Peristaltic Pump Autosamplers for Solids Measurement in Stormwater Runoff

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ABSTRACT: Regulatory agencies approve automatic samplers containing peristaltic pumps as a sample collection method for stormwater characterization and for treatment-device evaluation. Autosampler performance, as discussed in the limited available literature, can vary across the entire particle size range typically found in stormwater from different source areas and outfalls—reasonably consistent performance for particle sizes <250 μm, but much less consistency for particles >250 μm. Therefore, a series of experiments was undertaken to quantify the upper range of consistent particle capture that may occur with sampling stormwater suspended sediment and particulate-bound pollutants. These experiments, based on triplicate sampling at each experimental condition, found that peristaltic pump autosamplers commonly used in stormwater monitoring could not repeatedly and effectively capture particles >250 μm from a simulated stormwater whose particles have a specific gravity of 2.65. It was expected that the effective size for autosamplers would be correspondingly larger for particles having smaller specific gravities. The height of the sampler had no influence on particle recovery up to a height of 2.5 m, with slightly decreasing recoveries of large particles occurring at greater heights, as a result of reduced sampler intake velocity. Therefore, to characterize the solids across the entire size range and specific gravities that may occur in stormwater runoff, autosamplers should be deployed in conjunction with bedload and floatables sampling. Water Environ. Res., 80 (2008).

KEYWORDS: stormwater, sampling, autosamplers, solids sampling, analysis.

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Introduction

Accurate quantification of solids in stormwater runoff has been a concern for many years, both because of the receiving water effects of the solids and their associated pollutants and because most stormwater control devices are measured by their ability to remove these solids. Research by both this team and others has shown that median particle sizes in stormwater runoff can range from 8 μm (i.e., residential/commercial area runoff collected at an outfall before discharging to a detention pond) to greater than 1200 μm (i.e., runoff from a highway inlet that is periodically subject to anti-skid agent application during winter road maintenance) (Figure 1; City of Portland, 2004; Cristina et al., 2002; House et al., 1993; Kim and Sansalone, 2008; Li et al., 2005; Morquecho, 2005; NJDEP, 2003; Pitt, 1979). The “street dirt” particle size distribution (PSD) represents actual street dirt samples collected from the streets of San Jose, California, during U.S. Environmental Protection Agency (Washington, D.C.) street cleaning tests (Pitt, 1979) and are similar to many other street dirt sampling projects that have been conducted elsewhere. Although not representative of stormwater runoff sample PSDs, some stormwater professionals, unfortunately, assume that similar “street dirt” PSDs represent stormwater runoff conditions, which typically is very misleading. The distributions of the simulant requirements for full-scale laboratory testing for manufactured treatment device certification by the New Jersey Department of Environmental Protection (Trenton, New Jersey) (NJDEP) and the City of Portland Bureau of Environmental Services (Oregon) (BES) also are included in Figure 1 for comparison. These agency-prescribed simulant distributions lie between the PSDs from tests of two California highways.

Stormwater solids settling in sewer pipes and sedimentation devices is primarily a function of the particle’s settling velocity, which relates to the individual particle’s size and density. Table 1 (adapted from Pitt and Clark, 2006) presents settling conditions for particulates moving in two different pipe diameters with two different pipe slopes and for flow depths ranging from 10 to 100% of the pipe diameters. This table shows the distances the particles may travel before settling to the bottom of the pipe and starting to move as bedload or accumulating in the pipe itself. They are estimated using Manning’s equation to calculate the stormwater velocity and the combination of Stokes’ and Newton’s laws for settling rates. These are maximum transport distances, assuming the particles originate from the surface of the flow. As can be seen in the table, only the smaller particles remain suspended in the water column for lengthy distances.

