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Improved Automatic Sampling for Suspended Solids

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Research Project
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16. Abstract (Limit: 250 words)

Portable automatic field samplers have been found to overestimate concentrations of suspended sediment larger than 88 micrometers (coarse silts and sands) when sampling using existing methods. Samplers configured with intake manifolds were also found to substantially oversample coarse silts and sands.

This research improves the performance of automatic water samplers for sampling coarse silts and sands. A sampling intake was developed that extracts samples from multiple locations in the cross-section. The new sampling intake increases the range of sediment size where sampling accuracy is within +/- 10% to sand particles less than an equivalent diameter of 250 micrometers. The sampling intake also performs with a predicted bias at larger sediment sizes. The new intake thus demonstrates improved sampling accuracy and precision.

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Final Report

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Executive Summary

Impairment due to suspended solids pollution is a common water quality management issue. It is most common for a water body to be primarily or secondarily impaired due to suspended solids pollution (MPCA, 2008). In addition, suspended solids are associated with additional pollutants including heavy metals, phosphorus, polycyclic aromatic hydrocarbons (PAHs), and pathogenic bacteria. Thus, removing suspended solids is one of the primary water quality improvement objectives of stormwater treatment.

Monitoring is one means of obtaining suspended solids concentration and particle data. Automated sampling has evolved to be the preferred method of stormwater runoff monitoring efforts due to several factors. Chief among these is the ability of automated equipment to operate in standby mode and to be ready to sample after a storm event occurs. Automated equipment is also capable of collecting multiple flow-paced or time-weighted samples during a single storm event. This is especially important given the large variation in pollutant concentrations that have been found within single storm events (Li et al., 2005). It is now standard practice to sample at intervals along the hydrograph, with the sampling intervals determined either by elapsed time or cumulative flow volume.

Transport of stormwater particles is principally dependent on the size and density of the particles and the velocity (as it relates to turbulence) of the flow in which they are carried (Bent et al. 2001). Particles such as coarse silts and sands in excess of 62 μm have been found to comprise a significant portion of total solids in stormwater runoff, both in terms of mass and surface area (Lin et al., 2009). Due to their sheer prevalence in urban environments, these particles are significant contributors to total pollutant loads.

Portable automatic field samplers are thus common tools for monitoring watersheds – both for establishing baseline conditions and assessing the performance of management practices. Automatic samplers have been used frequently in studies to characterize stormwater particles, as well as for evaluating the performance of stormwater treatment practices. However, portable automatic field samplers have been found to overestimate concentrations of coarse silts and sands contained in suspended sediment.

The goal of this research is to improve the performance of automatic water samplers for sampling coarse silts and sands (e.g. 62 μm to 350 μm). For this purpose, a sampling intake was developed to extract samples from multiple locations in the cross-section. The new sampling intake substantially increases the range of sediment size where sampling accuracy is within +/- 10% but performs with a substantial remaining bias for larger sediment sizes. The bias, however, seems to be consistent such that the true distribution up to 0.35 mm can be developed when the proper transformation is performed. The new intake thus demonstrates improved sampling accuracy and precision.

Chapter 1. Introduction

Impairment due to suspended solids pollution is a common water quality management issue. It is most common for a water body to be primarily or secondarily impaired due to suspended solids pollution (MPCA, 2008). In addition, suspended solids are associated with additional pollutants including heavy metals, phosphorus, polycyclic aromatic hydrocarbons (PAHs), and pathogenic bacteria. Thus, removing suspended solids is one of the primary water quality improvement objectives of stormwater treatment.

Key to pollution prevention efforts in urban areas are the installation and maintenance of stormwater best management practices (BMPs). Improving the design of stormwater BMPs requires more accurate information about stormwater particles. For stormwater BMPs which treat particles through settling, the particle settling velocity distribution is important and particle size is the primary variable to determine settling velocity. For stormwater BMPs which remove particles via filtration/infiltration, knowledge of particle size and composition is also important. As always, better knowledge of what is coming down the pipe enables a better distribution of resources to meet water quality goals.

Monitoring is one means of obtaining suspended solids concentration and particle data. Automated sampling has evolved to be the preferred method of stormwater runoff monitoring efforts due to several factors. Chief among these is the ability of automated equipment to operate in standby mode and to be ready to collect samples when a storm event occurs. Automated equipment is also capable of collecting multiple samples during a single storm event. This is especially important given the large variation in pollutant concentrations that have been found within single storm events (Li et al., 2005). It is now standard practice to sample at intervals along the hydrograph, with the sampling intervals determined either by elapsed time or cumulative flow volume.

Portable automatic field samplers are thus common tools for monitoring watersheds – both for establishing baseline conditions and assessing the performance of management practices. Automatic samplers have been used frequently in studies to characterize stormwater particles, as well as for evaluating the performance of stormwater BMPs.

Transport of stormwater particles is principally dependent on the size and density of the particles and the velocity (as it relates to turbulence) of the flow in which they are carried (Bent et al. 2001). The varied slopes and conduit sizes of a typical storm sewer system create changing transport conditions from source to sink. Dynamic rates of runoff from tributary catchments induce changing flow rates and velocities within the system. At any given time, particles of a particular size and density may be transported as bed load in one location in the sewer system, as suspended particles in another location, and may be aggrading as a sediment deposit in a third location. Sediment transport in storm sewer systems is not the primary focus of this research, rather the methods necessary to accurately sample suspended sediment in urban stormwater. Accurate sampling of suspended sediment is considered here as a key component in measuring pollutant loading.

Research analyzing the size and density of stormwater particles has been performed in many regions of the world. A commonly used, assumed distribution is the settling velocity distribution measured during the Nationwide Urban Runoff Program (NURP). The NURP settling velocity distribution was developed using settling velocity measurements from 46 different samples from 13 unique sites (Driscoll 1986). Some guidelines recommend practitioners use the NURP distribution, and the NURP distribution is also used as the default distribution in modeling software such as the P8 Urban Catchment Model. The most intensive studies have involved the collection and subsequent analysis of all stormwater runoff from small catchments (Kim and Sansalone, 2008; Fowler et al., 2009). These studies have demonstrated the particles characterized in the NURP distribution may be finer than the particle size distributions found in many transportation-heavy urban watersheds, especially in the higher-intensity design storms.. Variation between and within studies has been found and attributed to soil type, land use, topography, rainfall intensity, and proximity to prior rainfall , or pollutant build-up time (Goonetilleke et al. 2005, Egodawatta et al. 2007). Figure 1 shows the variation in particle size distribution for both the NURP distribution and other PSDs found in more recent runoff studies of highway runoff.

