COLLECTING A BETTER WATER-QUALITY SAMPLE: REDUCING VERTICAL STRATIFICATION BIAS IN OPEN AND CLOSED CHANNELS

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Abstract

Collection of water-quality samples that accurately characterize average particle concentrations and distributions in channels can be complicated by large sources of variability. The U.S. Geological Survey (USGS) developed a fully automated Depth-Integrated Sample Arm (DISA) as a way to reduce bias and improve accuracy in water-quality concentration data. The DISA was designed to integrate with existing autosampler configurations commonly used for the collection of water-quality samples in vertical profile thereby providing a better representation of average suspended sediment and sediment-associated pollutant concentrations and distributions than traditional fixed-point samplers. In controlled laboratory experiments, known concentrations of suspended sediment ranging from 596 to 1,189 mg/L were injected into a 3 foot diameter closed channel (circular pipe) with regulated flows ranging from 1.4 to 27.8 ft^3/s. Median suspended sediment concentrations in water-quality samples collected using the DISA were within 7 percent of the known, injected value compared to 96 percent for traditional fixed-point samplers. Field evaluation of this technology in open channel fluvial systems showed median differences between paired DISA and fixed-point samples to be within 3 percent. The range of particle size measured in the open channel was generally that of clay and silt. Differences between the concentration and distribution measured between the two sampler configurations could potentially be much larger in open channels that transport larger particles, such as sand.

INTRODUCTION

Collection of representative water-quality samples in fluvial systems can be complicated by large sources of variability, both temporal and spatial. For example, Horowitz (1995) found both horizontal and vertical concentrations of suspended sediment in a stream or river tend to increase with increasing distance from stream banks and depth. These increases were associated with greater concentrations of sand-size particles. This is especially notable with very fine to coarse sand-sized particles, in that suspended concentrations may be considerably higher within 3 feet of the channel bed (Guy, 1970). The stratification of solids in a flowing water column may result in biased concentration data collected from open channels.

Watershed managers depend on assessment and monitoring of water quality and flow data to help target pollutant reductions, identify the most important sources of pollutants, and evaluate the benefits of select stormwater management practices. One of the most common uses of water-quality data is to calibrate and verify urban pollutant models. Sediment concentrations and particle size distributions are especially important to assure the models provide useful results because studies have shown concentrations of urban pollutants generally increase with decreasing particle size, yet the majority of mass lies in coarse particles (Evans et al., 1999; Sansalone and Buchberger, 1997; Characklis and Wiesner, 1997; Waschbusch et al., 1999; Li et al., 2005). Once tested, models can be one of the only cost effective approaches to developing watershed plans in urban areas when confronted with the high cost of monitoring all potential sources of runoff and the stormwater management practices used to treat it. For example, the Wisconsin Department

of Natural Resources (WDNR) has promulgated a series of stormwater performance standards that will require qualifying cities to reduce the annual total suspended solids (TSS) load in urban runoff by 20 percent (Wisconsin Administrative Code NR 151, 2002). Models are used by both the WDNR and permitted entities to help determine if the goal is achieved. Another example is the development of total maximum daily loads (TMDL) for impaired waters under section 303(d) of the Clean Water Act (U.S Environmental Protection Agency, 2011). Urban areas around the country are subject to development of TMDLs that require the calculation of the maximum amount of a pollutant a waterbody can receive. Without accurate flow and pollutant concentration data to calibrate and verify models used to determine TMDLs, they could generate erroneous results that could significantly reduce the effectiveness of watershed planning. Millions of dollars are spent annually by environmental managers, engineering consultants, and others to mitigate, control, and prevent sediment and sediment-associated pollution in our nation's waterways. Accurate concentration data are vital to their decision-making process.

To help reduce uncertainty, the use of surrogate technology has been explored as a means to estimate time-varying sediment concentration (Wood and Teasdale, 2013). While this approach has been successful, it is generally focused on sediment and does not address the wide range of pollutants commonly imposed on the regulated community. To obtain reliable and representative data, Bent and others (2000) suggest the automatic sampler intake should be placed near the point at which the concentration approximates the mean sediment concentration for the channel cross-section over a full range of flows. This concept for intake placement has great merit, but the mean cross-section concentration is constantly changing as flow conditions vary (Edwards and Glysson, 1999). It is unlikely that specific guidelines for locating a sample intake for flow conditions at one water level would produce the same intake location relative to the flow conditions at a different water level. To resolve this, the USGS recommends use of equal-width-increment (EWI) samples to develop a cross-sectional coefficient to be applied to fixed-point sample concentrations (Edwards and Glysson, 1999). However, collecting depth- and width-integrated samples over a range of conditions may not be possible for a number of reasons, such as brief duration of runoff, limited access, hazardous conditions, and rapidly varying flows, especially in urban streams (Harmel et al., 2010). These techniques are also impractical for most closed systems used to convey urban stormwater. Furthermore, traditional fixed-point samplers can artificially bias sediment concentration in a water sample, especially in flashy or ephemeral streams where the zone between bed and suspended load may vary depending on water depth. Ideally, the location of the sample intake should be adjusted to reflect changing water depths.