The rapid settling of large particles (>100 μm), as seen in Table 1, in stormwater drainage systems explains why large particles seldom are seen in samples from autosamplers from outfalls of typical drainage systems. The large particles settle and become integrated to the bedload, which then travels along the pipe bottom below the intake for the autosampler or accumulates in the pipe and buries the autosampler intake. The bedload material also can become a cohesive deposit when dried between events and will not be amenable to further erosion and transport. In addition, Table 1 shows why correctly obtaining representative samples having a broad range of particle sizes is very difficult when using fixed-point samplers (i.e., autosamplers). In a quiescent body of water, such as a detention pond, applying settling calculations using Stokes’ Law demonstrates, again, the very short settling times for the larger particles. Within the first 1.5 minutes, all particles with a density similar to sand and greater than 100 μm will have settled

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to the bottom of the container. Lighter solids, with a specific gravity of 1.5, will take just less than 5 minutes to settle to the bottom. Unless the container is stirred continuously and vigorously, no fixed sampling point in the container will represent the concentration and PSD. Maintaining a homogeneous distribution of the particles in the water is difficult, even with adequate stirring (as discussed later), especially when large particles are present. However, at higher flows and higher solids concentrations, the differences between fixed-point autosamplers and cross-section, depth-integrated samplers is small (Bent et al., 2001; Breault and Granato, 2000; Horowitz et al., 1990; Krug and Goddard, 1986), such as the <20% difference noted in sediment concentrations between paired samples collected with a fixed-point autosampler and a cross-section, depth-integrated sampler (Bossong et al., 2006). However, the differences remain high (40%) at low solids concentrations (Graczyk et al., 2000).

The lack of sufficient turbulence in pipes to ensure a well-mixed water column is assumed to be the primary cause of the lack of representativeness of a fixed-point (automatic sampler) sample collected in a stormwater drainage pipe. As shown in Figure 1 and other studies (i.e., Smith, 2002), stormwater at source waters may contain sediment up to 3 to 4 mm in size, although these larger particles are not transported long distances and rarely are discharged at outfalls. Automatic samplers have been documented to capture particles in this size range, but no measure of consistency of capture has been provided. Similar to Bent et al. (2001), Burton and Pitt (2002) stated that automatic samplers are not efficient at sampling the largest particles, which are found in the bedload flows. They noted that particles having settling velocities in the 1- to 15-cm/sec range (100- to 1000-μm size) are found in grit chambers and catchbasins at inlets to drainage systems, but seldom are obtained in

Figure 1—Reported PSD of stormwater runoff and street dirt samples (residential/commercial: House et al., 1993; OH highway: Cristina et al., 2002; street dirt: Pitt, 1979; CA highway 1 and 2: Li et al., 2005; LA highway: Kim and Sansalone, 2008; source area inlet: Morquecho, 2005; NJDEP: NJDEP, 2003; Portland BES: City of Portland, 2004).
stormwater samples obtained by automatic samplers alone; therefore, they recommended the supplemental use of bedload samplers with automatic samplers to obtain better distributions of stormwater particulates in stormwater samples. Automatic samplers, while periodically capturing a portion of the larger particulate components of stormwater flows, may not be capable of adequately capturing a large fraction of these particles from a sample where a substantial fraction of the particles are greater than approximately 250 μm. Kayhanian et al. (2005) also noted concerns regarding bedload deposition burial of the sampler intake in infrequently maintained storm sewer pipes.

Errors associated with the overall process of collection and analysis of stormwater runoff solids have been documented (literature summary in Roesner et al., 2007). Only recently has attention been focused on quantifying the errors associated with each phase of this process, with most of the activity focusing on quantifying the concerns regarding analysis technique, including storage time and temperature and effect of PSD (Chan et al., 2008; Clark and Pitt, 2008; Clark and Siu, 2008a, 2008b; Guo, 2005, 2007; Li et al., 2005; Siu et al., 2008). Earlier work by the U.S. Geological Survey (Reston, Virginia) (USGS) (Bent et al., 2001; Edwards and Glysson, 1999; Winterstein and Stefan, 1983) quantified some of the concerns regarding the ability of automatic samplers to capture solids in the different size ranges and densities that can be associated with stormwater runoff. Guidance, as summarized below, has been developed to adapt wastewater automatic samplers to stormwater monitoring, with the research results reported within these guidance documents. What is missing from this earlier work is a systematic investigation, in a controlled setting, of the ability of autosamplers to capture particles in specific size ranges.

