Continuous *in situ* characterization of particulate sizes in urban stormwater: Method testing and refinement

Jeff Brown, Drew Ackerman and Eric D. Stein

ABSTRACT

Understanding the size distribution of stormwater particulates and the pollutants associated with each size fraction is becoming an increasingly important aspect of stormwater management. Traditional approaches to measuring stormwater particle size distribution are limited by the need to collect multiple samples and transport them to the lab for analysis. *In situ* laser refractometry offers an attractive alternative to traditional approaches for near real time, continuous analysis of stormwater particle size distribution. However, the high velocity, turbulence, and turbidity of urban stormwater present limitations for the application of current *in situ* particle size analysis instruments. This study evaluated and refined application of the Laser *In Situ* Scattering and Transmissometry (LISST 100X) particle analyzer for use in urban stormwater assessment. To ensure that the LISST provided meaningful results, the following tests were conducted: 1) the accuracy of the instrument to sample particles sizes expected to occur in urban stormwater was tested, 2) the method was refined to accommodate for the low transmissivity typically associated with urban stormwater, 3) potential artifacts associated with aeration and bubbles in the sample tubing were addressed, and 4) potential bias associated with pumping, which may differentially sample particle sizes in a non-representative manner was evaluated. With application of protocols outlined in this study, the LISST provides a new tool for continuous *in situ* analysis of stormwater particulates.

INTRODUCTION

Stormwater runoff is a major source for many pollutants of concern. Pollutants in stormwater are associated mainly with suspended particles, which act as a transport vector to downstream areas (Sansalone and Buchberger 1997, Lau and Stenstrom 2005, Surbeck *et al*. 2006, Lau *et al*. 2009). Numerous studies have documented the association of stormwater particulates with pollutants including organic contaminants/nutrients (Vaze and Chiew 2004), bacteria (Fries *et al*. 2006, Pachepsky *et al*. 2008) and trace metals (Chebbo and Bachoc 1992, Han *et al*. 2006b).

Particles in urban stormwater are not uniform; the size distribution varies throughout a storm and as a function of land use in the contributing catchments (Li *et al*. 2006). Smaller particles are often associated with higher pollutant concentrations due to their higher surface area to volume ratio (Herngren *et al*. 2005). Studies on particle size distribution in highway runoff conducted in Los Angeles (Han *et al*. 2006a, Li *et al*. 2006, Kang *et al*. 2007) and Cincinnati (Sansalone and Buchberger 1997, Sansalone *et al*. 1998, Kim and Sansalone 2008, Lin *et al*. 2009) have shown that pollutants are preferentially associated with particles smaller than 100 µm. For example, coliphages have been found to be preferentially bound to particles <5 µm (Davies *et al*. 2003).

Most previous studies of stormwater particles in surface runoff during storms rely on laboratory methods to characterize particle sizes in individual stormwater samples. Accuracy of these methods depends on the ability to transport samples from the field to the lab for analysis in less than six hours so that the analyzed particle size distribution is representative of field conditions (Li *et al*. 2006). Newer methods, such as *in situ* laser refractometry, allow for much higher resolution measurements by providing near continuous quantification of stormwater particle size distribution using flow-through systems at sampling locations. These methods allow for measurement of particles at short time intervals (i.e., minutes) that are not feasible with conventional sampling methods. The Laser *In Situ* Scattering and Transmissometry 100X (LISST; Sequoia Scientific, Inc., Bellevue, WA) is a commonly used *in situ* laser refractometer, which estimates particle size distribution by passing a laser through a parcel of water and measuring the amount of scatter that the particles induce. The LISST was designed to be used primarily in the ocean and in slow moving water where turbidity is low and transmissivity is high. Urban stormwater typically has much higher turbidity than ocean water and, to date, the LISST has not been tested for routine use in urban stormwater.

There are several technical challenges to using a LISST to characterize particle size concentrations in urban stormwater. First, the LISST was designed to be submerged to obtain particle information. Such deployment is not possible in urban storm channels due to the high velocity and debris associated with stormwater runoff. Second, the high turbidity of urban stormwater may exceed the instrument's optical tolerances, necessitating design modifications to ensure that the LISST will provide a representative sample (i.e., very high attenuation reduces the instrument's ability to accurately measure particles). Finally, pumping samples from high velocity flows often result in production of bubbles, which may appear like particles to the LISST; a situation that must be remedied to avoid artificially high particle counts. The study goal was to refine the LISST methodology to address these challenges so that the instrument could reliably be used for continuous quantification of particle sizes throughout an urban storm runoff event.

METHODS

Study Sites

The LISST methodology was tested and refined in the Ballona Creek watershed, located in Los Angeles, California. Ballona Creek provides an excellent laboratory for method testing as it is characterized by high velocity, high turbidity urban stormwater that is conveyed through a fully concrete lined channel. The watershed above the sampling point drains 230 km^2 and is approximately 85% developed (Ackerman *et al*. 2005). At the sampling point, the creek is a concrete trapezoid channel approximately 50 m across at the top and 40 m at the bottom with a side channel slope of 1.5:1. Samples were collected from a bridge approximately 10 m above the channel bottom.