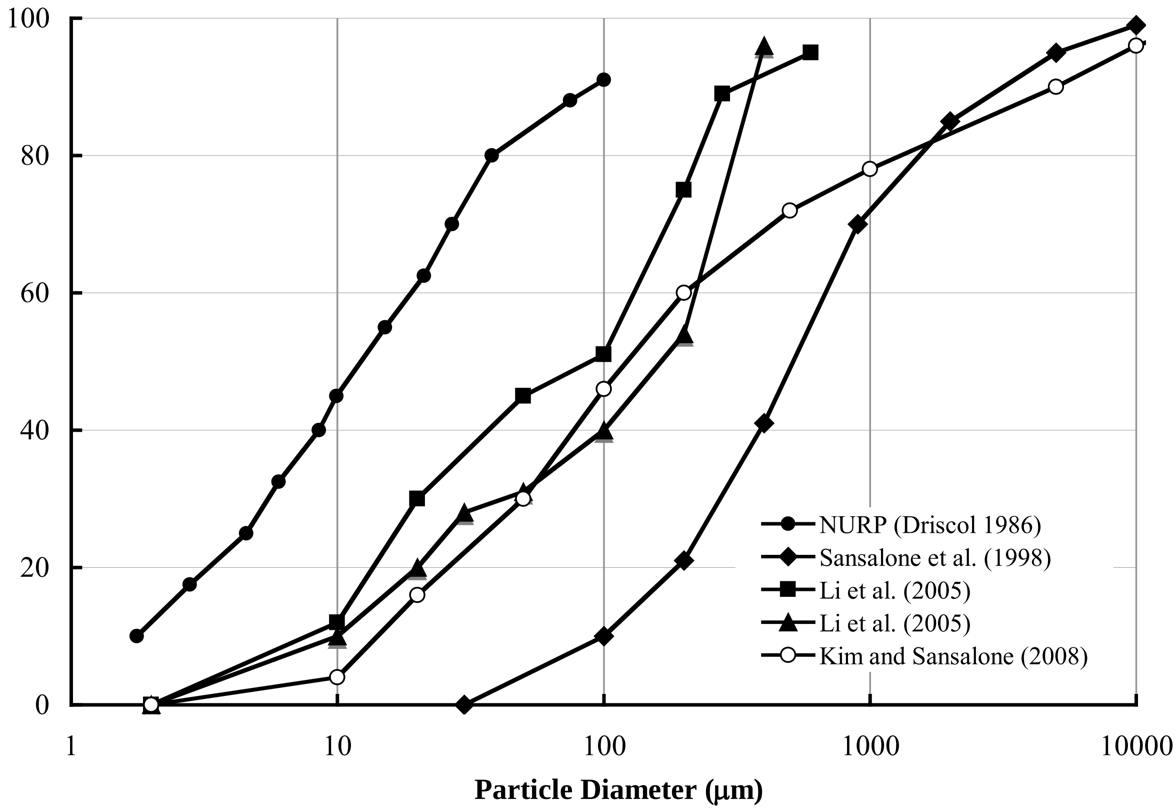

Figure 1. Comparison of cumulative size distributions (percent by mass greater than) for the NURP studies and receipt highway runoff studies. The NURP distribution was determined by conversion of measured settling velocity distribution to particle size assuming silica particles.

While coarse silts and sands in excess of 62 µm comprise less than 20 percent of the NURP distribution after an assumed conversion of the NURP settling velocity to silica particles, they comprise a majority of the more recent distributions of highway runoff.. Due to their sheer prevalence in urban environments, these particles are significant contributors to total pollutant loads.

Chapter 2. Suspended Particle Sampling Techniques

Many methods which have been developed for quantifying suspended particles are the result of a focus on particles in streams and rivers. Adapting these technologies to urban stormwater applications presents unique challenges. Shorter hydrograph durations (i.e. increased flashiness) are one characteristic of urbanized watersheds. A short hydrograph duration means that any sampling methods requiring personnel to be present on site must have a high degree of timeliness (and luck) to collect samples. Urban watersheds often consist primarily of closed conduits, which make manual sampling during a storm event difficult and potentially dangerous. For these reasons, automated sampling methods have become the preferred method of sampling in urban watersheds. Automated samplers can be placed in storm sewer conduits during dry periods via manholes or outfalls. Associated level and velocity sensors communicate flow conditions to the sampler. This allows the collection of samples based on time or volume intervals. Samples may be deposited into one collection container to form a composite sample or divided among multiple containers for more detailed analysis of the relationship between the collected matter and the storm hydrograph.

Isokinetic sampling, for example using a USGS-type point-integrating or depth-integrating sampler, involves the movement of a sample collector within the stream flow. The term isokinetic refers to the goal of drawing water into the sampler at the same velocity as the surrounding flow, thereby minimizing the disruption to flow lines at the point of sampling. Sampling at a higher or lower velocity than the surrounding stream flow leads to the under- or over-sampling of larger particles, respectively. By definition, isokinetic samplers employ an intake with an opening that faces upstream.

Isokinetic sampling is, for the most part, accomplished via human control from a boom on a boat or a bridge, and is designed to improve point measurements of suspended solids concentration. While this technique can be adapted to use automated and mechanized controls for use in a closed conduit storm sewer, it would be cumbersome. . The mechanical complexity of such a device is a further drawback. Isokinetic sampling is designed to improve point measurements of suspended solids from within 20% to within 5% of the real value. This research is designed to improve the cross-sectional mean suspended solids concentration sampled by an automatic sampler to within 20% over a range of particle sizes. Isokinetic sampling is a refinement that is not appropriate for this research.

Nor are point- and depth-integrating samplers perfectly accurate when it comes to the collection of suspended solids. Research into the performance of depth-integrating samplers relative to point-integrating samplers (where vertical profiles of velocity and sediment concentration are sampled and integrated) performed by Hicks and Duncan (1997) found that performance improves as the ratio of shear velocity to particle fall velocity (u_* / v_s) increases, where u_* = sqrt (τ_w/ρ), τ_w = wall shear stress and ρ = density of the water. This ratio can be termed the 'suspension ratio,' where $u*$ represents turbulence in the flow. Expressed in lay terms, for a given particle settling velocity, this ratio increases as the flow becomes more 'energetic'. Hicks and Duncan found disagreement as large as ±70% between depth- and point-integrating samplers for suspension ratios less than 4, with disagreement decreasing exponentially as the suspension ratio increased (e.g. greater mixing and suspension conditions). For suspension ratios greater than 30, errors were around ±5%.

Tube sampling, the focus of this paper, also has numerous drawbacks, but has an important advantage in its suitability for use with pump and container systems – the backbone of current automatic sampling technology. Such systems have been in use for some time and are well-suited to the needs of stormwater applications – especially urban stormwater. Research has found that the best intake orientation for tube sampling is an opening that faces downstream (Winterstein and Stefan, 1986). A downstream orientation also reduces the likelihood the tube openings will be become clogged with debris.