To address this concern, the USGS – Wisconsin Water Science Center has developed a fully automated Depth-Integrated Sample Arm (DISA). The DISA was designed to integrate with existing autosampler configurations for collection of water-quality samples in vertical profile thereby providing a better representation of average sediment and sediment-associated pollutant concentrations and distributions than traditional fixed intake samplers.

The primary objective of this study was to determine whether the DISA can collect water-quality samples from both open and closed channels over varying hydraulic conditions that are more representative of the average conditions in a water column, in terms of suspended-sediment concentration (SSC) and particle size distribution (PSD), than a traditional fixed-point sampler.

METHODS

The general field of application of the DISA was originally developed in 2008 for closed conduits used to convey stormwater runoff in urban environments, such as storm sewers. As such, its design was optimized for collection of a water sample in vertical profile from the center of a circular pipe or culvert. Operation of the DISA made use of a linear actuator with position sensing capabilities to drive a rotary sample arm assembly attached to the ceiling of a closed conduit. The actuator was controlled via datalogger to move forward or retract to one or more desired positions in the water column. Once in

position, the DISA intake remained in place until the autosampler completed its normal purge/withdraw cycle. A detailed description of the device can be found in Selbig and Bannerman (2011).

Evaluation of the DISA in a closed conduit was done in 2011 at Colorado State University's hydraulics laboratory (figure 1). The DISA was programmed to collect water-quality samples at four points spaced vertically from a flowing water column of known discharge. For example, if the depth of water to be sampled was 1 foot, the DISA was programmed to take the first sub-sample at 0 percent depth (bottom of pipe), 25 percent depth (0.25 foot above the pipe floor), 50 percent depth (0.50 foot above the pipe floor), and 75 percent depth (0.75 foot above the pipe floor). Although the depth of water varied during laboratory tests, the percentages remained the same. A pre-mixed manufactured sand with particle diameters ranging from 53 to 425 μm was injected at calibrated rates to create known concentrations ranging from 596 to 1,189 mg/L. Calibrated flows rates ranged from 1.4 to 27.8 ft^3/s. Full details of the experimental design can be found in Selbig et al. (2012).

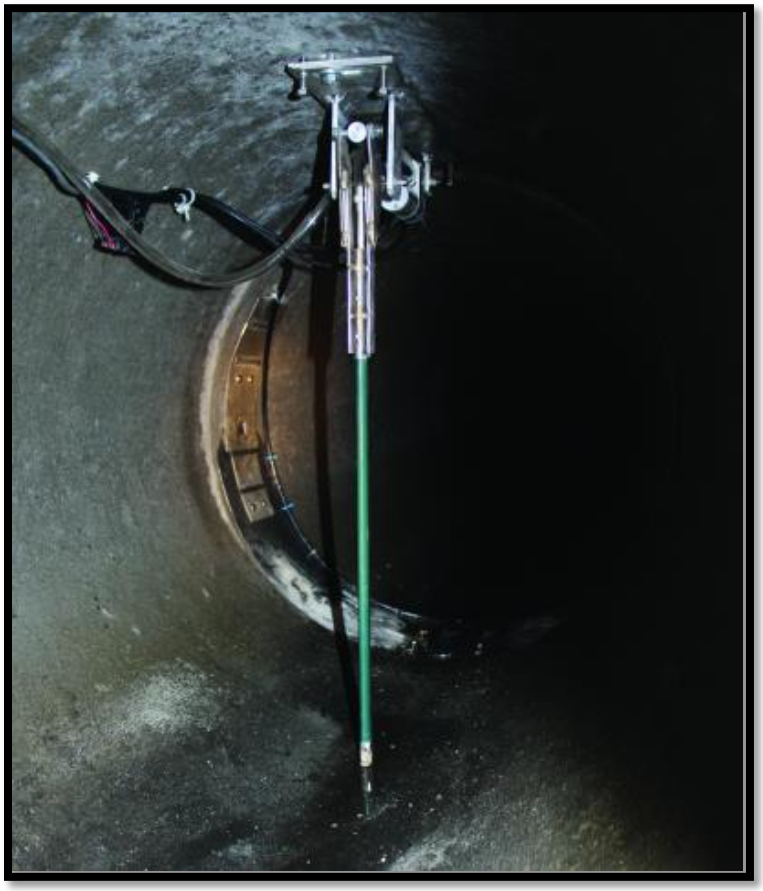

Figure 1 Image of the DISA in a closed conduit (storm sewer) with the sample arm extended in the vertical position. When at rest, the arm lies in the horizontal position near the pipe ceiling with the end of the intake pointing in the direction of flow. The sample arm (identified as green in this photo) can be sized to fit various conduit diameters. Photo by USGS.

