

Where

C_p = particulate-phase pollutant concentration (µg/L);
M_i = pollutant concentration on the particles in i^{th} size range, expressed as µg/g;
SS_i = solids concentration in the i^{th} size range, measured by TSS or SSC (mg/L); and
R_i = fractional recovery of suspended solids using TSS or SSC for the i^{th} size range.

The fractional recovery values will be equal to 1 in the case of SSC, where all particles are 100% recovered, regardless of size. The fractional recovery of TSS will be equal to 1 for small particles and

Table 2—Comparison of experiments with 1000 rpm mixing speed.

	Original pipette (1420 µm)	Cut pipette (1840 µm)	Open pipette (3950 µm)
Silicon beads			
<90 µm	100%	100%	100%
90 to 150 µm	72%	100%	89%
150 to 250 µm	68%	81%	78%
>250 µm	38%	58%	50%
Embedded sediment			
<106 µm	100%	100%	100%
>250 µm	75%	80%	90%

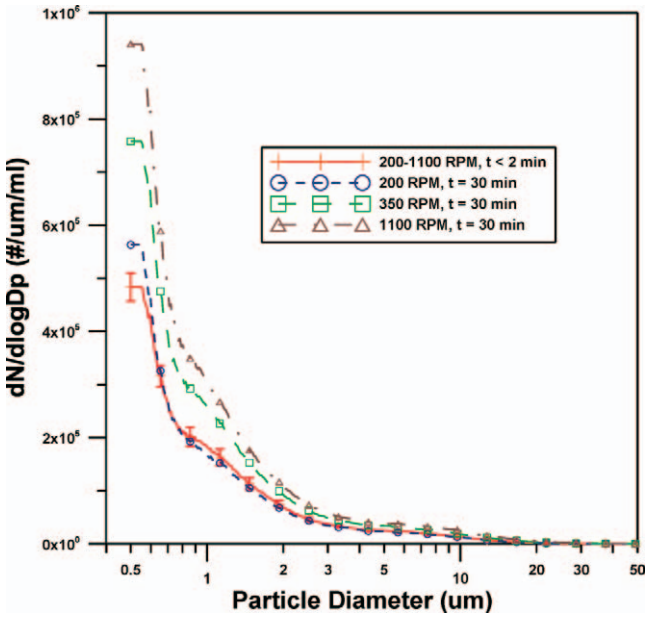

Figure 3—Number of particles versus diameter under various mixing speeds.

less than 1 for large particles, as shown in Figure 2. Each component in eq 2 can be obtained as described in the following sections.

Particulate-Phase Metal Concentration (M_i). The concentrations of metals associated with particles have been measured by various researchers (Deletics and Orr, 2005; German and Sevensson, 2002; Lau and Stenstrom, 2005; Morquecho and Pitt, 2003; Roger et al., 1998; Sansalone et al., 1998; Zanders, 2005). Table 3 shows particulate copper concentrations from these references. Copper is more concentrated on smaller particles, which is a typical trend and was chosen as representative of other metals, which can be analyzed in the same fashion. The concentrations for several other metals are shown in the cited references.

Particle Size Distribution and Suspended Solids Concentration (SS_i). The PSD has often been used to characterize stormwater. Generally, PSD from the following three types of collection techniques have been reported:

(1) Particles collected directly from the water column;
(2) Particles vacuumed from street surfaces; and
(3) Particles collected from sedimentation devices, which are typically called *embedded sediments.*

Table 4 shows the available literature references and divides them based on type. Sediments from sites 4 and 5 were collected by our laboratory and were used in developing Figure 4.

The averaged parameters for the three categories are shown at the bottom three rows of Table 4, and the particles collected from the water column are smallest with the greatest range of sizes and highest uniformity coefficient. The water column particles are distinctly smaller than the other two groups. The embedded sediments are slightly larger than the particles from vacuuming, but they have almost the same mean uniformity coefficient.