Previous research has sought to improve conventional tube sampling. A pivoting depth proportional sampling device conceived by Eads and Thomas (1983) is shown in Figure 2. The device pivots from the stream bed, with the opposite end kept at the surface by a float. The intention of this design is to keep the automatic sampler intake at a constant fraction of the depth.

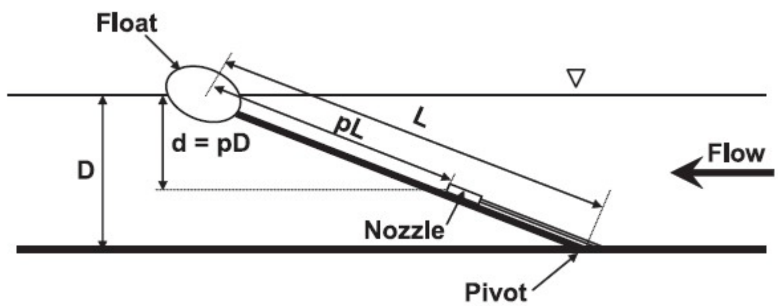

Figure 2. Eads and Thomas (1983) depth proportional intake device. Image reproduced from Lecce (2009).

Other intake devices for use with automatic samplers have also been developed to sample at a point proportional to the total depth. Lecce (2009) developed a self-adjusting intake for use behind bridge abutments and other in-stream obstructions as shown in Figure 3. The intake is extended downstream by a horizontal boom in order to sample outside of the separation zone (the eddies) present downstream of such structures.

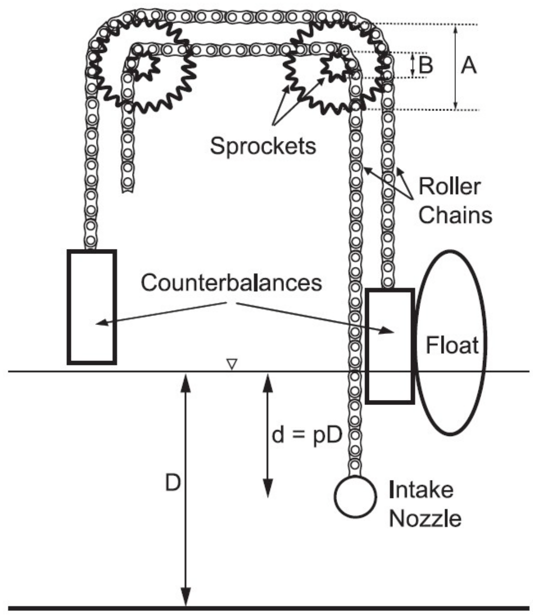

Figure 3. Depth proportional intake device (Lecce 2009).

Unlike point or depth integrating samplers, these sampling devices still do not sample from more than one point in the water column at a given point in time. Implicit in the selection of a sampling depth is the assumption that the concentration of particles at the selected depth will be representative of the mean particle concentration. This assumption becomes problematic when sampling particles with a wide range of settling velocities, especially as the particles of interest approach the settling velocities common among coarse silts and sands.

The analysis technique of Rouse (1937) can be used to develop a suspended sediment concentration relative to the cross-sectional mean concentration for fully-developed open channel flow based upon particle fall velocity, turbulence, and depth.

$$\frac{C}{\overline{C}} = h\frac{\left(h/y-1\right)^{\frac{v_s}{\kappa u_*}}}{\int_{y_0}^{h}\left(h/y-1\right)^{\frac{v_s}{\kappa u_*}}dy} \tag{1}$$

where C is suspended sediment concentration at depth y, measured from the bed, y_0 is a small distance above the channel bed, $\overline{C}$ is the cross-sectional mean suspended sediment concentration, v_s is settling velocity, u_* is channel shear velocity, h is channel depth and κ is von Karman's constant. Eq. (1) requires a numerical integration, with the result shown in Figure 4 for a water surface slope of 0.02 (a typical slope found in a storm sewer). Uniform flow in a wide open channel and particle density of sand is assumed.

Ratios of the predicted concentration over the mean concentration are plotted over the water columns for sediment sizes of silts (11 µm), coarse silts (50µm), fine sands (100 µm), sands (250 and 500 µm) and coarse sands (1,000 µm). Note that the ratio $C/C_{average}$ begins to depart markedly from unity for particles larger than 50 µm. Figure 4 indicates the challenge of accurately sampling coarse silts and sands in a flowing fluid, especially if one is limited to sampling from only one depth in the water column, because the sample is not representative of the cross-sectional mean concentration.

