Sediment Monitoring Bias by Automatic Sampler in Comparison with Large Volume Sampling for Parking Lot Runoff

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Abstract: A field study was conducted to assess biases of suspended sediment concentration (SSC) analyses (ASTM Standard D3977-97) performed on discrete samples obtained by automatic sampler in comparison with actual sediment concentrations from large volume sampling. Research results indicate that the biases attributed to the monitoring of sediment event mean concentration (EMC) and median particle size in parking lot runoff by automated samplers (nonisokinetic) were minimal. Large volume samples (~15,000 L) of the first-flush event runoff were taken from a storm-water sewer system for eighteen storm events over two years. The intent was to obtain a complete portion of a storm to accurately determine EMCs and particle size distributions (PSDs). Concurrently, flow-weighted discrete samples were obtained by automatic samplers for the same portion of the events. Thus, characteristics of sediments from a whole-storm sample were compared with those of subsamples obtained by an automatic sampler using nonisokinetic sampling. SSCs and PSDs were compared for the two respective field sampling methods. The two methods showed a strong correlation for median sediment EMCs ($R^2 = 0.98$, $n = 18$). Biases to particle size distributions were found to be both for the large particles (> 75–$150\ \mu$m) and smaller fines ($< 25\ \mu$m). Specific sediment size fractions captured by the large volume sampling and automatic sampler were not significantly different ($\alpha = 0.05$) for D_{50}, which = 58 and 46 μm, respectively. **DOI: 10.1061/(ASCE)IR.1943-4774.0000168.** *© 2011 American Society of Civil Engineers.*

CE Database subject headings: Stormwater management; Suspended sediment; Particle size; Sampling; Runoff.

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Introduction

Storm water is identified as the greatest threat to surface water quality (EPA 2002). Sediment, and specifically sediment concentration, is a common pollutant metric that is used as a surrogate measure of overall storm water quality and as a performance measure of storm water control measures (SCM) (EPA 1993; TARP 2003). Several guidelines have been developed to standardize the protocol for monitoring sediment concentration in storm-water runoff through the use of automatic samplers and their deployment in storm sewer systems, swales, or other storm water infrastructure (EPA 1992; EPA 2002; TARP 2003; WA DOE 2008). These protocols and guidelines intend to limit biases associated with methodology. Biases typically may result from either sampling or analytical methods.

Bias introduced from varying sampling techniques may lead to inaccurate reporting of suspended sediment concentration in storm water. Many studies have examined aspects of measurement techniques in relation to the representative sampling of sediment load (Eads and Thomas 1983; Furumai et al. 2002; Li et al. 2005; Kim and Sansalone 2008). A major source of error is associated with the analytical methods used to measure concentration. The United States Geological Survey (USGS) conducted a study of hundreds of paired water samples obtained from riverine samples and found that a strong correlation could not be developed between total suspended solids (TSS) and suspended sediment concentration (SSC) (Gray et al. 2000). The cause of this difference was the presence of coarse sediments in the samples. Storm water could be expected to have a finer gradation of sediments for low-energy storms than are mobilized in a powerful riverine environment. A study by Kim and Sansalone (2008) examining hydrodynamic separators showed 25–85% of the event-based mass was $< 75\ \mu$m, 65–99% of the treated effluent was $< 75\ \mu$m, and 85–95% of the mass retained within the system was the coarse fraction ($> 75\ \mu$m). The degree of influence of particle size on sediment concentration by methodology (TSS and SSC) was examined by Guo (2007) with manufactured sediments of a known partial size distribution (PSD), who found little difference in water samples with fine sediments and a large discrepancy with sediments as coarse as 100 μm. The usage of TSS is widely codified in law as a water quality compliance measure and is considered a conservative measure (Roesner and Pruden 2007). The use of SSC for performance monitoring and,

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in particular, certification of manufactured treatment devices is becoming increasingly widespread.

The type and configuration of automatic sampler used in storm water monitoring can be another source of bias. In order to obtain an accurate sample of particles with varying specific gravity and momentum characteristics, the samples should be withdrawn at the same velocity as the discharge (USGS 1998). A review suggests that for accurately sampling of suspended sediment in surface water, isokinetic samplers are necessary to accurately collect sand-size particles and correctly calculate sediment concentrations (USGS 1998; Horowitz 2008). Isokinetic samplers adapt sampling intake velocity to the velocity of the incoming discharge. The majority of automatic samplers used in monitoring programs are nonisokinetic samplers that do not vary the pump velocity within the sampling tube to mimic the incoming velocity. Because the intake velocity will be mismatched with respect to the stream velocity, particle settling and stratification within the sampling line can occur. The degree of settling and stratification will be dependent on particulate characteristics (size, shape, specific gravity), height, length, and geometry of sampling line, and duration of the sample interval.