LISST Setup and Processing

The LISST uses a collimated laser beam directed through the water column. The laser is scattered by particles and sensed by a multi-ring detector behind a receiving lens (Sequoia Scientific 2008). Thirty-two rings measure particle sizes ranging from 2.72 to 460.27 µm (Table 1). Manufacture's recommendations were followed to set up the instrument and process collected data. The LISST was blanked according to manufacturer's instructions (Sequoia Scientific 2008) and de-ionized water was used to quantify the background particle levels. The LISST blanking chamber and 2 mm and 10 mm flow-through cells were used for various tests. Particle

Table 1. Particle size range (µm) for each of the 32 LISST type C rings.

Size Bin	Lower	Middle	Upper
1	2.50	2.72	2.95
2	2.95	3.20	3.48
3	3.48	3.78	4.11
4	4.11	4.46	4.85
5	4.85	5.27	5.72
6	5.72	6.21	6.75
7	6.75	7.33	7.97
8	7.97	8.65	9.40
9	9.40	10.21	11.09
10	11.09	12.05	13.09
11	13.09	14.22	15.45
12	15.45	16.78	18.23
13	18.23	19.81	21.51
14	21.51	23.37	25.39
15	25.39	27.58	29.96
16	29.96	32.55	35.36
17	35.36	38.41	41.72
18	41.72	45.32	49.23
19	49.23	53.48	58.10
20	58.10	63.11	68.56
21	68.56	74.48	80.91
22	80.91	87.89	95.48
23	95.48	103.72	112.67
24	112.67	122.39	132.96
25	132.96	144.43	156.90
26	156.90	170.44	185.15
27	185.15	201.13	218.49
28	218.49	237.35	257.83
29	257.83	280.09	304.26
30	304.26	330.52	359.05
31	359.05	390.04	423.70
32	423.70	460.27	500.00

concentrations (µl/L) were determined using the LISST-SOP version 5.0 (Sequoia Scientific 2008) to measure non-spherical particle concentrations output.

Stormwater Sampling Setup

The LISST could not be submerged for *in situ* sampling because high flows and large debris create hazards that can result in loss or severe damage to the instrument. Consequently, modifications were required for use of the LISST in a pumped, flow-through manner. Stormwater from Ballona Creek was pumped vertically 10 m from the concrete channel bed to the LISST which was located on a bridge over the channel. Teflon tubing, 9.5 mm inside diameter, was encased in 25.4 mm angle iron that was bolted to the concrete channel bottom of the creek. Samples were pumped using a Masterflex I/P 77410-10 peristaltic pump with two heads in parallel and Masterflex Norprene I/P 73 tubing. Silicon tubing transported the sample to the bridge, through a filter with 480 µm mesh sump filter (Cole-Parmer Low-cost In-line Strainer System), then through the LISST flow-through cell. The bowl and mesh of the sump filter were manually switched out approximately every 15 minutes, or when they became clogged with leaves, small sticks, trash, etc. Pumping rates were maintained at >3 L/minute (0.8 m/s) to ensure that there was no settling in the tubing.

The operational end of the LISST was inserted into an acrylic box which was filled with de-ionized water, and the entire instrument was placed in a 121-L ice chest, on its resting blocks, to protect it during sampling (Figure 1).

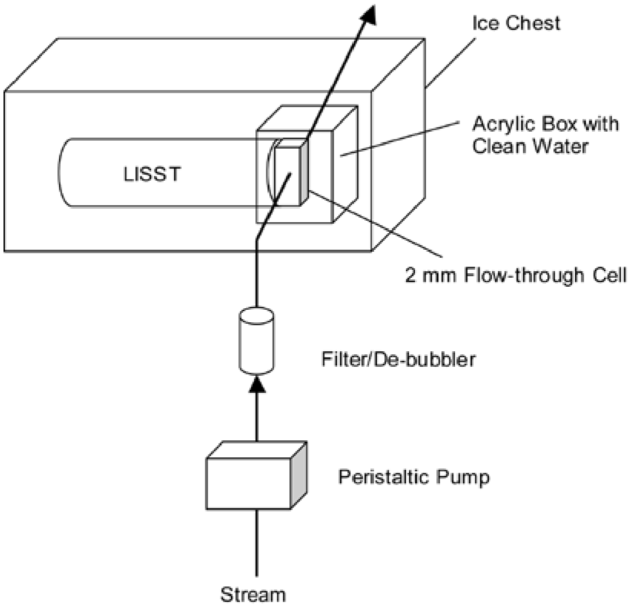

Figure 1. Urban stormwater channel sampling set up.