Figure 4 was created using the full data sets from the sources cited in Table 4, to compare the PSDs of the water column, embedded sediments, and vacuumed particles from streets. Figure 4 demonstrates that samples collected directly from the runoff contain a greater fraction of fine particles and may contain a smaller fraction of very large particles, if a poor TSS mixing procedure was used. Particles collected by street sweeping or vacuuming have a coarser distribution, and those collected from sedimentation basins contain the coarsest particles. This probably occurs because particle collection directly from the water column can capture all particles, while embedded sediments do not contain the smaller particles, which are not removed in sedimentation basins. Vacuuming devices typically do not capture the finest particles, and fine particles may not be completely recovered from the filter. These differences in technique may explain the PSD differences among sources.

Recovery of Total Suspended Solids or Suspended Sediment Concentration (R_i). The recovery of particles using the TSS method can be calculated from Figure 1 for silicon beads or Figure 2

Table 3—Heavy metals concentration associated with particles.

Particle size (μm)	Copper concentration (μg/g)	Reference
2 to 63	530	Deletics and Orr (2005)
63 to 250	310	
250 to 500	130	
>500	50	
<75	470	German and Svensson (2002)
75 to 125	270	
125 to 250	340	
250 to 500	200	
500 to 1000	50	
<43	220	Lau and Stenstrom (2005)
43 to 100	230	
100 to 250	230	
250 to 841	240	
841 to 2200	0	
0.45 to 2	2894	Morquecho and Pitt (2003)
2 to 10	4668	
10 to 45	735	
45 to 106	1312	
106 to 250	2137	
>250	50	
<50	420	Roger et al. (1998)
50 to 100	250	
100 to 200	200	
200 to 500	100	
500 to 1000	50	
25 to 38	691	Sansalone and Buchberger (1997)
38 to 45	353	
45 to 63	317	
63 to 75	326	
75 to 150	312	
150 to 250	127	
250 to 425	78	
425 to 850	63	
850 to 2000	20	
0 to 32	181	Zanders (2005)
32 to 63	197	
63 to 125	212	
125 to 250	184	
250 to 500	85	
500 to 1000	26	
1000 to 2000	21	

Table 4—Solid components in different types of water samples.

Solids source	Percent less than 10% μm	Percent less than 60% μm	Percent less than 90% μm	Uniformity coefficient	Reference
Water column	8	180	380	22.5	Li et al. (2006)
	2	12	25	5.5	Morquecho and Pitt (2003)
	15	110	280	7.3	Kayhanian et al. (2005)
	20	220	700	11.0	Site 5
Vacuuming	30	440	660	14.7	German and Svensson (2002)
	65	340	1500	5.2	Lau and Stenstrom (2005)
	24	210	810	8.6	Sartor and Boyd (1972)
Embedded sediment	30	450	650	15.0	Deletics and Orr (2005)
	10	440	650	44.0	Roger et al. (1998)
	70	400	1000	5.7	Sansalone and Buchberger (1997)
	40	200	920	5.0	Shaheen (1975)
	19	250	1000	13.2	Zanders (2005)
	90	500	1900	5.6	Site 4
Water column	11	131	346	11.5	Average
Vacuuming	40	330	990	8.3	
Embedded sediment	43	373	1020	8.6	

for embedded sediments. An empirical, smooth function to facilitate calculations was created to describe the particle recovery at 1100 rpm with the cut pipette. The embedded sediments data were selected for these examples. The continuous recovery function was applied to the range of measured particles shown in Table 4.

Removal Efficiency (η_i). To compare the effect of PSD on removal efficiency, particle removal efficiency (η) was calculated from the particle settling velocity and overflow rate. Particle settling velocity was calculated based on Newton's Law at 20°C for spherical particles with a specific gravity of 2.6. The overflow rate (surface area divided by flowrate) ranged from 0.01 to 3000 m/h.

$$\eta = V_p/V_o \tag{3}$$

Where

V_p = particle settling velocity (m/s or m/h; 1 m/h = 1/3600 m/sec), and
V_o = overflow rate (m/s or m/h).