In 2013, the DISA was modified and updated for use in open channels. Instead of being mounted to the ceiling of a closed conduit, the updated DISA is fully submersible and is anchored to the channel bed. The updated DISA includes a linear actuator with a variable rate of travel. In other words, when coupled with the static pumping rate of an autosampler, the DISA can move slower in shallow water and faster as the depth increases in order to keep the volume of water captured in each sample container consistent. Any

debris that may have accumulated on the sample arm assembly while acquiring a sample is cleared away by water discharging past as it retracts into the horizontal position

The first field-level evaluation of the DISA was done at Underwood Creek, an urban stream in Milwaukee, Wisconsin. The sampler was installed near the USGS streamgage on Underwood Creek in a section of restored channel that had its concrete lining removed in 2009. The channel was approximately 8 feet wide with a baseflow depth of approximately 2 feet and a streambed that consisted of sand, gravel and cobble. Inspection of the drainage basin revealed several large wet detention ponds intercepting stormwater runoff prior to drainage into the Underwood Creek. The DISA was attached to an aluminum frame that was anchored to the streambed using 0.75-inch steel rod. A fiberglass fairing was fabricated to shield the DISA from any debris as well as prevent the device from becoming buried in silt or organic detritus (figure 2). The sample intake was oriented in the downstream direction and was attached to an autosampler on the bank (figure 2). A second sample line was installed adjacent to the DISA similar to what would be used for a fixed-point intake associated with an autosampler (Edwards and Glysson,1999). The intake of the second sampler was located at a fixed depth of approximately 0.7 foot above the streambed. Each sampler was programmed to take a 1 liter sample for every 0.3 foot increase and 0.5 foot decrease in water level on the rise and recession limb of the hydrograph, respectively. Upon completion of each sub-sample, the DISA would return to a horizontal position near the streambed which cleared away any accumulated debris. Comparison of SSC and PSD were made between samples collected by the DISA and the fixed-point sampler. Additionally, EWI samples were periodically taken coincident with the DISA and fixed-point samples to represent a discharge-weighted concentration of the channel cross section. The coincident sampling was done in July and August, 2013 that included 3 stormwater runoff events where flows ranged from 7 to 817 ft^3/s

Figure 2 Image of the DISA in an open channel setting. The body is anchored to the streambed with the sample arm oriented in the downstream direction. Photo by USGS.

RESULTS AND DISCUSSION

Closed Conduits

In the 2011 laboratory experiments for closed conduits, the DISA was shown to improve the accuracy of sediment concentration and distribution by reducing stratification bias inherent in stormwater runoff in urban storm sewers. The results described herein are a digest of a paper previously published in the *Journal of Environmental Monitoring* and have been adapted from Selbig et al. (2012) with permission from The Royal Society of Chemistry.

For each trial flow rate, all four sub-samples collected by the DISA were combined to represent a single, average SSC. The resulting concentration was then compared to the injected concentration for assessment of sampling accuracy. A similar comparison was made for the fixed-point sampler. Although both samplers tend to overestimate SSCs in the water, the DISA had better agreement with injected concentration. Mean and median SSCs measured by the DISA came within 13 and 7 percent of the injected value, respectively, compared to 166 and 96 percent for the fixed-point sampler (table 1). An analysis of paired samples using the Wilcoxon signed-rank test confirmed that fixed-point concentrations were statistically greater than the DISA concentrations at the 5 percent significance level. The summary statistics detailed in table 1 suggest that as more of the water column is captured in a sample, a more accurate representation of the actual concentration will result. Increasing the number of collection points spaced vertically through the water column can also reduce variability through better averaging of the dynamic exchange of solids between stratified zones. The DISA demonstrates reduced variability as indicated by a lower coefficient of variation in table 1.

Table 1 Summary statistics of the percent of actual SSCs measured from the DISA (7 samples with sub-samples at 0, 25, 50, and 75 percent of water depth) and fixed-point (10 samples) samplers. A value of 100 represents perfect equality. A value greater than 100 indicates overestimation. Adapted from Selbig et al. (2012) with permission from The Royal Society of Chemistry.