LISST Testing

To ensure that the LISST provided meaningful results, the following tests were conducted: 1) the accuracy of the instrument to sample particle sizes expected to occur in urban stormwater was tested; 2) the method was refined to accommodate for the low transmissivity typically associated with urban stormwater; 3) potential artifacts associated with aeration and bubbles in the sample tubing were addressed; and, 4) potential bias associated with pumping, which may differentially sample particle sizes in a non-representative manner was evaluated.

Accuracy of particle size and concentration

The ability of the LISST to measure particle size accurately was tested using three certified size standards. This included a 5 µm borosilicate glass microsphere standard (certified mean diameter 5.6 µm ±0.5 µm, 0.7 µm standard deviation, Duke Scientific), a 20 µm borosilicate glass microsphere standard (certified mean diameter = 17.3 µm ±1.4 µm, 2.0 standard deviation), and a 100 µm soda lime glass standard (certified mean diameter 97.6 µm ±4.9 µm, 3.6 µm standard deviation). Each standard was prepared in concentrations ranging from 31 to 500 mg/L. Samples of the standards were measured in the LISST's 150-ml mixing chamber (5 cm path length) with the mixing chamber's magnetic stir bar activated. The LISST analyzed particle concentrations in each sample at one second intervals. An average concentration was calculated for each particle size based on approximately three seconds of collected data. A particle density of 2.5 g/cm^3 (indicated by the manufacturer) was used with the borosilicate standards to convert from µl/L to mg/L, while a density of 2.47 g/cm^3 (also indicated by the manufacturer) was used with the soda lime glass standard. An overall median particle size was calculated for each sample, weighted by the measured concentration of each particle size.

Bias

The ability of the instrument to accurately measure concentrations was assessed by analyzing a series of known particle concentrations. The material used for this analysis consisted of natural soil passed through a 63 µm screen. This soil was used to prepare solutions ranging in nominal concentrations from 16 to 500 mg/L. These solutions were analyzed in the mixing chamber, with immediate stir bar activation. Average concentrations of the total particles were estimated from three to five consecutive intervals. An assumed particle density of 2.6 g/cm^3 (equal to the density of quartz) was used to convert from µl/L to mg/L.

Precision

The repeatability of the instrument in estimating concentrations was assessed by analyzing a single sample multiple times. The 63 µm screened natural sediment prepared to a final concentration of 62 mg/L with de-ionized water was used. This solution was vigorously mixed, and 150 ml was added to the instrument's mixing chamber with immediate activation of the mixing chamber's stir bar. The LISST measured the particle concentrations at one second intervals; values from three to five successive intervals were used to calculate an average. The sample was analyzed three times, with the mixing chamber rinsed with de-ionizeded water between measurements. The coefficient of variation (CV; standard deviation divided by the mean) was calculated for the total concentration of the three separate analyses. The CV was also calculated for particle size classes, based on the Wentworth scale (1922), including silts and clays (2 - 63 µm), very fine and fine sands (63 - 250 µm), and medium sands (250 - 500 µm).

Representativeness

Depending on the strength and position of the pump intake, pumped samples may or may not include particles that are representative of those in the channel flow. Samples pumped from the stream through the LISST were compared to samples taken directly from the creek using a USGS depth-integrated sampler. Grab samples were collected from Ballona Creek at four time points during two storms (December 15, 2008 and February 5, 2009). The LISST continually sampled the stormwater at 1 sample per minute, averaging 10 bursts over 10 seconds. Both sets of samples were taken to a laboratory and analyzed for particle size distribution via a Coulter Counter under guidelines prescribed in Standard Methods for the Examination of Water and Wastewater (APHA, 20th Edition), Section 2560 D. The results from the Coulter Counter were compared with the results produced by the LISST.

Interferences

Because stormwater is typically too turbid for the laser to pass through without severe interference, reducing the laser path length was necessary to obtain reliable estimates of particle sizes. In order to attain adequate transmissivity with the stormwater analysis, a flow-through cell was used to reduce the laser path length from 5 cm to 2 mm, allowing higher concentrations of particles to be measured. The accuracy of the 2 mm sample cell was tested in the laboratory by analyzing a series of known particle concentrations. The 63 µm screened natural sediment was used to prepare solutions ranging from 62 to 6000 mg/L. These solutions were prepared in a 1.5 L flask with an activated magnetic stir bar and pumped through the 2 mm sample cell (attached to the LISST) with a Masterflex peristaltic pump at a flow rate of 4 L/minute. The samples were recirculated to the sample flask during the analysis, with the first 300 ml of sample purged from the system prior to data collection. The LISST measured particle size densities at one second intervals, with one minute of data used for each sample. An assumed particle density of 2.6 g/cm^3 was used to convert from µl/L to mg/L.

Stormwater is highly turbulent with air bubbles entrained in it. The LISST will interpret these bubbles as particles, resulting in erroneous measures. To allow the bubbles to escape the system prior to the sample entering the LISST flow-through cell, a 1.6 mm hole was drilled in the bottom of the sump filter for de-bubbling. The ability of the field setup to remove bubbles was tested in the lab by adding air bubbles to the system with an aquarium pump. The Masterflex peristaltic pump was used to pump clean water through the LISST, while an aquarium aerator was directly inserted into the tubing intake. The sump filter was put inline before the pump and inverted, with the hole in the sump used to remove the bubbles.