As Figure 5 shows, η decreases with increasing overflow rates. The lowest overflow rates shown in this figure are not realistic, because micro-mixing and non-ideal conditions prevent the smallest particles from being removed. Particles with diameters smaller than 5 μm are rarely removed in sedimentation devices (Tchobanoglous et al., 2003) because of this effect. The functions in Figure 5 can be used in eq 2, which is the fractional removal of different particle sizes at a given overflow rate.

Overall Removal Efficiency (E). The overall particle or particulate-phase metal removal efficiency (E) is defined by eq 4.

$$E = \frac{C_{inf} - C_{eff}}{C_{inf}} \tag{4}$$

The observed influent concentration (eq 5) must be expressed as the product of influent solids, particulate phase metal concentration, and recovery, which is unity for SSC and a function less than unity for TSS. The observed effluent concentration (eq 6) is calculated the same way, except that the particulate removal vector is added.

$$C_{inf} = \sum_{i=1}^{n} (M_i \cdot SS_i \cdot R_i) \tag{5}$$

$$C_{eff} = \sum_{i=1}^{n} (M_i \cdot SS_i \cdot R_i \cdot [1 - Re_i]) \tag{6}$$

Where

C_{inf} = observed influent concentration (kg/m^3; 1 mg/L=10^{-3} kg/m^3), and
C_{eff} = observed effluent concentration (kg/m^3).

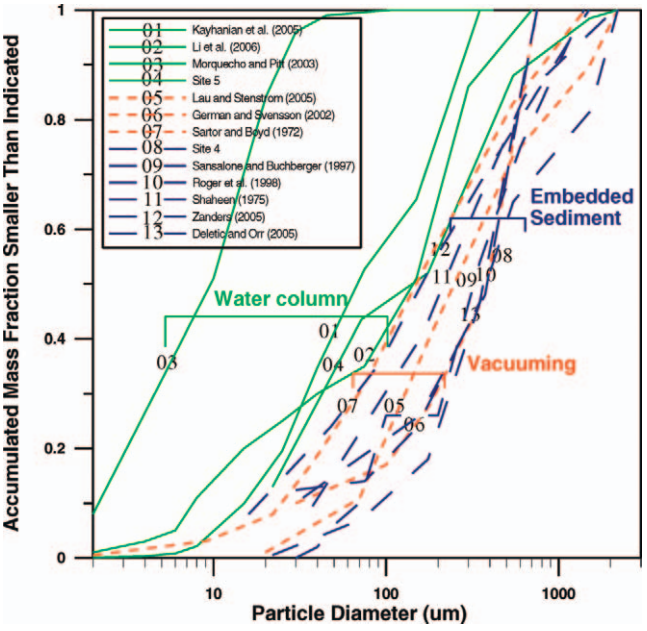

Figure 4—PSD of three groups among all the references.