One of the most cited references on the use of automatic samplers to sample suspended sediment in water is Edwards and Glysson (1999). They updated the USGS guidance on measuring fluvial sediment concentrations and provide updated information on automatic samplers, including the development and design of automatic samplers, selection of the intake location, and guidance toward selecting the sampling location in the water flowpath. The authors recommended that correlations be developed between the results from the automatic sampler samples and complete depth-integrated, cross-section samples over the full range of flows, especially because automatic samplers do not behave necessarily as isokinetic samplers across the entire range of flows seen in sewer pipes. Also, to capture a representative sample, the authors recommended that the pump tube velocity has to be greater than the settling velocity of the desired particles. The lack of isokinetic sampling likely introduces one part of the errors to the measurements resulting from intake inefficiency, particularly in the capture of particles greater than 0.062 mm. The Edwards and Glysson (1999) paper recommendations regarding sampler setup were based on the laboratory work of Winterstein and Stefan (1983), who investigated the effects of nozzle orientation on particle capture, particularly in the larger particle sizes. Winterstein and Stefan (1983) noted that sand-sized particles (>62 μm) are best captured when the intake is oriented downstream of the flow. Recently, modifications to the installation location of the intake have been proposed and implemented to improve collection efficiency over the wide range of flows found in storm sewer pipes (Kayhanian et al., 2005).

Edwards and Glysson (1999) also noted that an old series ISCO 1600-series sampler (Teledyne ISCO Inc., Lincoln, Nebraska) is unable to efficiently maintain a continuity of sediment concentration from the stream to the sample bottle. Bent et al. (2001) provided additional recommendations based on the uniqueness of sampling highway runoff. They note that testing of post-1993-design automatic samplers show that the samplers could accurately capture samples with PSDs in the range 20 to 128 μm across the range of possible elevations of the sampler above the water surface.

What is missing from the literature is whether the capture of stormwater particles is consistent and representative of the sediment concentration in the water column across all particle sizes from <1 μm to fine gravel (2 to 4 mm), or whether automatic sampling should be combined with bedload sampling to characterize the entire particle size range. Because of these concerns and to isolate the errors potentially inherent in the complete process of sampling and analysis, this research has focused on the limitations of the sampling equipment itself through analysis of samples of known concentration and through minimization of the other sources of error associated with sample collection. In particular, this research has selected a consistent methodology for solids analysis, ASTM D-3977B (ASTM, 1997) for suspended sediment concentration (SSC) (Clark and Siu [2008b] discuss the differences between traditional analysis methodologies), and a consistent method of sample preparation, the Dekaport cone splitter (Siu et al. [2008] address the errors associated with this sample preparation device). This research uses well-mixed and continuously stirred tanks to contain the solids simulant, because previous testing, as part of the testing of a manufactured treatment device, has shown that a lack of homogeneity in the solids distribution in the water column is a concern in laboratory flow-through testing.

**Materials and Methods**

The purpose of this research was threefold—to determine the approximate upper particle size range that autosamplers were able to collect repeatedly and whether either or both the sampler height and/or the PSD (as measured by the median particle size, d50, of the simulant) affected that upper limit. This research was performed in three phases. Phases I and III were performed at Penn State Harrisburg (Pennsylvania) (PSH) using an American Sigma 900 Max autosampler (American Sigma, Loveland, Colorado). This sampler was purchased in 2005 for field sampling of stormwater runoff. The intake tube was perforated with four rows of three 0.8-cm holes. Each row was separated from the other by 90 degrees. According to the manufacturer’s website for the sampler,

“... samplers feature a positive displacement peristaltic pump constructed of corrosion-resistant Delrin... our samplers produce a 3.3 ft/sec velocity at 3 ft lift in a 3/8 in. ID intake line.”