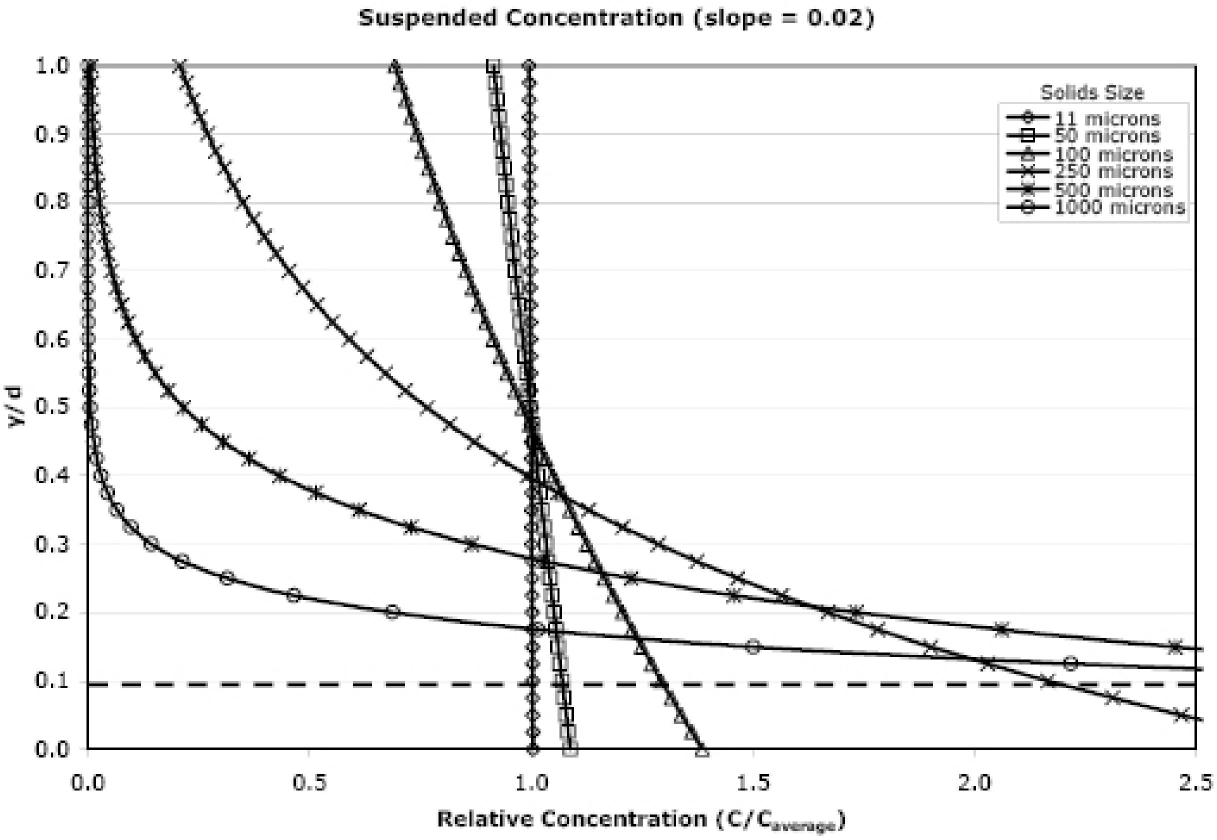

Figure 4. Suspended solids concentration in a given flow condition as function of depth (Rouse, 1937). Image reproduced from Gulliver et al. (2010).

An important distinction must also be made between suspended particle sampling technologies and suspended particle measurement technologies. Sampling technologies collect a physical water sample for analysis. Measurement technologies are used to quantify suspended particles on-site or from a collected sample.

Suspended solids measurement technologies include acoustic methods, laser diffraction, nuclear measurement, optical backscatter, optical transmission, spectral reflectance, vibrating tube analysis, impact measurement and video microscopy. These methods all have varied advantages and disadvantages when it comes to quantifying suspended particles, but – critically – all of these methods are measurement techniques and do not involve the actual collection of samples. While these methods may be useful for the analysis of collected samples, total accuracy is dependent upon the underlying sample collection methods. Due to the association of pollutants with particles in stormwater runoff, accurately quantifying these pollutants requires both the collection of the dissolved pollutant fraction, as well as the accurate collection of the suspended matter. Sampling technologies which collect both the dissolved and suspended fractions include manual (or grab) sampling, isokinetic sampling, and tube sampling for automatic samplers.

Chapter 3. Evaluating Current Automatic Sampling Methods

The performance of an automatic sampler was evaluated in a controlled laboratory environment to determine its sampling accuracy for inorganic particles ranging from silt, with a median particle diameter of 20 µm, to medium sand up to 355 µm (Gettel et al., 2009). A laboratory setup was constructed to replicate sampling conditions in a storm sewer conduit. Sediment was fed into a 45 cm (18 inch) diameter steel pipe at an upstream feed point. Samples were taken with an automatic sampler 10.6 m (35 ft) downstream of the feed point. Water surface slopes varied between 0.45 and 1.55%. Approximately 20 baseline samples were taken to establish background concentrations and samples were analyzed using the Suspended Sediment Concentration (SSC) method (Eaton et al., 1995).

Samples were taken with different sediment size ranges and with multiple sampling intake configurations. Intake configurations included a tube oriented parallel to the flow – facing upstream and facing downstream. A manufacturer-recommended sampling manifold – shown in Figure 5 and referred to by the manufacturer as a "strainer" – was also tested in configurations which included being fixed to the pipe, as well as being allowed to move freely within the flow.

Figure 5. Manufacturer-recommended sampling manifold, with a diameter of approximately 2.5 cm (1 in).

Typical results are shown in Figure 6 and Figure 7. The particle size range tested is shown the vertical axis and the sampled concentration as a percent of fed concentration is shown on the horizontal axis. Note the different horizontal axis scales between Figure 6 and Figure 7. Results obtained using the intake tube of the sampler indicate that although fine silts and clays (less than 44 µm) were sampled to within 127 percent of the fed concentration, coarse silts and sands were not sampled accurately. Coarse silts sampled at 153 percent of the fed concentration and some sands sampled in excess of 1500 percent of the fed concentration with the tube opening facing downstream (results for the tube opening facing upstream, not shown, were as high as 6500 percent of the fed concentration). When the intake manifold was used, all silts and clays were sampled within 127 percent of the fed concentration, but fine sands between 180 and 250 µm were sampled at 303 percent of the fed concentration.

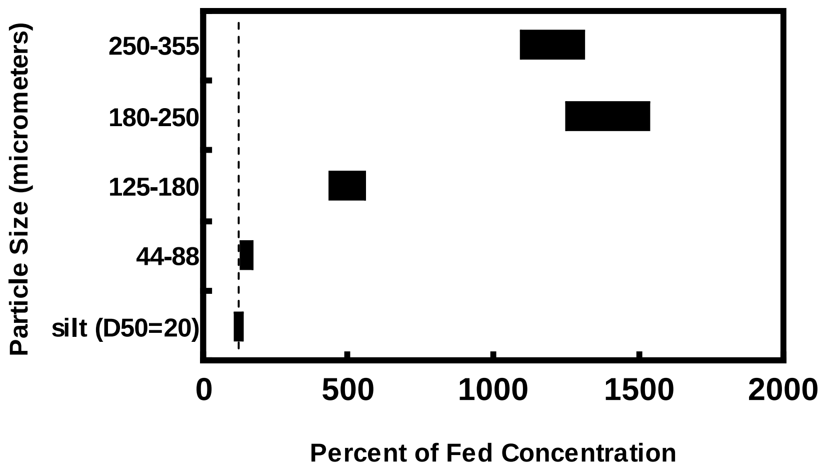

Figure 6. Percent of fed concentration versus particle size for sampling tube facing downstream, each bar represents 95% confidence interval of the mean percent of fed concentration.

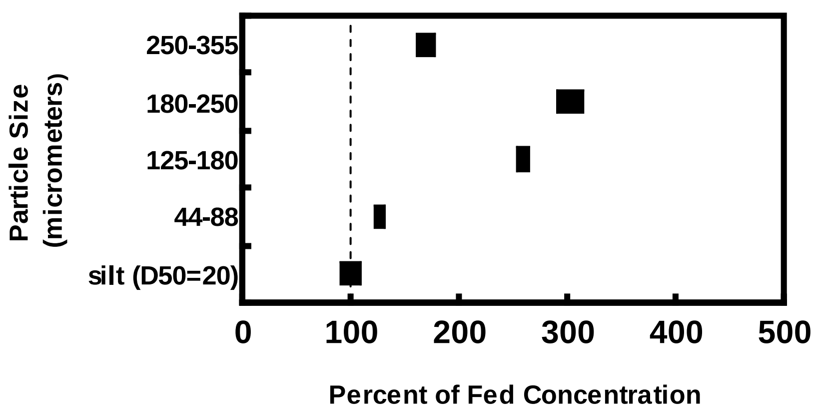

Figure 7. Percent of fed concentration versus particle size for sampling manifold in the fixed configuration, each bar represents a 95% confidence interval of the mean percent of fed concentration.