Statistic	**FIXED**	**DISA**
Minimum	37	92
Maximum	795	135
Median	196	107
Mean	266	113
Standard Deviation	238	15
Coefficient of Variation	0.9	0.1

Slight changes in the distribution of particles in a sample could result in modest changes in the overall SSC of a sample. Larger particles would carry more mass resulting in a larger mass concentration. Therefore, larger sediment concentrations measured in the fixed-point samples are likely due to the over-sampling of coarse particles that tend to accumulate near the bottom of the water column. This solids stratification concept was illustrated in one laboratory test after comparing the average concentration, by particle size, between the DISA and fixed-point samplers to the actual, injected value (figure 3). Both DISA and fixed-point particle concentrations showed relatively close agreement to the actual value for particle diameters less than 106 μm; however, differences become greater as particle diameters increase. In this particular laboratory test, the fixed-point sampler overestimated actual concentrations by 33

percent for particles less than 53 μm to 185 percent for particles between 212-300 μm (figure 3). The DISA was better able to represent the full range of particles, limiting the oversampling of particles between 212-300 μm to just 47 percent greater than the actual value (figure 3).

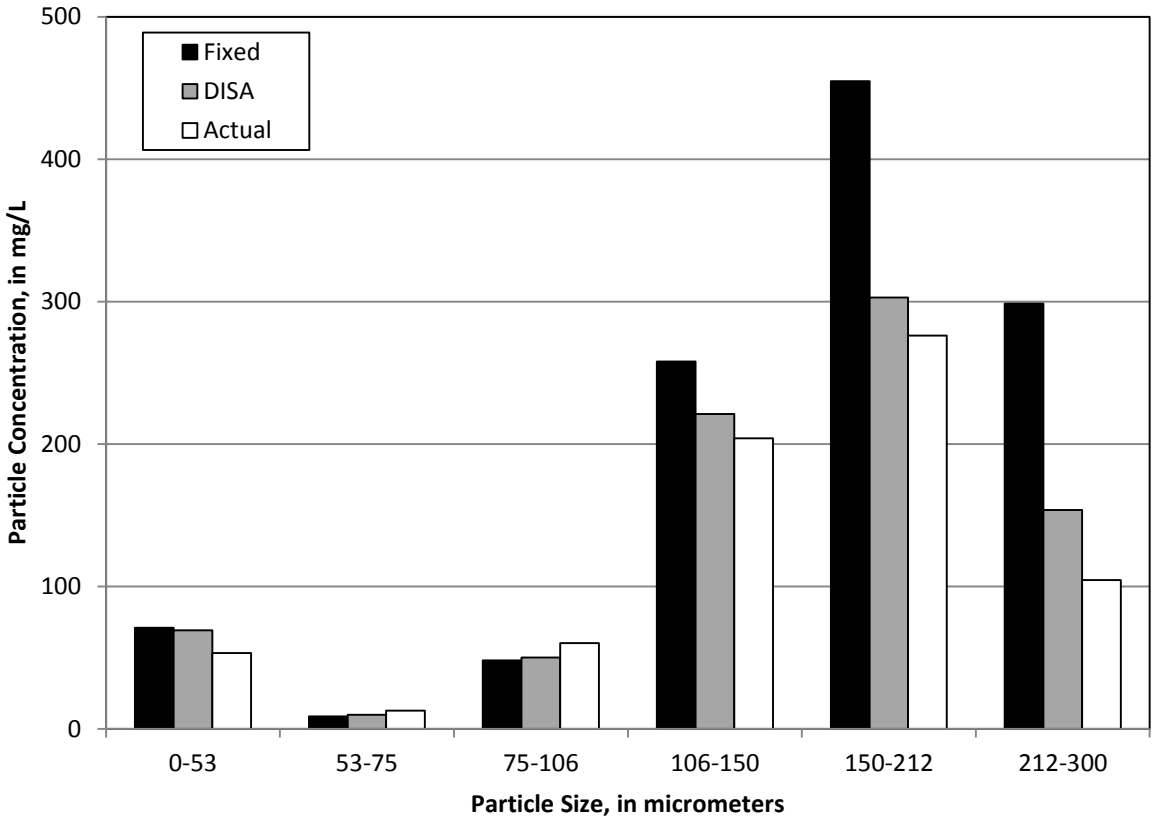

Figure 3 Comparison of the concentration of particles, by size, measured in the DISA and fixed-point samplers to the actual, injected concentration for one laboratory test in a closed conduit, 2011. Reproduced from Selbig et al. (2012) with permission from The Royal Society of Chemistry.