RESULTS

Accuracy of Particle Size and Concentration

For each of the particle size standards, the mode of the size distribution corresponded with the average particle size indicated by the manufacturer (Figure 2). However, the LISST slightly overestimated the weighted median particle size for each standard. The weighted median particle size of the 5.6 µm (±0.5 µm) standard was 7.4 µm, while the 17 µm (± 2.0 µm) standard was 24 µm, and the 97.6 µm (±4.9 µm) standard was 128 µm. This overestima-

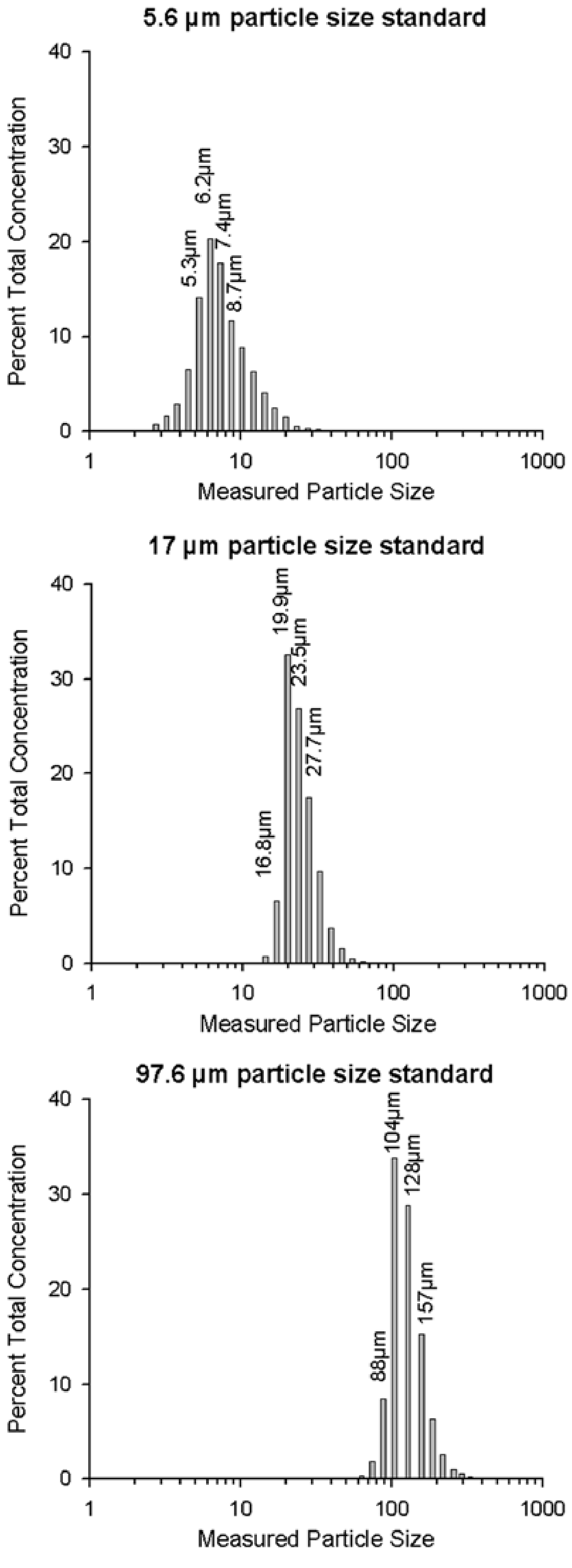

Figure 2. Particle size distribution (measured via LISST) as percent concentration with respect to particle size standards.

tion was consistent throughout the range of concentrations analyzed for each of the standards.

Bias

Measured concentrations of the screened natural sediment ranged from 71 to 120% of the nominal value (the expected concentration based on sample preparation). The percentage of the nominal value tended to increase with higher concentrations of the screened soil, from 71% for the 16 mg/L sample to 120% for the 500 mg/L sample.

Precision

Overall, there was good reproducibility among the replicate concentration measurements. The CV for replicates of the total particle concentration (CV = 3%) was within the acceptable level of precision (CV <20%) for grain size analysis by the California State Water Resources Control Board's Surface Water Ambient Monitoring Program (California State Water Resources Control Board 2002). There was also low variability among measurement of the Silt and Clay size class (rings 1 - 20; CV = 4%), as well as for the Fine and Very Fine sand size class (rings 21 - 27; CV = 1%). The variability among replicates of the Medium Sand size class was relatively high (rings 28 - 32; CV = 46%). However, the concentration of the Medium Sands size class was low in the 63 µm screened sediment, accounting for 1% of the total concentration.