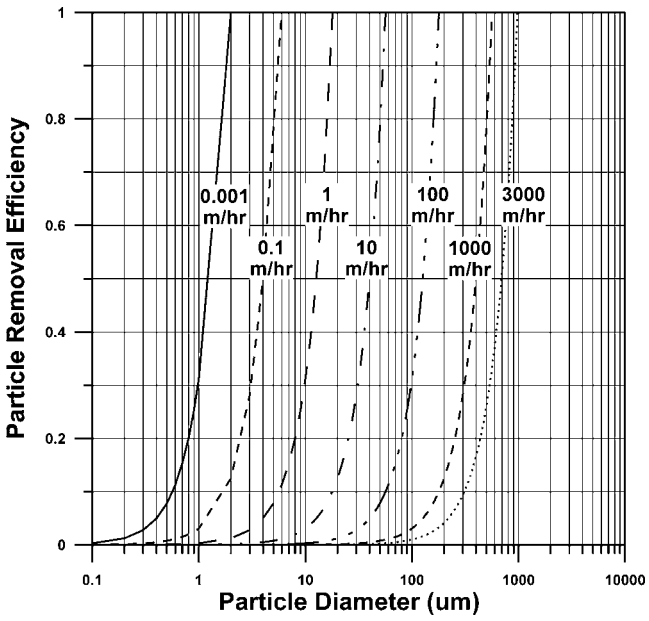

Figure 5—Relationship between particle removal efficiency (PRE) and particle diameter.

The equations above can be used to calculate the removal efficiency for suspended solids or particulate-phase metal pollutants. For demonstration purposes, six distinct size groups were selected. Morquecho and Pitt's (2003) size ranges and copper concentrations were selected from Lau and Stenstrom's (2005) data. Linear interpolation between particle sizes in Lau and Stenstrom's data was used to match Morquecho and Pitt's particle size ranges.

Table 5 shows an example calculation for copper and TSS recovery using the cut pipette and 1100 rpm mixing speed for embedded sediments from site 5. An influent concentration of 250 mg/L TSS or SSC size settling basin with an overflow rate of 100 m/h were assumed.

Efficiency (E) can be calculated using either TSS or SSC, depending on the data availability. When TSS measurements are used, suspended solids concentration can be obtained using the recovery function in Figure 2. When the SSC measurements are used to calculated E, the recovery rates for all size ranges are set to unity. If the metal concentrations (M_i) are set to unity, then eqs 5 and 6 calculate the TSS or SSC concentration removal efficiency, depending on the value of the recovery vector.

Table 6 shows the overall removal efficiency for particles and particulate-phase copper in an ideal sedimentation tank using TSS or SSC as analytical methods. Table 6 is based on the favorable recovery function for the cut pipette and 1100 rpm mixing speed. The particulate-phase copper concentrations from all seven literature references shown in Table 6 were evaluated. Three overflow rates were simulated. The largest difference in removal efficiency between TSS and SSC was 16.6% at 1000 m/h of overflow rate for German and Svensson (2002). The trends shown in Table 6 show little difference between using SSC and TSS for low overflow rates (i.e., high removal efficiency), but the difference becomes larger as the overflow rate increases, which allows the larger particles to pass to the effluent, and TSS is unable to quantitatively recover the large particles, overestimating removal efficiency.

If the recovery function for a standard pipette and 450 rpm mixing speed are used for the same calculation as shown in Table 6, experimental biases will become larger. This experimental condition might work well for sampling light, flocculent solids associated with wastewater treatment, but it provides only 28.4% recovery for the largest embedded sediments and only 1.6% for the largest silicon beads. For these conditions, the differences in observed suspended solids concentration, using Lau and Stenstrom's (2005) data for demonstration, are 84 mg/L for poor mixing and 147 mg/L for good mixing. For the same condition, copper removal efficiency of 73.1% is predicted, which is quite different than the removal efficiency predicted with the higher recovery vector (56.2%).

Suspended solids estimation errors involved in TSS or SSC methods may partially explain the poor performance reported in the literature of certain BMPs. For example, the utility of street sweeping is widely debated (Kang and Stenstrom, 2008) and may be explained, in part, by poor technique in measuring the larger particles in runoff from swept and unswept control studies. Also, undetectable differences between influent and effluent quality in hydrodynamic separators were reported by Geosyntec Consultants (2006) in the International BMP database. Laboratory studies (Woodward-Clyde Consultants, 1998) found that such devices can remove 95% of sand particles (specific gravity 2.6) greater than 425 μm, 78% of particles between 250 and 425 μm, 47% of particles between 150 and 250 μm, and 20% of particles between 75 and 150 μm. The lack of significant removals reported in street sweeping studies or in the database could be easily explained if poor TSS sampling techniques were used in the database studies. Subsampling for TSS at 400 rpm would not detect the most significant removal ranges of the sweepers or separators, which falsely suggests that they do not affect water quality.