Another source of bias with sediment monitoring is the location of the sampling probe intake. Sampling guidelines and protocols provide guidance as to the location of the sampling probe in the water column and the method of extracting water samples. Vertical sediment concentration gradients will exist in a typical channel cross section, the degree of which is dependent upon particle and flow characteristics. As a result, the location of the intake will affect the accuracy of sediment concentration (Eads and Thomas 1983; Horowitz 2008). Sampling lines commonly located at the invert will sample the highest effluent concentration and overestimate the average sediment concentration as well as bias the PSD (Teledyne Isco 2001).

Bias to particle size could influence the evaluation of other contaminants such as metals and phosphorous that have sorption affinities based on both particle type (e.g., clays, organics) and size fraction (e.g., sands). One study showed that certain pollutants have a tendency to adhere to certain sediment sizes (Sansalone and Buchberger 1997). Total phosphorous was shown to have an affinity for midrange particles (53–300 μm), while fines are most important for *Enterococci* (10–30 μm), *E. coli* (0.45–30 μm), and heavy metals (2–63 μm). Full cross-section samples are one means to prevent bias associated with vertical sampling location.

A wide range of reported values exist for PSD, depending on location, land use, event hydrology, and sampling and laboratory method. An extensive review of sediment studies by Kim and Sansalone (2008) reported a median particle size of 136 μm (silt to fine sand) from eight runoff events from an interstate highway. In another study, Sansalone et al. (1998) found a tendency toward much larger particles with $> 50\%$ of particles being > 600 μm. One would expect that median particle sizes will, in general, tend toward fines for low-energy rainfall runoff events, often representing a significant portion of total rainfall events. In Durham, New Hampshire, 52% of events are less than 0.51 cm (0.2 in.) total rainfall depth.

The objective was to assess biases attributed to SSC analyses (ASTM D3977-97; ASTM 2000) of flow-weighted composite samples obtained by automatic sampler in comparison with actual sediment concentrations from large volume or total capture (TC) sampling (Table 1). This research examined potential biases associated with recommended guidelines for monitoring sediment concentration in storm-water runoff. This was accomplished by monitoring first-flush effluent from a storm-water sewer system. Nonisokinetic automatic samplers were used with sampling intakes located at the storm sewer invert. The results obtained by automatic samplers were compared to that obtained by capturing large volume samples taken for the equivalent portion of the first-flush runoff volume. This large volume or total capture sample is the complete volume and sediment load for the first-flush and considered to be minimally biased for determination of the actual sediment concentration, mass, and PSD.

The study was performed at the University of New Hampshire Stormwater Center field facility (Roseen et al. 2006). The stormwater runoff was monitored at the terminal end of a storm sewer that drains a curbed and guttered 9-acre commuter parking lot built in 1996. The West Edge parking lot is located on the University of New Hampshire campus in Durham, New Hampshire, and is at nearly 80% capacity eight months of the year. The lot is plowed, salted, and sanded regularly during the winter months. Winter maintenance includes a mixture of approximately 90% salt and 10% coarse sand. Average annual precipitation is 122 cm distributed throughout the year, with average monthly precipitation of 10.2 cm ±1.3 cm. The mean annual air temperature is 9°C, with the average low in January at −9°C, and the average high in July at 28°C.

The time of concentration for the parking lot is 22 min with land slopes between 1.4–2.0%. At the terminal end of the drainage system, a distribution box was built to distribute this storm water to a system of nine 30.5-cm (12 in.)-diameter pipes, configured to each receive equal parts of the runoff. The effective drainage area for the experiment was 0.4 ha (1 acre). The sediment event mean concentration in the storm-water runoff at this site is typical for a commercial and residential land use (Fig. 1).