A similar ISCO sampler (6712 Portable Autosampler, Teledyne ISCO Inc.), used in the phase II tests at the University of Alabama (Tuscaloosa) and purchased in 2004, has the following comparable product description, indicating that the results seen here with the two sampler brands are interchangeable:

“... portable sampler pump uses 3/8 in. ID vinyl or Teflon tubing...typical line velocity @ head height: 3.0 ft/s @ 3 ft; 2.9 ft/s @ 10 ft; 2.7 ft/s @ 15 ft (0.91 m/s @ 0.9 m; 0.83 m/s @ 4.6 m).”

A cylindrical tank that can hold 210 L of liquid was used as part of the test setup in phases I and III. Figure 2a gives the schematic of the tank used, including tank dimensions. Figure 2b shows a photograph of the inside of the tank with the stirring tool and the automatic sampler intake extended from the end of a polyvinyl
chloride (PVC) pipe. At the bottom of the tank, the outlet can be seen (bottom left, closest to center); this is the point where the sample mixture flows out of the tank for grab sampling once the spigot is turned on. A different test setup (in terms of sample mixing) was used in the phase II testing. A 14-L churn splitter was used for mixing and sampling (picture not shown). Grab sampling occurred near the position of the automatic sampler intake.

For the first phase of sampling, the installed tubing length on the sampler was a short 1.8 m to focus on inherent sampler characteristics and to minimize effects associated with longer tubing and higher pumping heights. This was held constant for all runs. Tubing was visually inspected between runs for particle retention on the tubing walls, with none seen. For the second and third phases of sampling, the tubing lengths were 8.0 and 7.6 m, respectively, to better represent typical field conditions with larger pumping heights.

In phase I, two silica-based samples (ground silica, sand+silica (mix)) were used to investigate solids recovery for this autosampler using a tubing length of 1.8 m and two heights (0.8 and 1.1 m). The particle sizes for these materials are given in Figure 3. The ground silica (Sil-Co-Sil 250, U.S. Silica Company, Beckley, West Virginia) had a \(d_{50}\) of 90 \(\mu m\), while the sand+silica had a \(d_{50}\) of 260 \(\mu m\). When compared with the PSDs in Figure 1, the ground silica has a \(d_{50}\) similar to the non-Ohio highway runoff, and the sand+silica mixture resembled the street dirt. Both mixtures had smaller \(d_{50}\) values than the Ohio highway runoff, which may have contained remnants of anti-skid agents. The rationale for selecting these larger-sized mixtures and the sand used in phase III was to determine the size limits for particle capture by the autosampler.

The samples were collected from a well-mixed (continuously stirred) 210-L tank holding a 500-mg/L test solution made up of the test particles added to tap water. The sampler tubing was contained inside a PVC pipe with the intake extended below the pipe. The intake port was placed in the flow path with one set of holes in line with the direction of flow in the mixed tank. A schematic plus a photograph of the intake tube setup is given in Figure 2. The tank was rinsed thoroughly (three times with tap water) between the ground silica and mix runs.

The samples were collected using the manual sample collection option in the “stormwater sampling” program of the autosampler. The sampler purged the intake line before and after sample collection to prevent cross-contamination. Three samples were taken of each solids sample at three heights within the sampling container (within 5 cm of the bottom, approximately mid-depth, and just below the water surface) while the water was stirred continuously and manually to create a small vortex in the tank. Samples were collected from two different locations of the autosampler—where the sampler pump was (1) approximately equal with the water surface in the container and (2) approximately 1.1 m above the container’s water surface. The water surface elevation evaluated whether the sampler would encounter problems sampling at the water surface level, while the 1.1 m height represented the lower end of typical sampler installations.

These samples were split, using a Teflon USGS/Dekaport cone splitter (Rickly Hydrological Company, Columbus, Ohio), into three fractions—unsieved, sieved through a 500-\(\mu m\) U.S. standard
sieve (W.S. Tyler, Mentor, Ohio), and sieved through a 250-μm U.S. standard sieve. They were analyzed for SSC following the ASTM D3977-97 method. This analytical procedure used the entire bottle to minimize any errors associated with aliquot subsampling. Previous analysis of the cone splitter errors for a wide range of sediment concentrations by Siu et al. (2008) and of the analytical procedure by Clark and Siu (2008b) at the 500-mg/L concentration used in the testing showed coefficients of variation (COV, ratio of standard deviation to mean) of less than 5% and less than 2%, respectively.