Representativeness

Little difference was observed between the particle concentrations in stormwater as measured by the LISST and those measured using laboratory techniques. The five comparisons of the flow-through generated LISST particle size distributions and the size distributions from the Coulter Counter showed little variation (Figure 3). The median relative percent difference between the LISST and the Coulter Counter for the five samples was 8% for the Silt and Clay fraction, 20% for Very Fine and Fine Sands, and 139% for the Medium Sands.

Interferences

Lab tests showed that with the 2 mm flow-through cell, the LISST can be used throughout the range of suspended sediment concentrations seen in typical urban stormwater. The highest concentration analyzed (6000 mg/L) had an optical transmission of

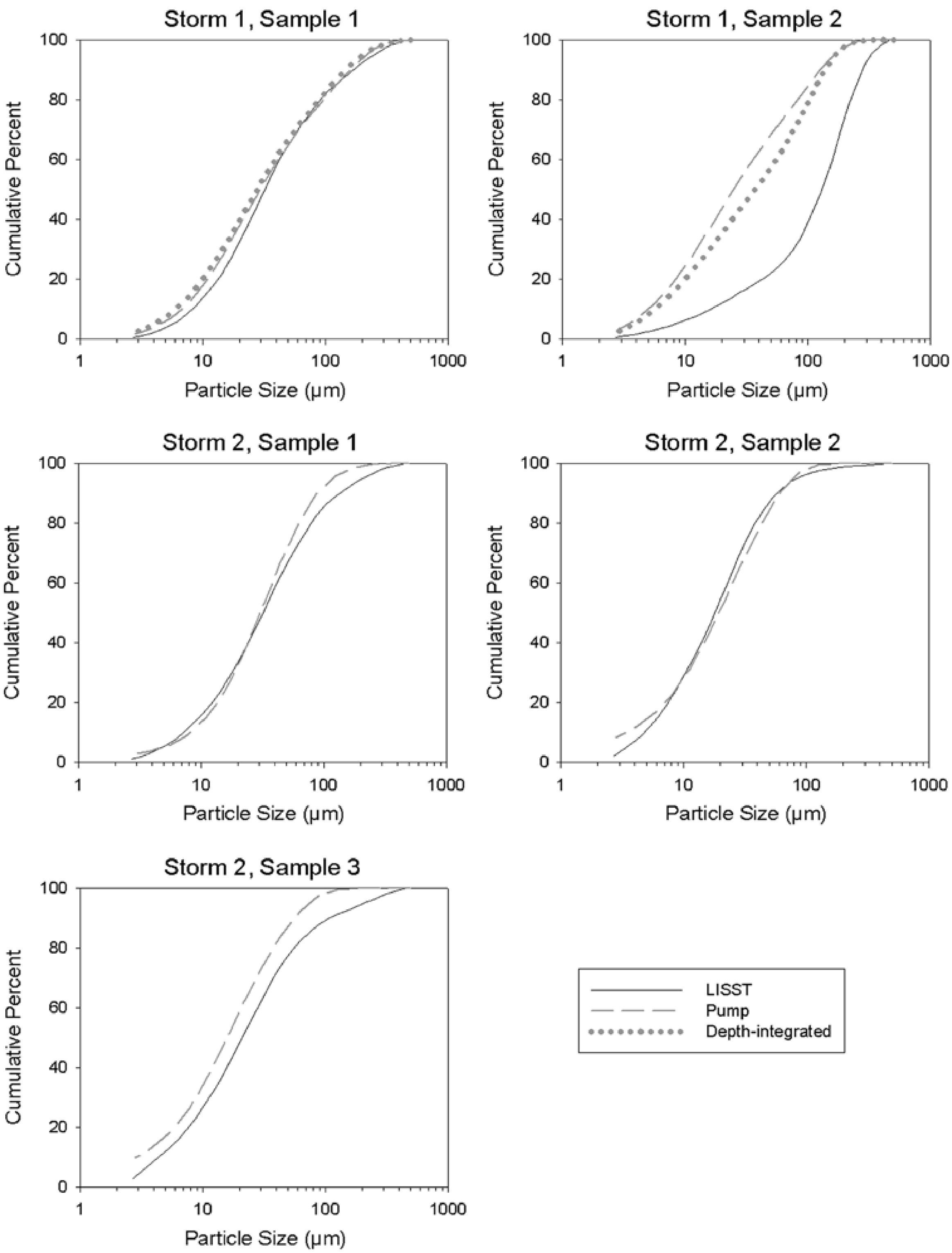

Figure 3. Comparison of LISST and laboratory particle size distributions from the depth-integrated (Storm 1 only) and pumped samples for two storms.

24%, while the second highest concentration (4000 mg/L) was associated with an optical transmission of 39%; optical transmissions must be greater than 20% to be acceptable, according to the LISST manufacturer. For comparison, the upper 90th percentile of TSS concentrations in stormwater from urbanized catchments of southern California is approximately 1000 mg/L (Stein and Yoon 2007).