Materials and Methods

Equipment Description

Flow into the experimental sampling area was controlled by a gate located in the distribution box and at the head of a single 30.5-cm pipe. Located at the pipe outlet was a pair of Teledyne Isco 6712 samplers. Sampling intakes were located at the pipe invert, 12 cm behind a Thel-mar compound weir. Depth of flow was measured using a Teledyne Isco 730 bubbler and a Global Water WL400 pressure transducer colocated at the sampling intakes. Flow was converted into discharge using a stage-discharge rating curve for the compound weir. The location of sampling intake, flow measurement method, and rainfall collection data followed recommended guidelines (EPA 1992, 2002). The samplers were located above the outlets with 4-m suction head. A 15,000 L basin used for collection of the large volume samples was located immediately downstream of the outlets. The basin was lined with two tarps: a 2.5-mm-thick, 9- by- 6-m polyethylene tarp, which would be removed and cleaned; and a larger 2.0-mm-thick multipurpose polyethylene liner underneath. The basin volume is equivalent to approximately 0.254 cm (0.1 in.) runoff depth.

Sample Collection

Approximately one storm per month was targeted for monitoring owing to the time required to prepare for and process large volume samples. Three concurrent sampling methods were run. When runoff began to discharge from the outlet, the automatic sampler programs were initiated. One of the automatic samplers was used to collect 1 L flow-weighted discrete samples throughout the time during which the large volume sample was taken. Automatic sampler 1 was used to determine sediment concentration. A second automatic sampler was used to take a single flow-weighted composite sample. Automatic sampler 2 was used to determine particle size distribution.

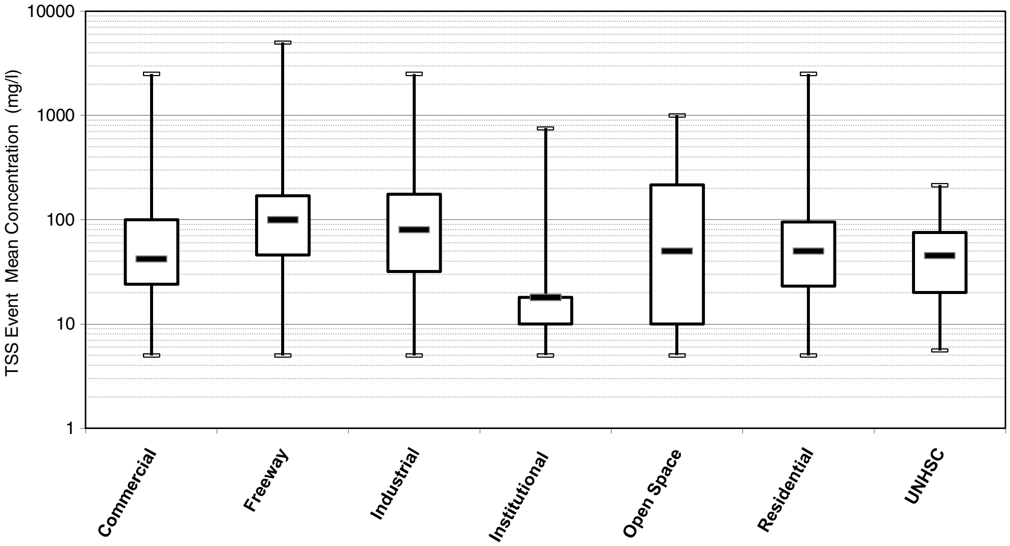

Fig. 1. Total suspended solids event mean concentration for varied land uses and at the UNH Stormwater Center; data in (mg/L)

The 15,000 L basin was allowed to fill during which time the samplers operated. Once the basin filled or the event ended, flow was shut off at the distribution box, and the sampling programs completed. The basin was then covered by a tarp to prevent potential contamination of the large volume sample during the time to follow. Large volume samples were taken for the first flush of each event, or the portion of the event anticipated to have the largest sediment load. A typical first-flush volume sampled would be equivalent to approximately 0.254 cm (0.1 in.) runoff depth.

Analytical Method

Automatic samplers were programmed to sample up to 24 bottles of 1 L flow-weighted samples per storm event (EPA and ASCE 2002; Huber 1993). Eight to nine of these samples were selected for sediment analysis to develop an event mean concentration (EMC). The sampling event hydrograph was then evaluated, based on distribution of samples and clarity of sample water, to select samples for analysis for concentration and size distribution. The EMC calculation evenly weighted the time lapse between consecutive discrete samples as commonly performed (Charbeneau and Barrett 1998; Stenstrom and Kayhanian 2005).