It was observed that current sampling technology substantially overestimates all suspended sediment sizes above silts with the sampling tube alone (Figure 6) and above coarse silt concentrations with a sampling manifold (Figure 7).

Chapter 4. Experimental Methods

The same experimental setup used to evaluate the accuracy of existing sampling methods was used to develop and evaluate improved sampling devices. The experimental test stand consisted of a 0.45 m (18 inch) diameter steel pipe with a total length of 12.2 m (40 ft). Access ports cut into the pipe near the upstream and downstream ends allowed access for sediment feeding and sampling. The distance between the access ports was approximately 11 m (35 ft). The upstream end of the pipe was attached to a headbox containing a baffle wall and a sharp-crested weir. Mississippi River water was pumped to the headbox. Two 18,100 kg (40,000 lb) weigh tanks downstream of the setup were used to determine the stage-flow relationship for the weir. Subsequent experimental runs then used the headbox stage to compute the flow rate. A schematic of the setup is shown in Figure 8. A more detailed schematic of the sediment feeding and sample collection setup is shown in Figure 9.

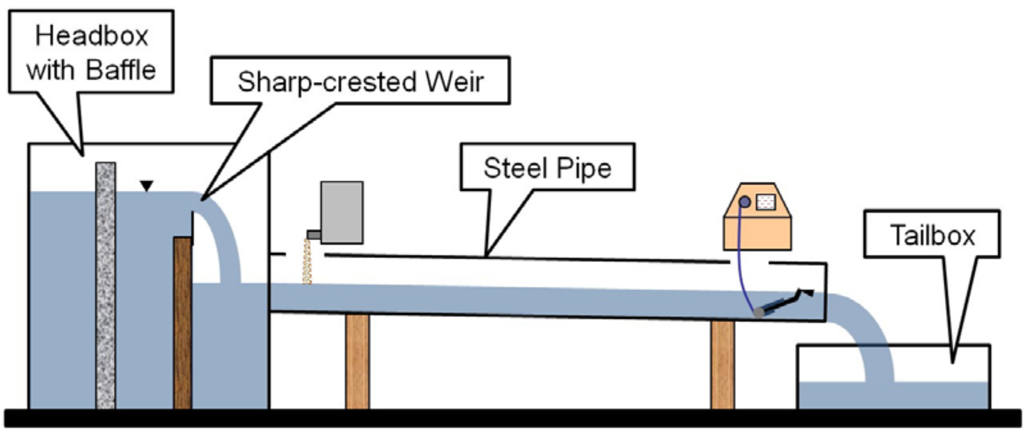

Figure 8. Experimental setup schematic.

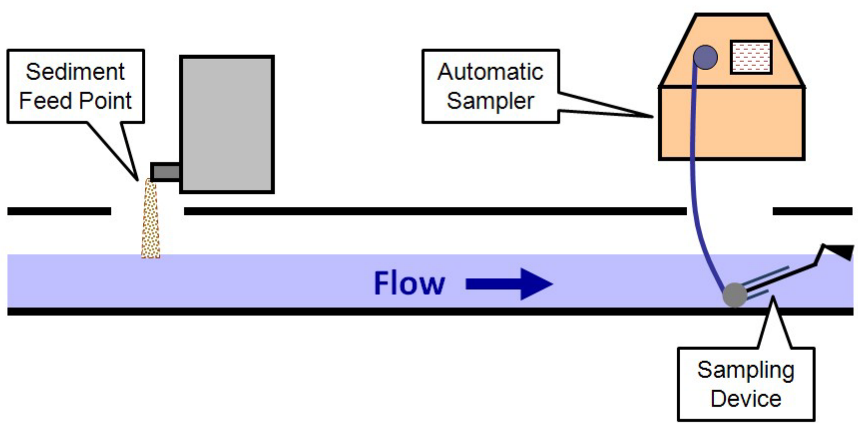

Figure 9. Sediment feeding and sampling schematic.

Quartz sediment was sieved to generate sediment stocks of known size ranges. Sediment sizes used ranged from coarse silt (44 to 88 µm) to medium sand (420 to 500 µm). One sediment size range was used per experimental run, and sediment was fed via a screw-type mechanical feeder into the upstream end of the pipe. Sediment feed rates were established by capturing and weighing sediment from the feeder multiple times over timed intervals. Incoming Mississippi River water suspended sediment concentrations were measured and found to be small. They were subtracted from all measurements.

Flow to the head box was controlled by a multi-speed pump and a globe valve. The valve was located approximately 5 m (15 ft) upstream of the head box. Steady-state flow was established by selecting a pump speed and valve setting and allowing the water to run through the setup for several minutes. During this time the water level in the head box was monitored. Once the water level experienced no measurable fluctuation, the reading was recorded. Additional water level measurements were recorded during the course of the experiment to ensure the flow conditions remained constant. For the sake of comparing results between runs, two flow rate targets were established for later runs. The "low" flow rate was approximately 2 cfs (57 l/s), and the "high" flow rate was approximately 4 cfs (113 l/s).

The water surface slope was measured through the use of five pressure taps located along the length of the pipe. Baseline samples were taken to establish the background solids concentration in the flow. After baseline sample collection, the sediment feeder was turned on and sediment was allowed to run for one minute prior to sampling. Samples of 400 to 600 mL were then taken with a stormwater sampler or comparable peristaltic pump. The use of a peristaltic pump avoided the backwash cycle used with automatic samplers and allowed multiple samples to be collected in a shorter period of time. The samples were then immediately refrigerated for later analysis via the Suspended Solids Concentration (SSC) method (Eaton et al., 1995).

Chapter 5. Results

Different sampling methods were pursued over the course of this project. Emphasis was placed on producing a device which was simple to operate, inexpensive to fabricate and maintain, minimally obstructive to pipe flow and adjustable to a range of pipe sizes. Initial efforts focused on improvement of tube and manifold sampling. In theory, as subsamples are taken from an increasing number of points within the water column, the total sample collected should increasingly approach the true mean sample. Thus, efforts were made to produce a sampling manifold capable of sampling across the water column.

Variations on manufacturer manifolds were designed and tested. The first major design variant was a manifold with the tube end attached to the bottom of the pipe with floats affixed to the other end. This design variant was similar to the depth-proportional sampler developed by Eads and Thomas (1983), with the exception that instead of using a single intake tube, a manifold was employed. The presence of the float made the device prone to submersion by drag forces under higher velocities, making this design unsuitable for use in a sewer pipe.