Open Channels

Based on the proven efficiency of the DISA in a closed conduit, it was assumed that when installed in the open channel of Underwood Creek, the DISA would yield a SSC and PSD more representative of the average condition than a fixed-point sampler. Overall, there was close agreement in SSCs between the DISA and fixed-point sampler over a range of flow conditions (figure 4). Examination of SSCs in both DISA and fixed-point datasets revealed a highly skewed distribution. Therefore, the median is a more appropriate representation of the population center than the mean (Ott and Longnecker, 2001). The median difference in SSC between paired samples was 3 percent greater in the DISA than the fixed-point sampler. While this difference is small it is statistically significant. Hypothesis testing by use of the Wilcoxon signed-rank test (Helsel and Hirsch, 1992) showed the DISA to be statistically greater than the fixed-point ($p > 0.05$). This is likely the result of only a few samples where differences in SSC between the two sample collection methods were large.

Of the 32 samples collected, only 6 showed any significant departure from a line of equality. These 6 samples (identified as red in figure 4) were all collected during the same July 21, 2013 storm event near

the peak of the hydrograph. Of the two EWI samples collected during this event, SSCs in the corresponding DISA samples were 79 and 95 percent larger and the fixed-point 43 and 57 percent lower (figure 5). It is unclear why both samplers differed from the concurrent EWI samples or why SSCs in the DISA sampler were much larger than those in the fixed-point while the vast majority of other samples collected during this and other events show close agreement. One explanation could be the proximity of the DISA intake to the channel bed. Since the DISA begins its sample collection approximately 2 inches above the streambed, sediment transporting as bedload could have been collected by the DISA and thus elevate resulting SSCs, especially for this particular event. This zone of sediment transport would have been precluded from both the EWI (minimum of 4 inches above the bed when using a DH-81) and fixed-point samplers (set at 8 inches above the bed). However, if the DISA were, in fact, sampling a portion of bedload, the majority of resulting SSCs should have been larger than those in corresponding fixed-point samples for all sampled events. Another explanation may be a large amount of organic debris found entangled around the fixed-point sampler during the July 21 event (figure 6). This may have resulted in lower SSCs by preventing exposure to the full range of suspended particles in the water column. The DISA, by design, is self-cleaning and therefore did not experience a similar problem. In either case, a simple adjustment to the DISA can prevent future sampling of bedload whereas preventing debris from accumulating on a fixed-point sampler is more challenging. The majority of data (with exception of the 6 samples from the July 21 event) suggest concentrations of sediment in both the DISA and fixed-point samplers were similar in an open channel setting, but generally greater than those measured by the EWI samples (figures 4 and 5).