Phase II focused on the ability of the samplers to recover particles in specific size ranges at different sampler heights above the water container holding the water to be sampled. This sampling was performed at the University of Alabama using an ISCO 6712 portable sampler (Teledyne ISCO Inc.). The sampler programming settings were identical to those used in the PSH testing. The challenge solution for the second phase of testing was a mix of two sands and two Sil-Co-Sil ground silicas. The mix was 25% each of Sil-Co-Sil 106, Sil-Co-Sil 250, sand (90 to 250 μm), and sand (300 to 450 μm) (in Figure 3, this test mixture is labeled “2 sand+2 silica”). The mix had a $d_{50}$ of 90 μm, similar to the $d_{50}$ of the ground silica. Unlike the ground silica, however, the 2 sand+2 silica mix evenly covered a much wider range of particle sizes to obtain a significant mass in the larger particle sizes for accurate analyses, not to better represent stormwater PSDs. The sample concentration for this phase of testing was a high 5000 mg/L, to minimize problems associated with high variability in the analysis of low concentration samples (Siu et al., 2008). A 14-L churn splitter (Rickly Hydrological Company) was used to create a well-mixed sample that was then sampled by the automatic sampler and by manual sampling. The laboratory analyses were performed as described above for phase I. Manual samples also were collected from the churn splitter near the placement of the automatic sampler intake to determine the actual concentration in the water near the intake for each test. The PSD of the collected samples was analyzed by wet sieving using U.S. standard sieve sizes of 20, 45, 106, and 250 μm (W.S. Tyler). Samples were collected at the following four different sampler heights: 2.4, 4.0, 6.7, and 7.9 m.

The phase III experiments focused on the upper end of the particle size range found in source area stormwater runoff. These tests also investigated the ability of the autosampler to recover these larger particles near the upper limit of the recommended height of the sampler above the water surface. Therefore, this phase covered a “worst-case” condition for the autosamplers. Phase III used the sand previously used in the sand+silica mix, but without the added silica, and had a $d_{50}$ of approximately 300 μm (sand PSD, Figure 3). This test was performed using the same concentration as phase I, 500 mg/L, and the height of the sampler pump above the water was 6.3 m. The intake of the sampler was located next to the spigot on the container where the grab samples were collected (see Figure 2).

Triplicate samples were collected at each sampling condition, except where otherwise described. All statistical analyses were performed using the one-way analysis of variance option in SYSTAT (version 11, Systat Software Inc., San Jose, California) with a posteriori Bonferroni pairwise comparisons for those runs. P-values have been included in the discussion; $\alpha = 0.05$ was used to differentiate in the text whether a result was significant.

Results and Discussion

The goal of this research was to address, systematically, the questions previously raised regarding the effectiveness of peristaltic-pump-driven autosamplers (specifically those that had been designed for the wastewater industry) at capturing the coarser and heavier solids that may be found in stormwater runoff. Because the focus was on the limitations of the autosamplers themselves, the testing methodology was designed to minimize the errors not associated with autosamplers, such as analytical methodology and effects of nonturbulent flow on solids suspension in the water column. To further test the autosampler’s limitations, the testing was performed with solids simulants where the PSD was in the upper range reported for urban runoff. Compared with the results described below, performance would be expected to improve for samples with PSDs typical of urban runoff. These simulants included particles typically not found in large quantities in stormwater outfall samples (i.e., those with specific gravity of 2.65 and larger than 100 μm). Hence, this research demonstrates the solids recovery abilities by both automatic and manual sampling in the presence of near-optimal water column mixing and coupled with a “worst-case” particle size range scenario of stormwater solids (where specific gravity = 2.65, i.e., sand-sized particles).