The second design variant was a manifold with its tube again fixed to the bottom of the pipe and a metal deflection plate, or "wing," at the other end. Flow moving past the device exerts an upward force on the plate, ensuring the plate remains at the water surface and the manifold remains positioned across the water column. Unlike the float, the wing maintained its position over the range of flow velocities tested.

An "equal-volume" manifold with a wing was also tested. The manifold employed five sets of four holes that increased in size with increasing distance from the tube end of the manifold. The holes gradually increased in diameter from 5 mm to 12 mm. The purpose of this design was to sample equal volumes of water and sediment from each set of holes, as determined by manifold computations (Roberson, et al., 1995). Because the holes were positioned at different depths, the collected sample would, in theory, better represent the mean concentration across the water column.

Improved sampling results were observed with the manifold-wing devices, but improvements were not consistent across sediment sizes and flow rates. It was posited that the geometry of the manifold itself led to poor sampling. Specifically, the arrangement of holes around a cylindrical manifold creates intake locations of high pressure in front of the manifold and low pressure along the sides. Flow can pass through the manifold while the sampler is in standby mode – a feature which may be desirable for keeping sediment from accumulating inside the manifold. However, such flow-through may also occur during sampling and may have an adverse effect on sampling accuracy. It is also unclear what effect a change in the flow velocity has on the performance of such a manifold.

An effort was made to produce an intake design that eliminated the largest number of unknowns from the sampling process. The manifold was eliminated completely, and a simple frame was built with one end hinged to the bottom of the pipe. This frame is similar to that employed by Eads and Thomas (1983), except with multiple tubes and sampling heights. The end of the frame was fitted with a wing. Four individual sampling tubes were attached to the frame and routed through its base. The tubes were mounted so that the opening of each tube was located roughly at the median depth of each quartile of the water column. The improved sampling device is illustrated in Figure 10. Photos detailing the wing attachment are shown in Figure 11. Note that the frame is bent upwards near the wing. This allows the device to lie nearly flat against the invert of the pipe during low flow conditions. Also note the plastic flaring attached to the wing which serves to reduce sharp angles that might lead to debris entrapment.

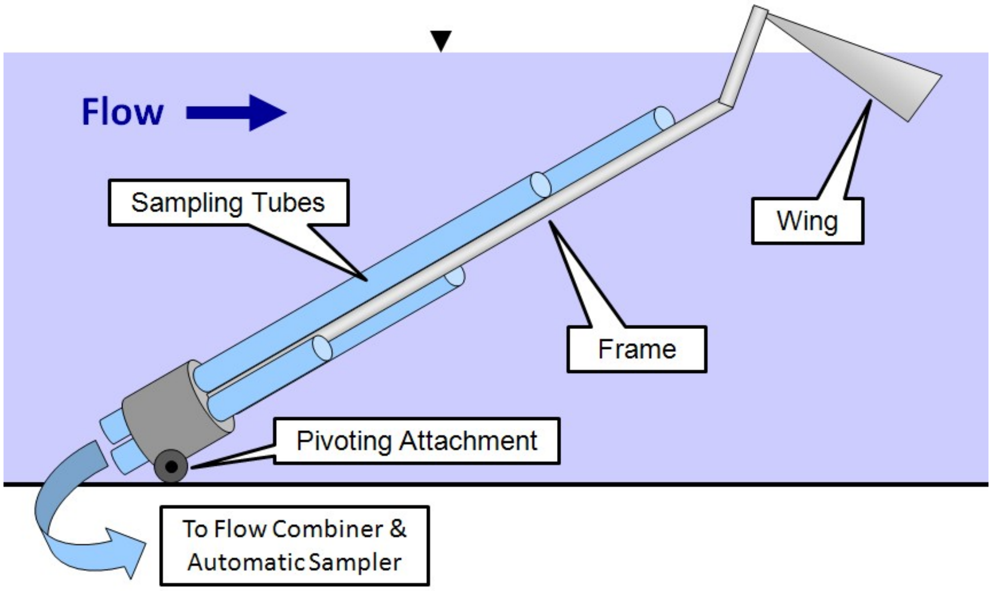

Figure 10. Improved sampling intake device.

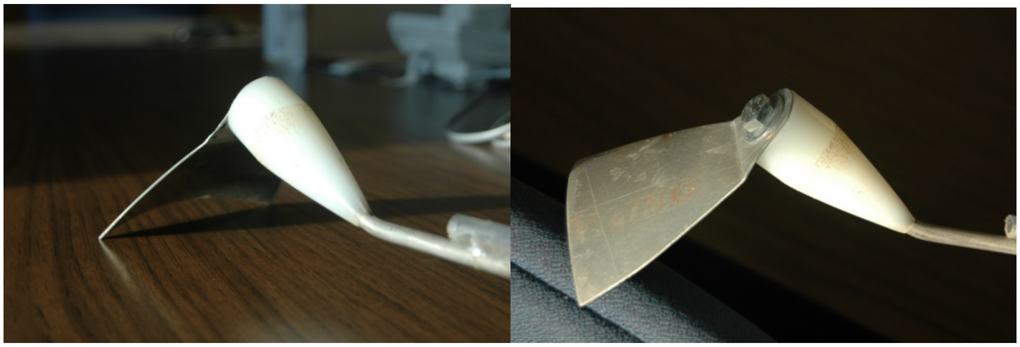

Figure 11. Photographs of wing attachment.

A short distance from the frame, the four tubes enter a flow combiner. Figure 12 shows an external schematic of the flow combiner. Figure 13 shows a cross sectional view of the flow combiner in profile perspective. The arrows indicate the direction of the flow during the sampler intake cycle. The flow combiner is axisymmetric to ensure equal flow rates through all four tubes, and is composed of two machined, plastic parts. Figure 14 shows these parts in streamwise view (top) and in cross-sectional profile view (bottom).

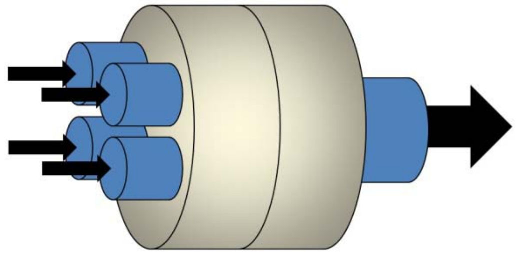

Figure 12. Flow combiner schematic.

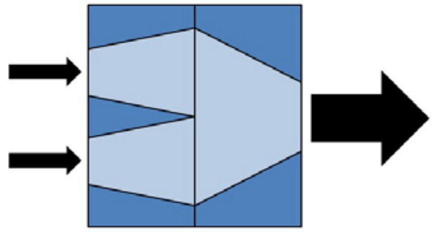

Figure 13. Flow combiner in cross section profile view.