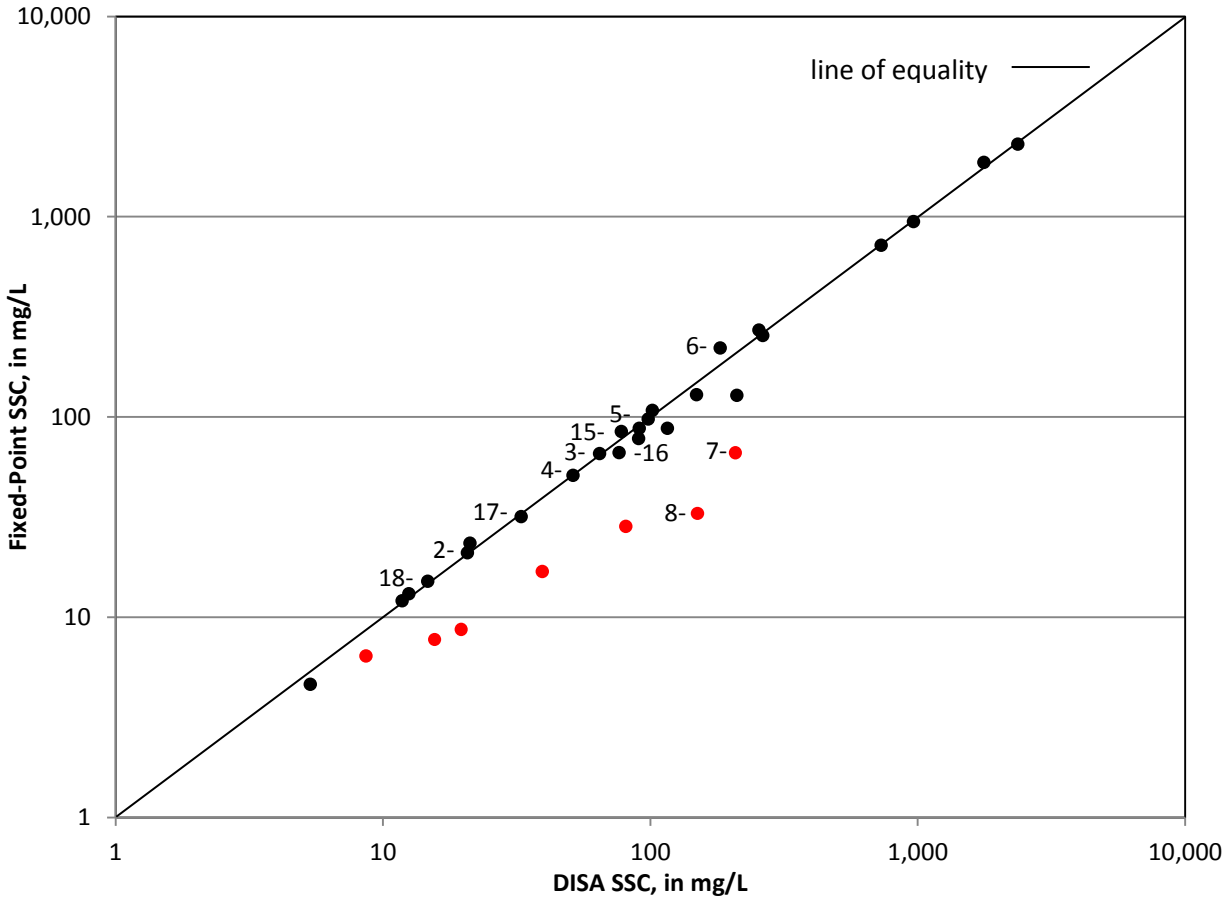

Figure 4 Concentration of suspended sediment in paired samples using the DISA and fixed-point collection methods. Red dots represent samples with the greatest departure from the line of equality, all of

which were collected during a single storm event. Labels refer to the corresponding EWI sample number detailed in figure 5.