The first question examined was the effect of particle size on solids recovery, because the particulates in the challenge samples were silica-based (having identical specific gravities of 2.65). The differences seen in the recoveries should be related strictly to the ability to keep these larger particles well-mixed in the sample and their ability to be drawn into the sampler intake, up the tubing, and deposited in the automatic sampler containers. The data are shown in Figures 4 and 5 for water-surface level and elevated (1.1 m) sampler positions, respectively (S&S = sand+silica; Sil = ground silica only; triplicate samples at each condition).

![Figure 4—Solids recovery by the autosampler at the water-surface level (S&S = sand+silica; Sil = ground silica only; error bars equal one standard deviation; triplicate samples at each condition).](image-url)
mixed sample, even when the mass fraction greater than 250 µm was seen between the samples in this data analysis (based on triplicate analysis at each PSD and elevation combination), even though a slight increasing trend in concentration was visible from the top of the test solution container to the bottom. If these samples were not well-mixed, Stokes’ Law would predict that the trend of decreasing measured concentrations from bottom to top would be more pronounced and potentially statistically significant (thus, requiring the use of a depth-integrated sampler).

The phase II testing investigated the recoveries over a wider range of sampler heights than the phase I testing. The four heights of the sampler intake above the water level in the test sample container were 2.4, 4.0, 6.7, and 7.9 m. The solids simulant was the 2 sand+2 ground silica mixture. The effects of elevation of the sampler intake on solids recovery are shown in Figure 6. Only two samples plus a grab sample from the test sample container were collected at each height. Therefore, insufficient samples were collected for a complete statistical analysis of the data.

The results showed that the solids recoveries at each height were similar to each other and to the grab sample obtained from within the sampler container adjacent to the automatic sample intake, with the exception of the one elevated-concentration sample collected at the 2.4-m height. This confirmed the results seen in the phase I testing, but over a wider range of sampler elevations.

The relatively poor recoveries of all samples compared with the test solution concentration of 5000 mg/L indicated that the initial sample was not mixed effectively, with much of the largest material collecting on the bottom of the container and not being resuspended during the test solution’s rigorous churning. The grab samples from the test solution container and the samples collected by the automatic sampler had similar concentrations, but both sets were well below the 5000-mg/L test solution concentration. This result differed from the phase I study, in which the test solution container was more effectively mixed. This difference stressed the need to ensure that sampler intakes be located in very well-mixed flows or that the autosamplers be supplemented with bedload samplers when large particles are to be sampled.

Each of these samples also was split into the following five particle size ranges: 0 to 20, 20 to 45, 45 to 106, 106 to 250, and >250 µm (Figure 7). The size distributions were calculated based on the mean SSC concentration in each size range. Based on this PSD analysis, the sampler was able to recover the entire particle size.
range in the influent at the 2.4 m elevation. However, at the higher elevations of the sampler, the recoveries decreased substantially for the larger particle sizes. This was evident by the shift in the median particle size in these samples, which shifted from 180 to 500 μm for the 2.4-m elevation to between 30 and 60 μm for the 4.0-, 6.7-, and 7.9-m sampler elevations.

The phase III experiments addressed the third question pertaining to the recovery of large particles at a sampler height near the upper end of the recommended operating elevation, by focusing on the ability of the autosamplers to collect sand-sized particles. Concurrent with the operation of the automatic sampler, grab samples were collected from the spigot of the test solution container. The sampler intake was located adjacent to the spigot at the elevation of the spigot in the tank with one set of inlet ports facing the direction of flow during mixing. The samples were split into the following four size ranges: <106, <250, <500, and <1000 μm. The results are shown in Table 2.