Samples were stored at 4°C prior to analysis, with typical holding times of 24–30 h. Samples were analyzed for sediment concentration by the SSC method of ASTM D3977. The SSC method was used in addition to the more common method for TSS. PSD analysis was performed by the light-scattering method using laser diffraction (ISO 2009).

Large-volume samples, captured and covered in the sampling basin, were allowed to settle for 48 h. Following 48 h of settling, a serial decantation process was begun. Settling time for a 2 μm spherical particle for this basin was calculated to be approximately 48 h. The clarified portion of the sample was decanted, and the volume was measured and sampled for sediment concentration. The initial clarified portion of the sample was typically 50% of the TC sample volume. The remaining TC sample and settled particulates were transferred into an 11,400 L (3,000 gal.) tank. Following another 48 h of settling, serial decantation continued with measurement of volume and sampling for sediment concentration. This process was repeated until the sample was reduced to approximately 100 L. The sediments were wet-sieved without drying using the method of ASTM Standard D2217 (ASTM 1988). Organic materials and gross solids were removed above a 4.5-mm-size fraction. The entire mass of total capture solids was sieved with the exception of the gross solids component, which was not included in the PSD. Size analysis was performed by wash-sieving $>$ 0.075 mm and a hydrometer test for sediments less than 0.075 mm (ASTM D422; ASTM 2002). Sediment concentrations for the TC sample was determined by totaling the mass of the recovered sediments combined with the mass determined in the volume decanted divided by the total volume captured. The mass of fine sediments removed through decantation was included in the calculation of the sample mass for the total capture. This mass was included for both EMC and PSD. Using Stokes' law, a 2-day settling time was calculated for particles < 3 μm diameter, given the sampling basin dimensions and assumed particle shape and density. The mass of fine sediments (clays) was then added to the 0.5–2 μm range for use in the PSD calculations. A storm event from each quarter season was selected for a specific gravity analysis using Method D854 (ASTM 2010). A subsample of the sediment from each event was used.

Results

Sampling and Event Characteristics

Eighteen events over the course of two years were monitored. Fig. 2 shows the depth of rainfall over the watershed, storm depth sampled (in terms of effective precipitation), event and sampling duration, and peak rainfall intensity for each event. Sample volumes were all less than 15,000 L, representing a first-flush volume. During this first flush, the pollutant concentration is assumed to be highest (Li et al. 2006; Aryal et al. 2006). Sampling duration varied with respect to storm duration and intensity.

The intake velocity within the sampling line of the automatic sampler with 4-m suction head is 0.85 m/s. The range of velocities in the outlet pipe for each can be seen in Table 2. For three of the 18 storms (on 7/21/06, 7/28/06, and 9/27/07), the maximum flow velocity exceeded the intake velocity of the sampler, all far exceeded the median concentration, and the 9/27/07 storm had the highest concentration and peak velocity observed. In the remaining storms, and away from the peak runoff rate in these three storms, the flow velocities in the pipe were less than the sampler