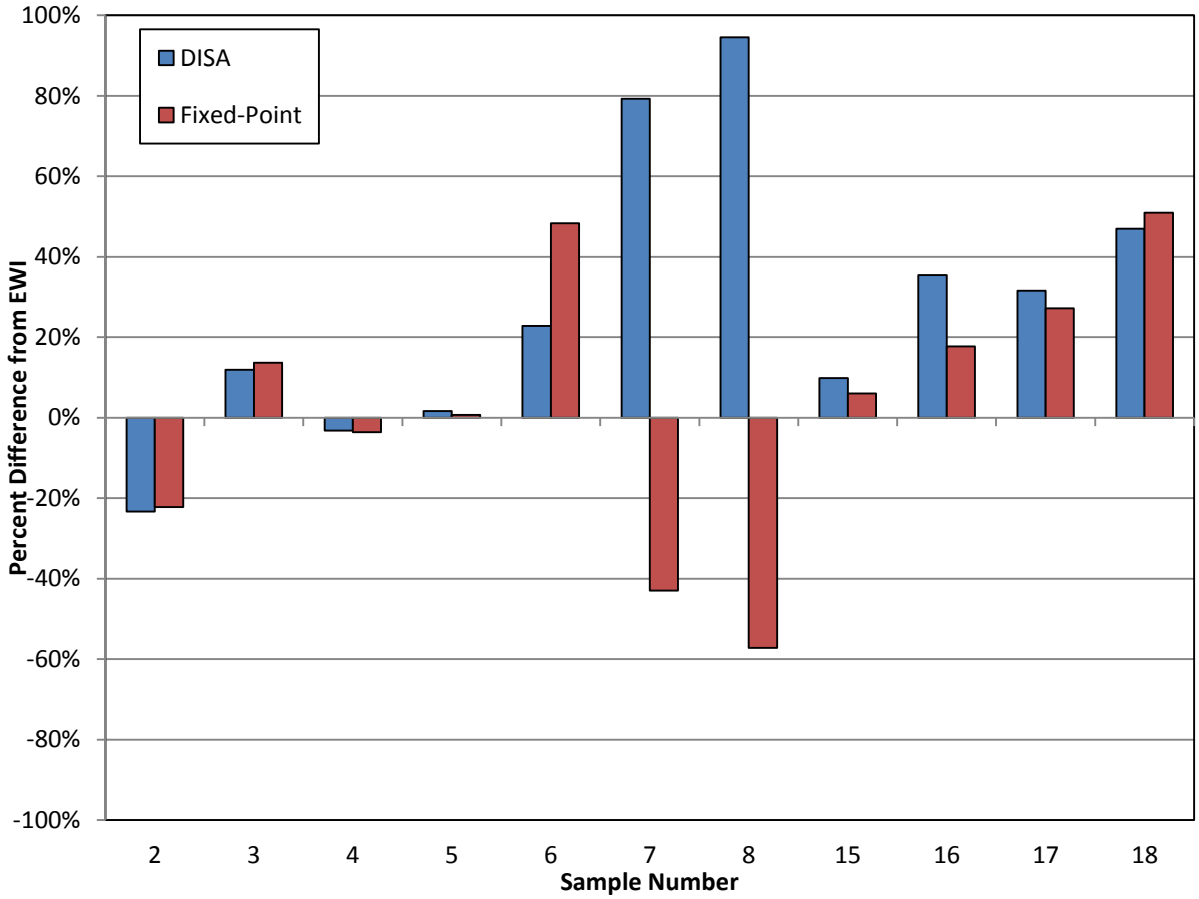

Figure 5 Percent difference in suspended sediment concentration measured in the DISA and fixed-point samplers to those measured in the EWI sampler.

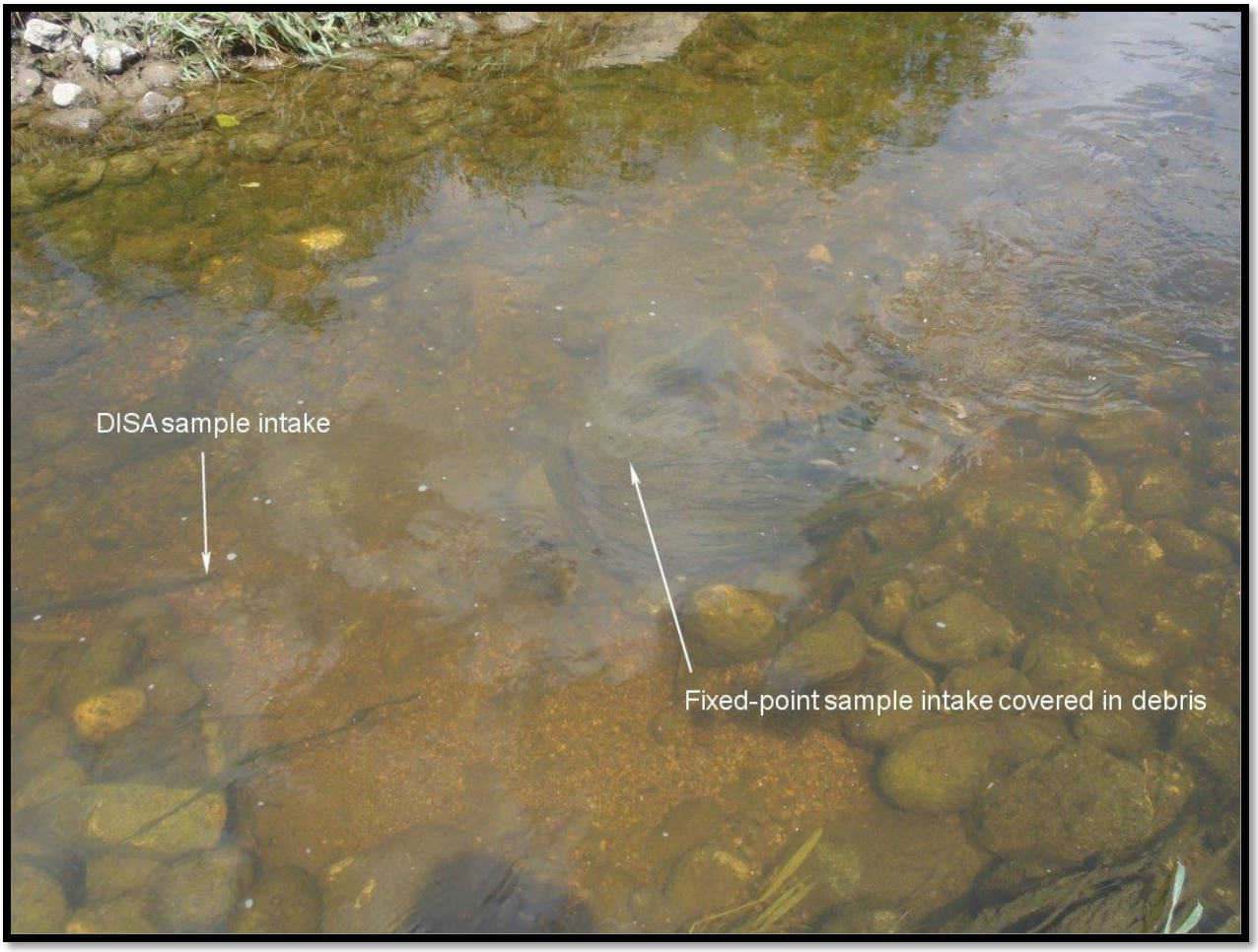

Figure 6 A large amount of organic debris covering the fixed-point sampler may have caused resulting SSCs to be much lower than corresponding DISA samples. Photo by USGS.