Because this phase focused on the sampler’s ability to capture larger particles, the test mixture contained fewer than 10% of the particles smaller than 106 μm. The results showed that, unlike the grab samples, the autosampler captured only a small fraction of the particles greater than 500 μm. The statistical analyses showed the autosampler recoveries were not significantly different between 500 and 1000 μm (based on triplicate analysis at each size range), although they were statistically significantly different between the 106-, 250-, and 500-μm particle sizes. These differences for each particle size were not seen for the grab samples, with the exception of the significant difference at the 106-μm size. The grab sample solids concentrations were significantly different from the autosampler concentrations for the 250-, 500-, and 1000-μm particle sizes. For samples sieved at 1000 μm, the autosampler was able to recover only approximately 25 to 30% of these large solids in the mixture, while grab samples recovered close to 100% for sieve sizes 250 to 1000 μm. A second observation from this data set was that both the recoveries and COVs were greater in the grab samples. The lower COVs in the autosampler samples indicated that the autosampler had a greater precision (and, therefore, better repeatability) during the sample analysis, but, as discussed above, the autosampler had a lower percentage recovery in sample collection for the larger particles.

Preliminary testing of the sand + ground silica mixture at a 6.7-m sampler height (data not shown) with vigorous manual stirring that created a deep vortex in the center of the tank indicated that, compared with the grab samples’ concentrations for each particle size range, autosampler recovery of particles less than 1000 μm was approximately 85%, while it was approximately 95% for particles less than 106 μm (which contained a large percentage of the smaller ground silica particles). Therefore, it was anticipated that collected runoff samples would adequately represent (in a very well-mixed water column) the runoff being sampled, if it contained a small fraction of the larger-sized particles. However, when the particle sizes in the runoff were biased toward the larger size ranges (large fraction of particles greater than 250 to 500 μm), such as in highway runoff in areas subjected to winter applications of anti-skid agents, the autosampler may not have been able to reliably capture representative samples, even from a well-mixed water column. Based on this research, the upper limit of reliable particle size capture by these peristaltic pump autosamplers appeared to be between 250 and 500 μm for particles having a specific gravity of 2.65. The upper limit of reliable particle capture would be expected to increase as the specific gravity of the particles decreased. In addition, while the sampler port location attempted to replicate the optimal location in the flowpath, as described by Edwards and Glysson (1999), recoveries of the larger particles may have increased and variabilities among replicate samples may have decreased if other intake port locations and intake configurations were used. Given these limitations, however, it was apparent that an upper limit existed where the precision of solids recovery by autosamplers decreased, potentially to the point of being unacceptable.

Referring back to the calculations from Pitt and Clark (2006) (see Table 1), the large particles in stormwater flows (>100 μm) were likely to settle out within a few meters of pipe flow in the stormwater drainage system. These solids may have travelled along as bedload or accumulated as sediment and would not have been accounted for in the collection of water samples using the automatic sampler at an outfall location. Accounting for this size range of particles would have required additional sampling of the bedload itself. Even if the water column was well-mixed, such as by a flushing, turbulent flow, the results from this research showed that these particles (>500 μm) may not have been represented consistently in the samples collected by the peristaltic-pump-driven autosamplers.

Bedload sampling has been incorporated to many projects where a complete accounting of the solids loading was required. For example, at a residential site in Madison, Wisconsin, Selbig and Bannerman (2007) installed bedload samplers as part of street cleaner tests. Their data found that the bedload (not captured by the automatic samplers) totaled approximately 5% of the annual sediment load from the study area. By using continuous video cameras at the bedload samplers, they found that this material was

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<th>Particle size fraction (μm)</th>
<th>Grab sample mean concentration (mg/L)</th>
<th>Grab sample COV</th>
<th>Autosampler mean concentration (mg/L)</th>
<th>Autosampler COV</th>
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transported mostly during the initial observed flows in the pipe, not during the complete event (Bannerman, 2008). The percent bedload not captured by an automatic sampler could have been expected to increase at sites, such as highways, where the fraction of large particles in the runoff was greater than that found at residential stormwater outfalls.

Discussion exists in the stormwater profession as to whether the entire range of solids or a fraction of that range are environmentally important and should be monitored. As this research shows, autosamplers cannot be relied upon to provide information about the solids component in stormwater across all size ranges potentially of interest. However, they appear to be very reliable for investigating the solids fraction less than 250 μm and dissolved components, provided that the sampler intake ports are installed in a flow direction and configuration that optimizes particle collection efficiency and minimizes blockage by pipe debris.