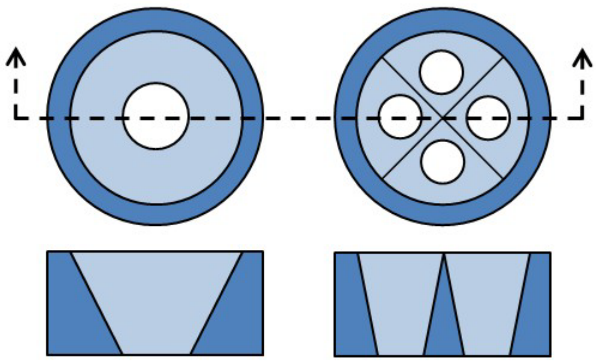

Figure 14. Flow combiner components in streamwise view (top) and cross section profile view (bottom).

The four smaller tubes were cut to equal lengths to ensure equal friction losses – and therefore flow rates – through each tube. The three tubes with intake openings mounted closer to the base of the frame were taken up along the side of the pipe between the base of the frame and the flow-combiner. A test was performed to compare the flow rates through each tube with the flow combiner, and flow rates were found to be equal.

Various methods of mixing were tested, including vanes, weirs and mixing blocks of various sizes and shapes. Focus was placed on passive mixing, rather than mechanical mixing to avoid requiring a motor and power supply. While some passive mixing devices improved performance with one or more sediment size ranges or flow rates, no mixing device was found that reliably improved sampling accuracy without worsening it under other conditions. For this reason passive mixing is not part of the recommended improvements to automatic sampling.

The frame length needs to be sufficient to span the entire water column. Care should be chosen to select a frame length appropriate for the expected maximum flow depth. Also note that based on the specific wing design chosen, there will be a maximum angle (maximum depth) whereby increasing the flow velocity will not serve to increase the vertical angle of the device.

Results for the improved device are given in Tables 1 and 2, with the results shown in Figure 15. The figure presents data for eight runs with four sediment size ranges. The device was tested at low and high pipe discharge for each sediment size range. Low discharge was approximately 2 cfs, while high discharge was approximately 4 cfs. Flow depth was approximately 6 in (15 cm) for the high flow runs and 4 in (10 cm) for the low flow run, yielding mean flow velocities between 5 and 7 ft/s (1.5 to 2 m/s).

5 shows the ratio of the background-adjusted mean sampled concentrations to the fed sediment concentrations, as well as the 95% percent confidence interval of the mean. This confidence interval was computed using a student-t distribution for the number of samples collected for each run.

Table 1. Final sampling device high flow runs.

Run Number	**106**	**107**	**108**	**109**
sediment size range (μm)	125 to 180	180 to 250	250 to 350	450 to 500
pipe flow rate (cfs)	3.8	3.9	3.9	3.9
background conc. (mg/L)	6.3	9.2	15.7	17.2
fed sediment conc. (mg/L)	136	141	147	151
sampled conc.* (mg/L)	127	156	87	54
no. of samples	7	6	7	6
sampled*/fed (%)	93	111	59	36
sampled*/fed ** (%)	85 to 102	100 to 121	46 to 72	10 to 61

Table 2. Final sampling device low flow runs.

Run Number	**106**	**107**	**108**	**109**
sediment size range (µm)	125 to 180	180 to 250	250 to 350	450 to 500
pipe flow rate (cfs)	1.8	1.8	1.9	1.8
background conc. (mg/L)	20.7	9.2	15.7	17.2
fed sediment conc. (mg/L)	134	129	124	139
sampled conc.* (mg/L)	144	140	79	27
no. of samples	7	7	7	7
sampled*/fed (%)	108	108	64	20
sampled*/fed ** (%)	98 to 117	96 to 121	49 to 79	13 to 27

* background-adjusted mean

** 95% confidence of the mean

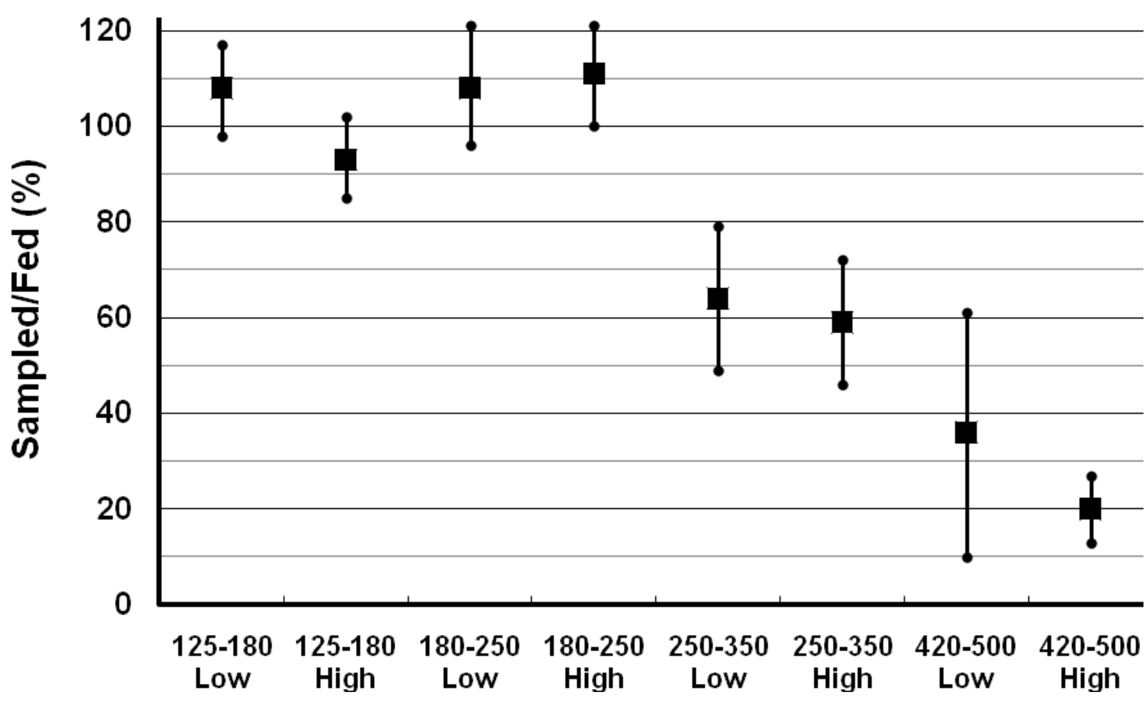

Figure 15. Results for improved sampling device, with particle diameters given micrometers. 95% confidence intervals of the mean are shown.