The 2 mm flow-through cell was able to analyze higher concentrations of particles in stormwater than the 10 mm flow-through cell that comes standard with the LISST (Figure 4). With the 2 mm flow-through cell, concentrations of at least 1800 µl/L (4680 mg/L) had an acceptable optical transmission, while the 10 mm flow-through cell had a maximum reliable concentration of approximately 600 µl/L (1560 mg/L). In a deployment of the LISST using the 2 mm flow-through cell during a storm event on December 15, 2008, measured concentrations tended to be approximately 1.5 times the nominal value throughout the range of concentrations measured.

The de-bubbler setup successfully removed bubbles from the sample. Using the de-bubbler to pump clean aerated sample water, measured particle concentrations were typically <40 µl/L (<100 mg/L), which was similar to background levels seen in testing. By comparison, aerated concentrations of 20,000 µl/L (equivalent to 52,000 mg/L quartz) were measured without the de-bubbler (Figure 5).

Example Application

An example of particle size characterization of stormwater using the modified sampling and analysis method is shown in Figure 6. The LISST was able to measure particle size concentrations on a continuous basis for a storm event from December 15, 2008, identifying changes in concentrations throughout the storm.

DISCUSSION

The results from our study demonstrate that the LISST can reliably determine particulate sizes in urban stormwater. Analysis of both known standard particle sizes and sieved natural soils produced consistent, accurate results. In the field, comparison of laboratory analysis of stormwater both pumped and grab samples with the LISST revealed minor differences that were within generally acceptable ranges of variability. In laboratory experiments, the LISST used in this study tended to overestimate particle size, which is similar to the findings of Traykovski *et al*. (1999), but in contrast with Gartner *et al*.

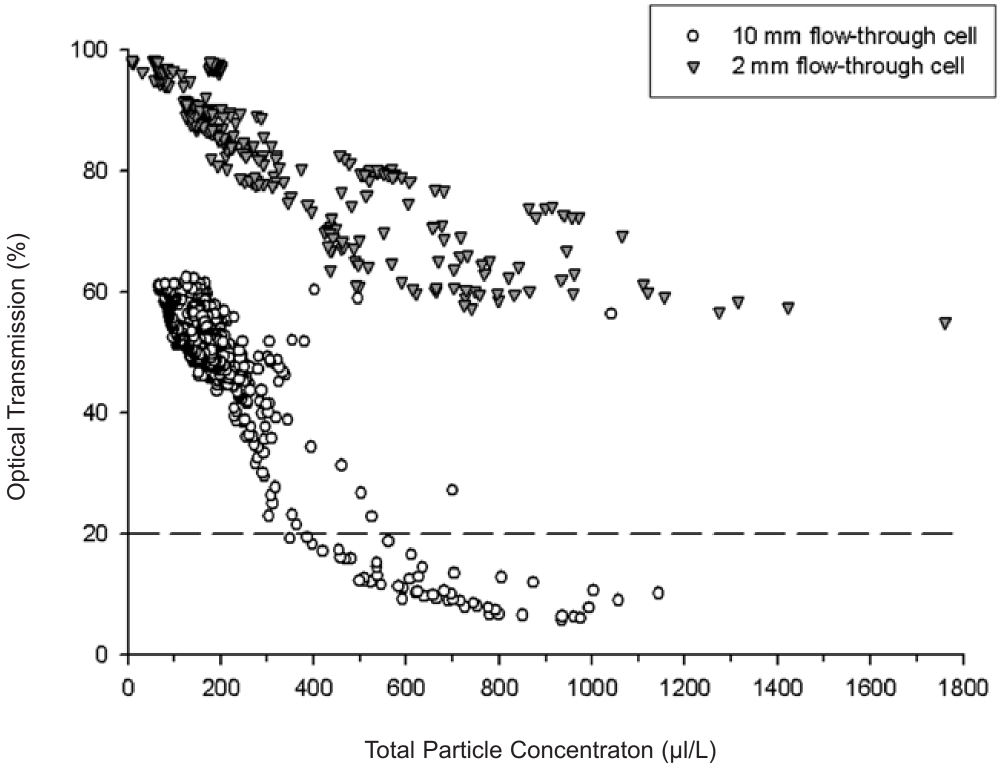

Figure 4. Comparison in optical transmission ranges between the 2 mm and 10 mm flow-through cells. The dashed line corresponds with the optical transmission reliability threshold, below which the particle size measurements become unreliable. The 2 mm flow-through cell provided a greater range of acceptable particle size measurements than the 10 mm flow-through cell.