Given the lack of agreement on whether monitoring should focus only on smaller particles and the diversity of research results on pollutant associations with particle sizes, the authors suggest that much could be learned through conducting mass balance monitoring and using a combination of automatic samplers and bedload samplers. For example, when the USGS and the Wisconsin Department of Natural Resources (Madison) monitored a hydrodynamic stormwater control device at a public works yard in Madison, Wisconsin (Waschbusch, 1999), automatic samplers were used at the influent and effluent of the device to calculate removal of pollutants. The calculated removal of particulate solids was approximately 28%. However, when the effluent solids load was subtracted from the influent solids load and compared with the mass captured in the sump, the sump contained a greater amount of sediment than predicted by load subtraction. When these sump data were used to correct the particulate solids removal performance of the stormwater control device, the removal of particulate solids was found to be approximately 33%. Similar findings were evident when stormwater flows. This research clarified the limits on, and errors associated with, solids measurements using peristaltic-pump driven autosamplers. Even in a well-mixed container (with vigorous manual continuous stirring) with the sampler pump at and less than 2 m above the water level, the samplers were unable to consistently collect >250- to 500-μm solids with a specific gravity of 2.65 (the concentration after the 250-μm sieve was statistically identical to the concentration of the unsieved sample). This upper limit should increase as the specific gravity of the particles decreases. The solids recoveries in the well-mixed container were affected only by the differences in the PSD of the challenge solutions (approximately 50% recovery for solids d_{50} of 500 μm and approximately 80% recovery for solids d_{50} of 100 μm). Recoveries should increase as the solids d_{50} decreases to ranges more common of non-highway stormwater runoff collected at outfalls. The smaller d_{50} resulted in much longer settling times and, therefore, was easier to keep suspended in the turbulent water while being pulled up by the autosampler. In a less well-mixed challenge sample container (possibly better representing typical poorly mixed flows in pipes and at outfall sampling locations), the recoveries of the particulates were worse. Particulate recoveries also decreased slightly in the upper size ranges when the sampler elevation exceeded 2.5 m above the water surface, likely as a result of the decreased water velocities in the sampler intake line.

This research supports the long-discussed hypothesis that autosamplers are not effective at sampling the larger particles (>250 to 500 μm) that may be found in stormwater runoff, even if the water column is well-mixed and the sampler elevation above the water surface is less than 2.5 m. For the highest level of accuracy across the entire particle size range that could be found in runoff, bedload sampling should accompany the use of automatic samplers. For testing of stormwater controls, mass balance analyses that compare influent and effluent samples must be supplemented with methods that directly quantify the collected material in the device to obtain accurate particulate solids and associated pollutant removals.

**Conclusion**

Stormwater professionals have discussed the effects of the use of autosamplers on the accurate representation/collection of solids in stormwater flows. This research clarified the limits on, and errors associated with, solids measurements using peristaltic-pump driven autosamplers. In a well-mixed container (with vigorous manual continuous stirring) with the sampler pump at and less than 2 m above the water level, the samplers were unable to consistently collect >250- to 500-μm solids with a specific gravity of 2.65 (the concentration after the 250-μm sieve was statistically identical to the concentration of the unsieved sample). This upper limit should increase as the specific gravity of the particles decreases. The solids recoveries in the well-mixed container were affected only by the differences in the PSD of the challenge solutions (approximately 50% recovery for solids d_{50} of 500 μm and approximately 80% recovery for solids d_{50} of 100 μm). Recoveries should increase as the solids d_{50} decreases to ranges more common of non-highway stormwater runoff collected at outfalls. The smaller d_{50} resulted in much longer settling times and, therefore, was easier to keep suspended in the turbulent water while being pulled up by the autosampler. In a less well-mixed challenge sample container (possibly better representing typical poorly mixed flows in pipes and at outfall sampling locations), the recoveries of the particulates were worse. Particulate recoveries also decreased slightly in the upper size ranges when the sampler elevation exceeded 2.5 m above the water surface, likely as a result of the decreased water velocities in the sampler intake line.

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**Credits**

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