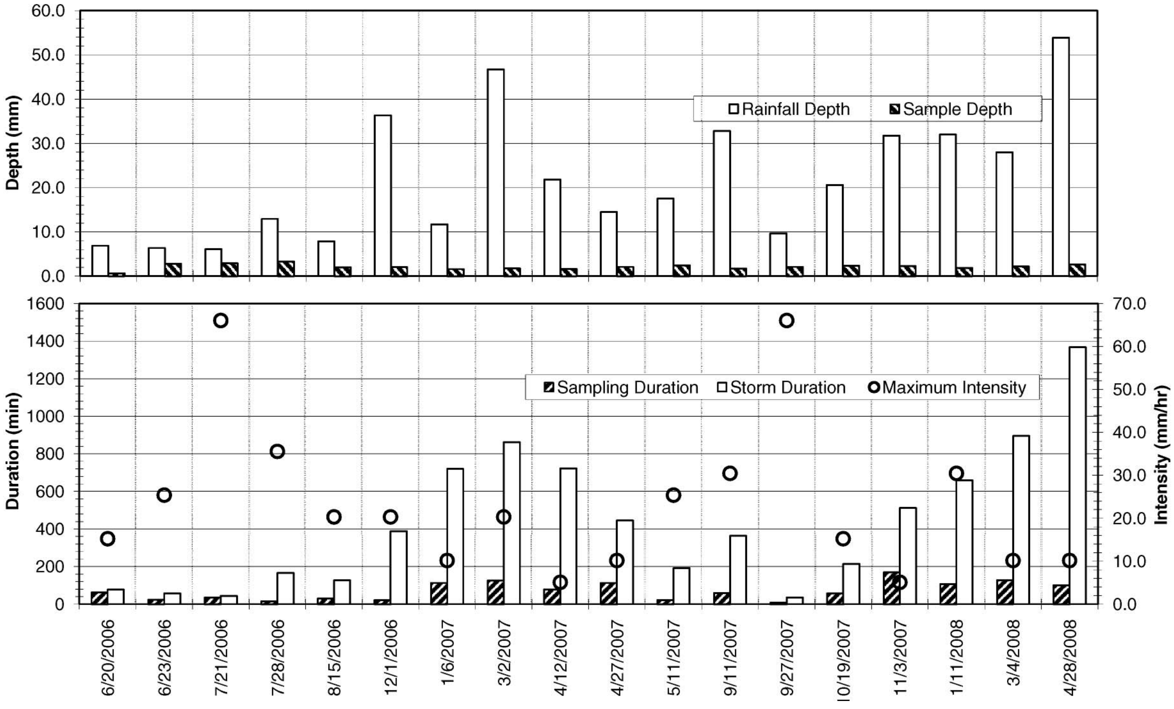

Fig. 2. Sampling and event duration and depth with maximum intensity

Table 1. Analytical Experimental Design for Sediment Characterization

Sample collection method	Sediment concentration method	Particle size characterization method
Method 1: Large volume sample, total capture (TC)	Measurement of 15,000 L sample volume, serial decantation, entire sediment recovery	Wash sieve and hydrometer (ASTM D422D)
Method 2: Automatic samplers (AS)	SSC analysis (ASTM D3977) of 1 L discrete samples	Particle size analysis by laser diffraction (ISO 13320:2009)

Table 2. Flow Velocities Observed during Storm Events

Number of storms	Range of medians (m/s)	Max (m/s)	Min (m/s)
5	0.003–0.15	0.14	0.03
8	0.151–0.3	0.25	0.16
3	> 0.30	1.07	0.40

intake capacity. For storms in which intake velocity was less than flow velocity, it can be assumed that there may be some bias attributed to large particles within the sample line that could fall out of suspension.

Total Capture and Sampling Method

The median sediment EMCs from the TC and SSC by automatic sampler (AS) were 69.0 and 70.1 mg/L, respectively, as shown in Fig. 3. The median concentration for both methods is higher than what is expected for this land use type and reflects a first-flush sampling. In Fig. 1, the values for sediment EMC were determined using the TSS analytical method which previous research has shown

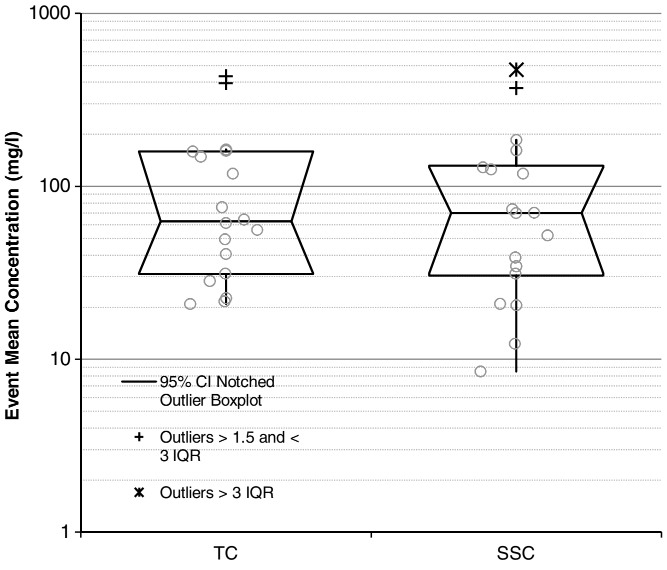

Fig. 3. Comparison of sediment event mean concentrations for two methods: total capture versus SSC by automatic sampler