Table 5—Copper removal efficiency using TSS influent and effluent data of Lau and Stenstrom (2005).

Particle diameter (μm)	Copper concentration (μg/g)	Solid fraction	Fraction recovered	Fraction removed	Influent concentration (μg/L)	Effluent concentration (μg/L)
20	220	0.010	0.98	0.013	0.54	0.53
70	230	0.098	0.93	0.153	5.3	4.4
175	230	0.29	0.84	0.959	13.9	0.58
550	240	0.34	0.58	1.000	11.8	0
1500	0	0.16	0.22	1.000	0	0
2200	0	0.10	0.11	1.000	0	0
Sum		1.000			31.5	5.6

Table 6—Metal and TSS/SSC removal efficiency results.*

Reference	Overflow rate (m/h)	Particle removal efficiency (%) when using TSS inf. TSS eff.	Particle removal efficiency (%) when using SSC inf. SSC eff.	Copper removal efficiency (%) when using TSS inf. TSS eff.	Copper removal efficiency (%) when using SSC inf. SSC eff.	Copper removal efficiency (%) when using SSC inf. TSS eff.
Morquecho and Pitt (2003)	5	21.5	21.7	9.9	10.0	10.9
	100	1.4	1.4	0.6	0.7	1.7
	1000	0.1	0.1	0.1	0.1	1.2
Lau and Stenstrom (2005)	5	98.7	99.3	98.7	99.0	99.1
	100	83.4	89.5	82.3	86.1	87.1
	1000	43.9	61.5	39.9	48.6	56.2
German and Svensson (2002)	5	93.3	95.6	85.1	87.9	88.2
	100	78.3	85.5	58.1	65.4	66.9
	1000	50.0	62.2	21.1	28.4	37.7
Sansalone and Buchberger (1997)	5	100	100	100	100	100
	100	70.0	80.0	41.2	48.1	52.0
	1000	42.1	57.3	16.1	23.2	31.6
Roger et al. (1998)	5	91.7	94.6	77.9	81.8	82.4
	100	75.7	83.8	42.7	52.3	54.4
	1000	50.6	62.9	20.2	29.6	36.4
Zanders (2005)	5	93.1	93.3	88.8	90.3	90.3
	100	67.6	68.5	45.0	50.5	50.7
	1000	38.3	39.5	9.9	14.1	15.0
Deletics and Orr (2005)	5	94.6	96.5	86.0	88.4	88.7
	100	79.1	85.9	50.4	58.0	60.1
	1000	51.0	62.9	18.9	26.6	34.8

* inf = influent; eff = effluent.

Conclusions

This work has demonstrated that the TSS method with improved subsampling can be used in stormwater investigations when particle sizes of 250 μm or less are anticipated. It has also demonstrated that serious errors can or may have occurred because of poor subsampling. Investigators monitoring stormwater need to be mindful of mixing requirements and advise contract laboratories of the need to properly mix stormwater samples and use a wide-tip pipette. The experiments using silicon beads and embedded sediments show that a wide-tip pipette and well-mixed samples are both necessary for performing stormwater particle analysis. These mixing and pipette recommendations were described in *Standard Methods* editions from 1955 to 1971, but have been minimized after 1971.

For BMP monitoring of devices that remove particles larger than 250 μm, which include most sand filters, sedimentation basins, and vortex separators, the TSS subsampling method should be able to accurately sample effluent suspended solids. The SSC method should be used when larger particles are expected or when the entire sample can be used for SSC without penalty (i.e., when no chemical analyses are being performed, because there is no need for a subsample or additional sample).

This work has also shown that attempts to correlate previously collected TSS and SSC data will not be possible in general, unless the PSD and recovery of different size particles are known or can be inferred from experimental conditions.

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