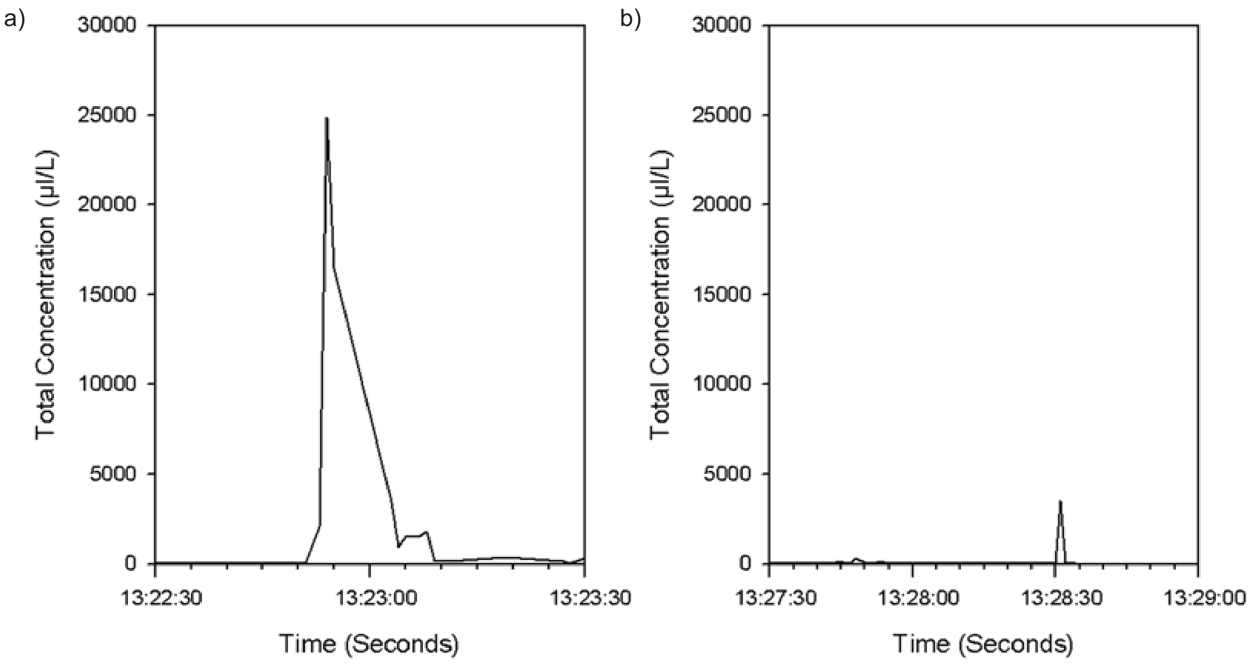

Figure 5. Measured particle concentrations with bubbles pumped through the LISST with and without debubbling. The de-bubbler was disabled for the analysis shown in Figure 5a. For this analysis, air was added to the system, then allowed to purge. Figure 5b shows an analysis when air was added continuously, with the de-bubbler engaged.

(2001), whose two LISSTs tended to underestimate mean particle size. This study suggests that such "calibration" measurements be done prior to LISST deployment in order to better quantify potential error and bias.

There are many difficulties in sampling urban stormwater for particles. The particle concentration in stormwater runoff is typically much higher (up to 1000 mg/L TSS; Stein and Yoon 2007) than typically can be measured with an instrument like the LISST. Using the narrow 2 mm flow-through cell instead of the standard 10 mm cell reduced the amount of water that the laser had to pass through, thus reducing interference and allowing higher laboratory and field particulate concentrations to be quantified. Use of pre-filter/de-bubbler allowed for screening of larger particles (and debris) that are outside of the detection range of the LISST. Screening reduces the LISST's ability to quantify the full range of particle sizes in stormwater. However, it also prevents the flow-through cell from clogging with organic matter (leaves, sticks, etc.) and trash, and removes bubbles that may cause artificially high particle counts. This is an acceptable tradeoff as the pollutants of concern are typically associated with smaller particles. Nevertheless, this limitation should be kept in mind if quantification of large sands or gravel is of interest. Another sampling related issue is that the intake tubing tended to clog with debris in the channel; therefore, the pump should be periodically back-purged. The sample line itself is subjected to high forces from the stormwater and needs to be armored to ensure a continuous sample can be obtained.

When using an instrument like the LISST to characterize urban stormwater particles, several points need to be in the forefront of sampling design. The LISST particle concentration output is volumetric (i.e., µl/L) while stormwater particulates concentrations are generally expressed as milligrams per liter. This study found that particulate density is highly variable throughout the storm. Thus, obtaining particle density information is required for the concentration conversion. This study used a constant density to convert from volumetric to mass concentration (2.6 g/cm^3, equal to the density of quartz), which will introduce additional error into the measurements. Direct measure of particle density (via a settling chamber or similar method) would allow for more accurate estimation of the mass concentration of particles.