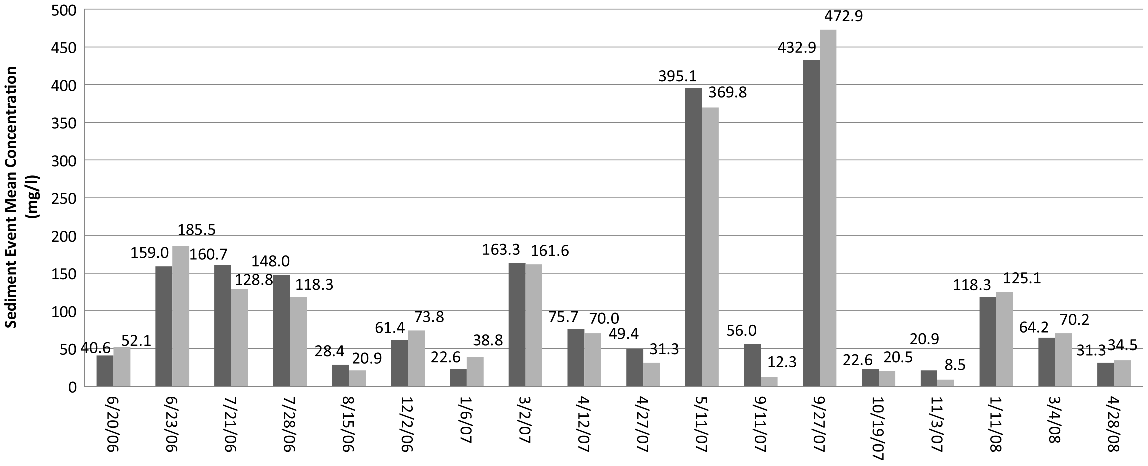

Fig. 4. Comparison by date of sediment event mean concentrations for two methods: total capture versus SSC by automatic sampler

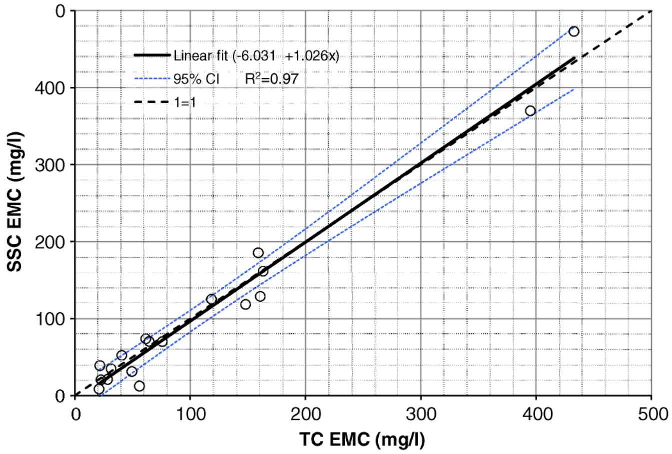

Fig. 5. Correlation between sediment concentrations by total capture versus SSC by automatic sampler

generally underreports total concentration (Gray et al. 2000). The typical median sediment concentration value for light transportation land use is 45 mg/L (Pitt and Maestre 2005). Fig. 3 illustrates the distribution of the sediment concentration for TC and SSC-AS, which are shown to be very similar. The distribution of the interquartile range (IQR) of the two methods illustrates strong similarities. An extreme outlier exists in the SSC-AS and is more than three times the IQR. This outlier occurred during the 9/27/07 event, the event with the greatest peak flow and maximum intensity (66.0 mm/h). The greatest outlier from the TC method also occurred during this event. Fig. 4 presents the comparison of sediment concentrations by the two methods and by date and illustrates the range of observations. Higher sediment concentrations typically occurred during storms in the summer months owing to high intensity storms and, often, long interstorm periods. This was observed for three storms in the summer of 2006 and for two storms in 2007. The five highest peak flow and rainfall intensity events are also the highest sediment concentrations (9/27/07, 5/11/07, 6/23/06, 7/21/06, and 7/28/06). There was a strong correlation between peak flow and maximum rainfall intensity ($R^2 = 0.80$) but not between TC concentration and maximum rainfall intensity ($R^2 = 0.43$). Peak flow and rainfall intensity correlation improved ($R^2 = 0.918$) if events with rain on snow (3/2/07 and 1/11/08) and another event (9/11/08) were removed. There was no trend in over- or underprediction of concentration for SSC-AS in comparison with TC. For 18 events, eight events occurred in which SSC was greater than TC. There were no strong trends in overprediction with respect to peak flow.