The DISA is designed to collect a vertical composite of the entire water column, rather than a single, fixed point thereby reducing any stratification bias caused by the presence of sand (>63 µm). A larger fraction of sand moving through a water column would likely increase heterogeneity which could increase the variability of resulting concentration data dependent on where a sample was acquired. If the water column were well mixed, differences between the DISA and fixed-point sampler would be minimal, as was the case in this study. Inspection of the PSD in DISA, fixed-point, and EWI samples showed median particle diameters (d_{50}) to be primarily that of clay and silt (<63 µm) (figure 7). Smaller particles are more easily mixed throughout the water column rendering placement of the sampler intake of less importance. Figure 7 also illustrates a general departure from equality between the d_{50} measured by the fixed-point and DISA samplers. Both sampler types show similar median particle diameters up to approximately 40µm at which point the d_{50} in the fixed-point and EWI samplers tend to remain the same while the DISA continues to increase. It is unclear whether this pattern would continue with increasing particle diameters. Additional testing in a controlled laboratory setting would help test the DISA's ability to accurately sample a wide range of particle concentrations and distributions.

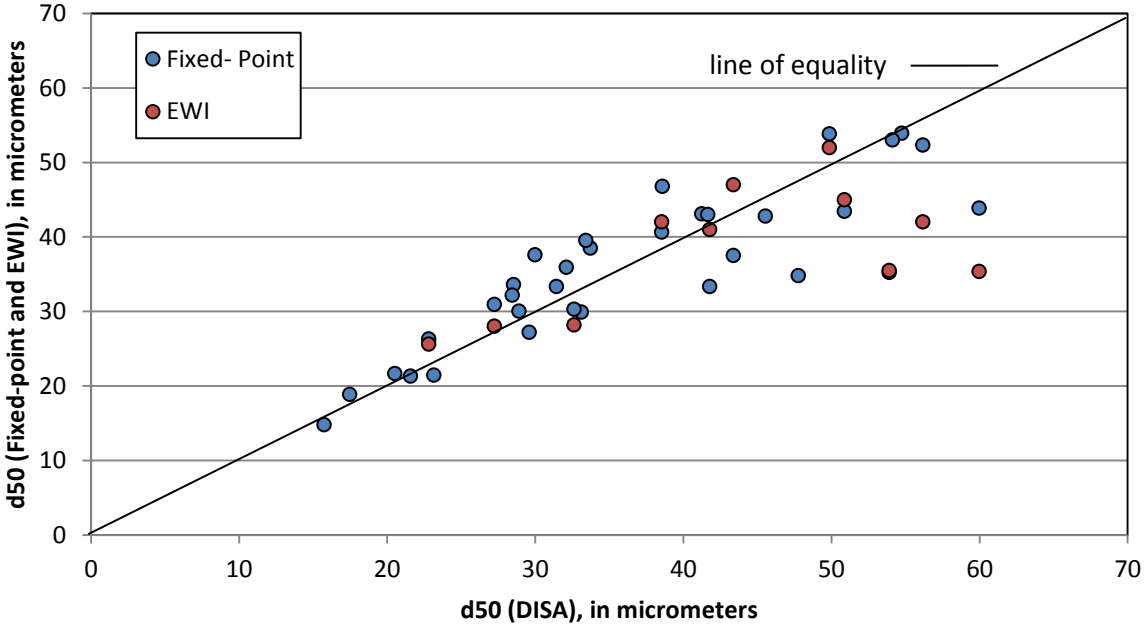

Figure 7 Median particle diameters in paired samples collected by the DISA, fixed-point and EWI samplers.

CONCLUSION

Stratification of particles in a flowing water column can be a source of bias and variability in sediment concentrations and distributions. In closed conduits, such as storm sewers, use of the DISA has shown that integrating samples from the entire water column, rather than from a single, fixed point, can result in a more accurate representation of sediment concentration and distribution, especially as the stratification of solids becomes more apparent with an increased presence of sand. When tested in an open channel, the DISA showed no marked improvement to the accuracy of sediment concentration or distribution compared to fixed-point and EWI sample collection methods. The small amount of sand measured in the water column at the open channel field site rendered placement of the sample intake of less importance. Differences between the median particle size and SSCs measured between the two sampler configurations could potentially be much greater in a fluvial setting with coarser sediment transport. An assessment of channel characteristics prior to sample collection can help determine if water-quality concentration data could benefit from the DISA sample collection method.

The DISA can improve water-quality datasets by reducing bias and variability in concentration and distribution of solids caused by stratification. In turn, environmental managers have greater confidence as they develop plans and policies to improve the quality of our Nation's waters.

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