Finally, it is important to calibrate the LISST prior to deployment by running samples with known size particles through the instrument in a controlled manner. For this study, using a 2 mm flow-through cell resulted in the instrument consistently overestimated concentrations by a factor of 1.5 across all

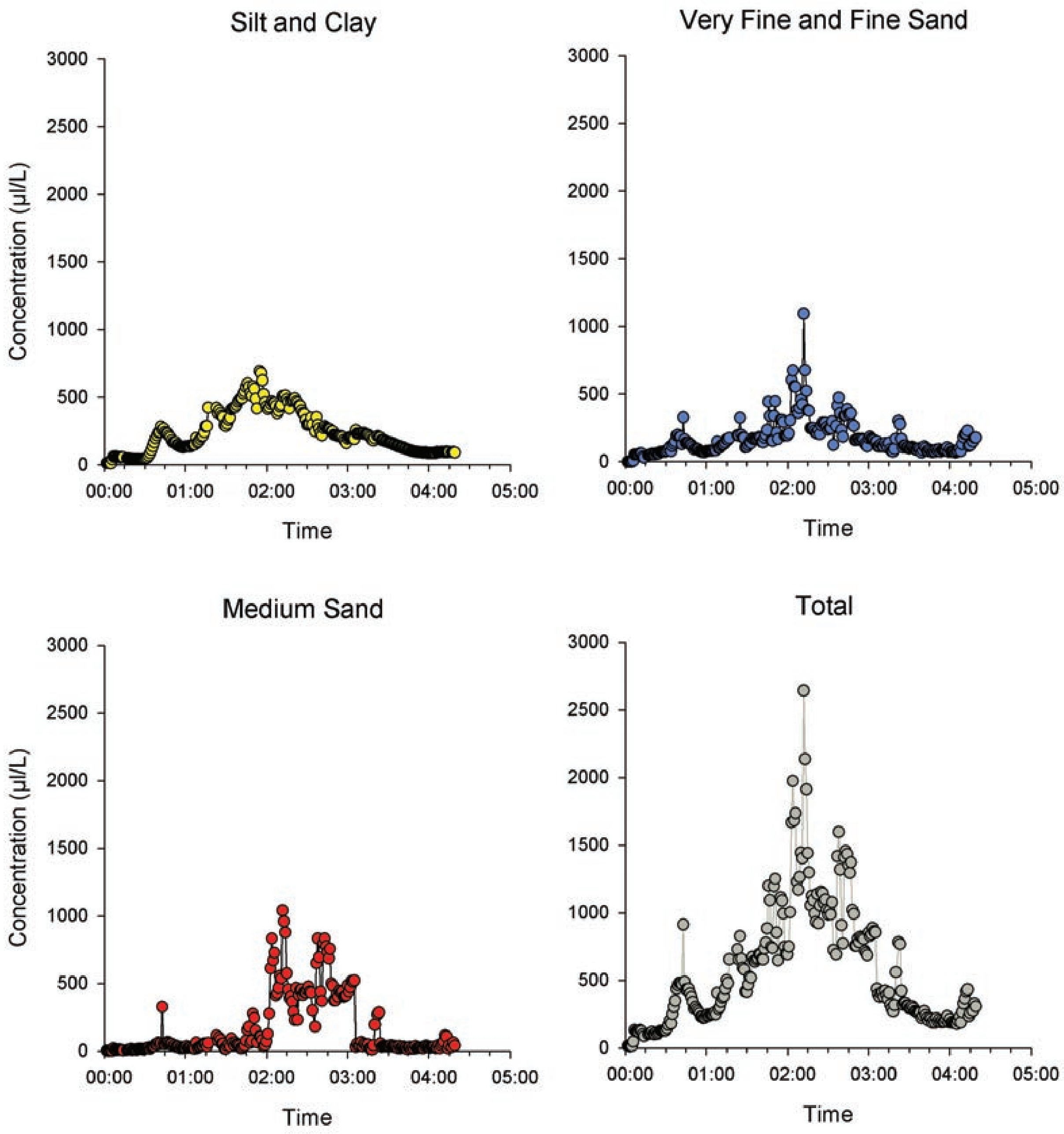

Figure 6. Storm continuous particle size concentrations. Storm water from December 15, 2008, at Ballona Creek analyzed for particle size distributions using the LISST with the 2 mm flow-through cell, and sump filter/debubbler.

size classes. Thus, values could be divided by this factor to correct errors for reporting purposes in this study. This norming factor should be re-evaluated for each instrument using native samples to determine if and what appropriate conversion factor should be.

Stormwater management options frequently focus on controlling particulates and the pollutants bound to them. Stormwater best management practices (BMPs) have varying degrees of performance, with removal efficiency differing by particle size. Typically, little information exists on particle size in urban runoff; when that information does exist, it is typically limited to a single sample characterizing the entire storm. This study has shown that the LISST can be used to continually characterize particle concentrations throughout a storm. Thus, use of a LISST deployed before and after water flows through a treatment facility may help managers determine the facility's effectiveness at controlling particle sizes of interest. Deployed over several storms, the LISST can subsequently provide managers with information that will allow them to refine BMPs with respect to variable particulate concentration throughout a sequence of storm events. Because the LISST is able to analyze particles in stormwater on a continuous basis, changes in particle size distribution throughout a storm event can be better characterized using this device, rather than relying on traditional grab samples, which capture only snapshots of conditions with several minutes or hours between samples.

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