Correlation between Methods and Sediment Concentration Results

The correlation between the sediment EMCs for the two methods, SSC by automatic sampler and the TC, is strong ($R^2 = 0.974$) as shown in Fig. 5. The results of sediment concentration for each method were normally distributed, and the two methods were found not to be significantly different at a 95% confidence level (t-statistic $= 0.07$, two-tailed p-value $= 0.947$, $n = 36$). Specific gravity was measured for four storms, and a substantial range was observed—$x = 2.23 \pm 0.50$) with a minimum of 1.86 (rainfall event on 5/11/07) and a maximum of 2.96 (rainfall event on 9/27/07). These results are lower than some of the findings of previous research (Li et al. 2006) but are within the range of a more recent publication (Kayhanian et al. 2008).

Suspended Sediment Particle Size Distribution

The range of particle sizes found in storm-water runoff varies significantly with land use, but the presence of sand size sediments or coarser are commonly found in storm water (Sansalone and Tribouillard 1999). The median value of all D_{50} values for sediments recovered in the total capture samples and SSC samples taken by automatic sampler was 58 μm and 46 μm, respectively. The distribution of three percentiles of the particle size distribution is illustrated in Fig. 6 ($n = 11$). The D_{75}, D_{50}, and D_{25} are presented for comparison of the distribution of the selected percentiles. The size distribution fits well within the range for PSD of sediments from this type of land use (Furumai et al. 2002; Li et al. 2005). However, the distributions of the D_{75} and the D_{25} are visibly different between the two methods, whereas the D_{50} distributions are visibly similar. Interestingly, both the coarse and fine fractions appear to be underrepresented by the automatic sampler. The mass of decanted fines ranged from 1–29% ($x = 10.7 \pm 9.7$). Two events stood out (10/19/07 and 11/3/07) and were 23% and 29%, respectively, of the total weight. These two storms were not remarkable in terms of flow characteristics but were during the fall months when pulverized leaf matter could have a significant contribution.

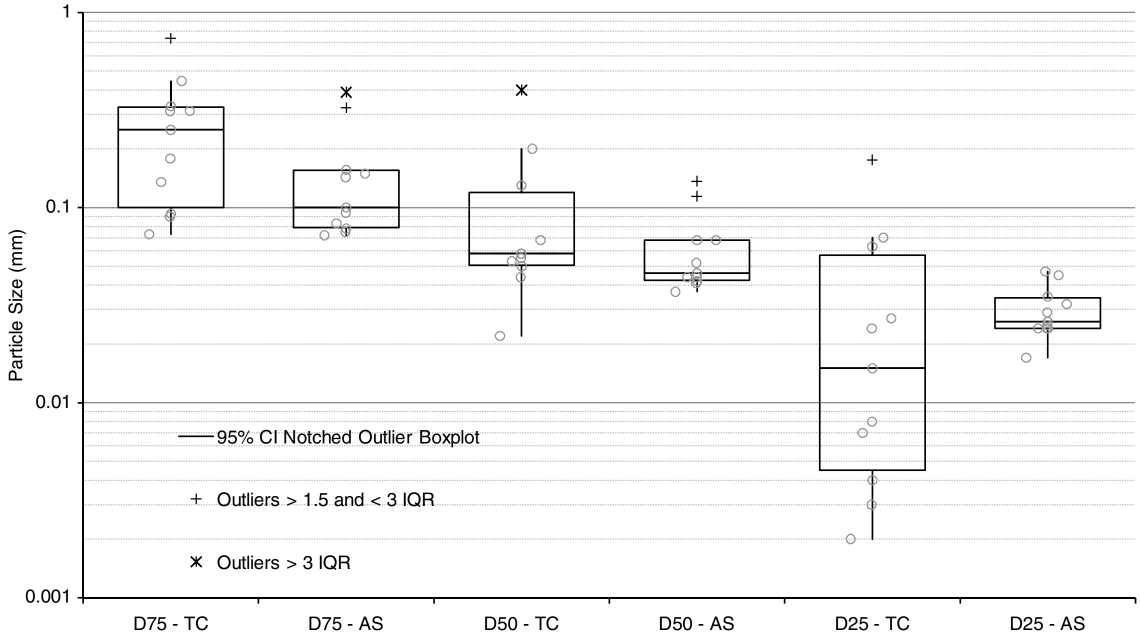

Fig. 6. Comparison of PSDs by sieve analysis (total capture) and laser diffraction (automatic sampler) at the 25th, 50th, and 75th percentile fractions by mass

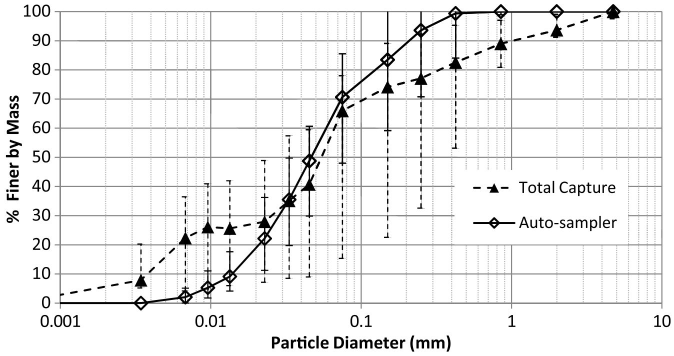

Fig. 7. Median particle size distributions by sieve analysis (total capture) and laser diffraction (automatic sampler); range of observed values indicated by error bars

The organic matter content was not determined for these events. A comparison of the median particle size for the three percentiles (D_{75}, D_{50}, and D_{25}) for the TC and automatic sampler methods suggests the differences are insignificant for this population size ($n = 11$, p-value $= 0.226$, 0.548, and 0.226, respectively). Both PSD outliers for the automatic sampler for D_{75} and D_{50} occurred during winter months (December 2006 and November 2007) during moderately low flows and are most likely the result of coarse sand deposited from winter maintenance practices. The outliers for the total capture (D_{50}, D_{25}) occurred in a single event during the event with the highest peak flow event (9/27/08). The greatest difference between the two methods was observed for the D_{75} particle where substantial changes in distribution can be observed (p-value $= 0.065$, $\alpha = 0.05$). Fig. 7 illustrates the median PSD observed for the two methods for the 11 events. The bias is visible both on the top and bottom of the size distributions; however, the midrange is quite similar. The automatic sampler distribution begins to underrepresent the coarse sediments above 75–150 μm.

Conclusion

This study demonstrated that the use of automatic samplers combined with the SSC method was an effective means for determining actual measured sediment concentration and loads (TC) for this type of land use and particle characteristics. For the combination of SSC with automatic sampler, there was a very strong correlation ($R^2 = 0.98$, $n = 18$) observed between the actual sediment concentration and the suspended sediment concentration. This was for a site where the median particle size ranged from 46–58 μm (for automatic sampler and total capture, respectively), common of storm water sediments. The notion that automatic samplers are underrepresenting sediment loads has become part of the literature (Eads and Thomas 1983; Gray et al. 2000; Furumai et al. 2002; Li et al. 2005; Kim and Sansalone 2008). However, many of these studies have focused on the use of TSS with automatic samplers. There is a host of potential errors when measuring sediment concentration, including samplers, sediment concentration methodology (TSS, TS, TVS, SSC, turbidity), and sample splitters (cone and churn splitters), to name a few. For the range of 18 storms studied, only three storms had maximum flow velocities that exceeded the sampler intake velocity at 0.85 m/s, another potential source of error.

The use of automatic samplers worked well for assessing the mean particle size (D_{50}) and was found to be not significantly different from the actual D_{50} as determined by the total capture. However, biases to particle size were observed both for particles larger than 75–150 μm and for particles smaller than 20 μm. The D_{75} and larger particles were substantially underrepresented by the automatic sampler (but not significantly for this population size). Studies have shown an extensive range of PSD (Kim and Sansalone 2008) and have often found the bulk of particle-associated contaminants (metals, phosphorous, petroleum hydrocarbons) to be < 100 μm (Furumai et al. 2002). This suggests that for similar sites, prescreening of samples with a 250 μm sieve prior to analysis may not be needed for sediment concentration if using SSC and may not be needed if particle size characterization is limited to D_{50}-size determination. However, for complete PSD assessment, the use of automatic samplers will lead to a negative bias of larger particles. For use in site characterization and performance assessments for storm water treatment device testing, SSC analyses with automatic samplers should meet the standard assessment criteria of sediment EMC and D_{50} determination but may be ineffective for the full particle size distribution.

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