Note the significant improvement in sampling accuracy when compared with the results for single tube and manifold sampling (Figure 6 and Figure 7, above). Note, also, that the confidence intervals overlap for the high and low flow run for each sediment size range. This indicates that the device performs consistently at both the low and high flow rates. While at first glance one might expect sampled to fed ratios to increase with increasing sediment size, this is not the case. This observed reduction in sampled to fed ratio is actually expected due to the fact that a large portion of the sediment load is found in the lowest section of the water column for the larger sediment sizes. This means that a large fraction of the mass to be sampled flows beneath even the lowest sampling intake point (located at approximately $1/8^{th}$ the water column depth).

Chapter 6. Comparison of Results with Two-Dimensional Theory

Sampling was performed along the centerline of the pipe, allowing the assumption of a symmetric distribution of particles in the transverse direction. While particle distribution in a pipe is a 3-dimensional problem, mixing in the transverse direction was ignored for simplicity. Rouse's (1937) two-dimensional model was utilized to compare with the experimental results.

The channel shear velocity, u_*, was computed from the water surface slope using the three water surface elevations immediately upstream of the sampling device, i.e., $u_* = sqrt\ (ghS)$, where g is the acceleration of gravity, h is channel depth and S is water surface slope. The location immediately downstream of the head box was excluded because the flow could still be accelerating, and the most downstream point was excluded due to its proximity to the free outfall, where the flow could once again be accelerating. For any given ratio of settling velocity to channel shear stress (v_s / u_*), the expected concentration at a point y can be computed. This ratio is the inverse of the dimensionless 'suspension ratio' used by Hicks and Duncan (1997). Settling velocity here was determined using the simplified settling velocity equation developed by Ferguson and Church (2004), using a specific gravity of 2.65 and settling coefficients for natural sediment grains.

Because sampling is being conducted at multiple points within the water column, we are interested in the value of the collected concentration. Equation (2) yields the expected collected concentration, C_c, as a function of the concentration at a number of sampling depths, C_{yi}. n is equal to the number of sampling points. For the final device tested, there were four sampling points.

$$C_c = \frac{1}{n}\sum_{i=1}^{n} C_{y_i} \qquad \textbf{(2)}$$

Observed results for the improved device are plotted against the values from Rouse's two-dimensional theory in Figure 16. The four sets of measured data for each flow rate correspond to the four sediment size ranges evaluated. The mean settling velocity for each size range was used to compute a value for v_s / u_*. Because the flow conditions were kept similar, v_s / u_* increases with increasing sediment size.

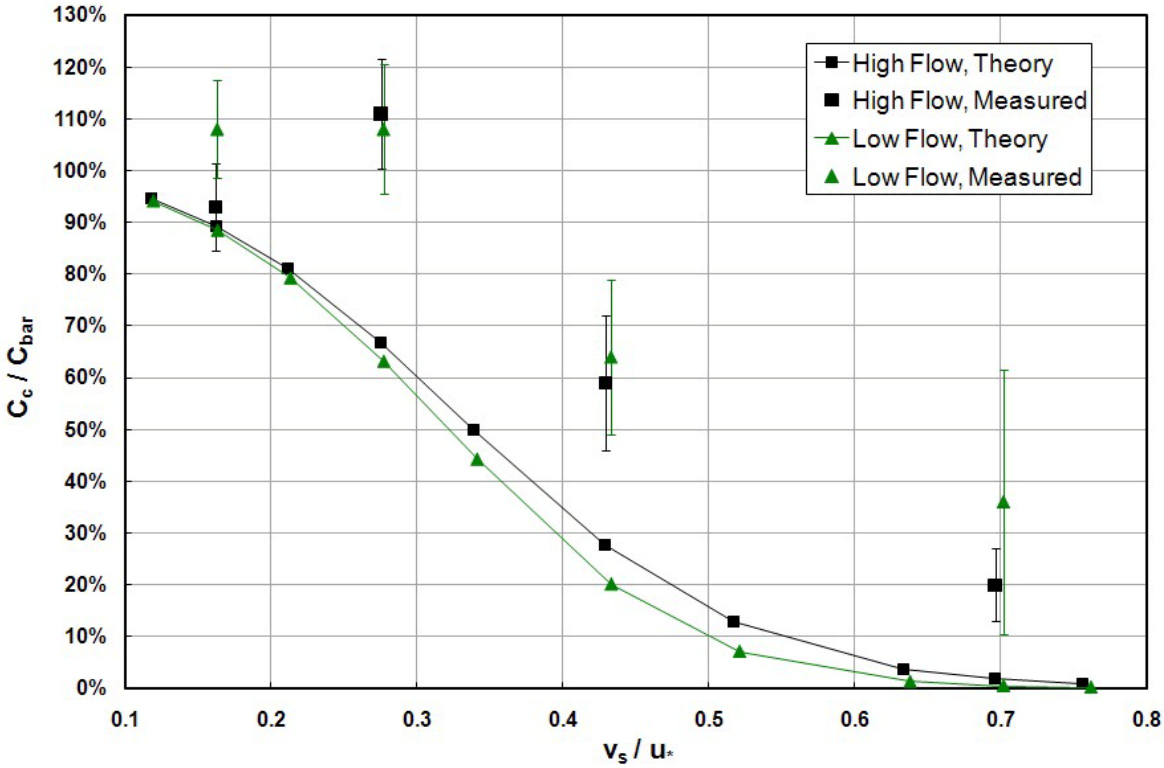

Figure 16. High flow and low flow (experimental run 109), 95% confidence intervals of the mean are shown.

Hicks and Duncan (1997), when investigating the performance of isokinetic samplers, found disagreement as large as ±70% between depth- and point-integrating samplers for fall speed ratios of $v_s / u_* > 0.25$. As shown in Figure 16, the improved sampling device achieves performance results of 110% +/- 10% of the *true mean concentration* for fall speed ratios which have a v_s/u_* values equal to 0.28. This represents a substantial improvement in sampling accuracy.

It is seen from Figure 16 that the performance drops as the ratio of settling velocity to shear velocity increases, which corresponds to the particle diameter approaching 0.5 mm. If the ratio of measured to fed concentrations are consistent at given values of v_s/u_*, however, a suspended sediment concentration can be calculated.

The discrepancy between Rouse's two-dimensional theory and pipe flow is explained as follows: The two dimensional model used for this analysis assumes a uniform distribution of sediment in the transverse direction. This is analogous to a slice taken out of an infinitely wide rectangular channel. Observed concentrations conducted along the centerline of a circular pipe are greater than those indicated by the two-dimensional theory. This discrepancy increases as the ratio of v_s to u_* increases, i.e. with increasing sediment size for the same flow conditions. Figure 17 (left) illustrates the distribution of particles of a uniform sediment size and density in a wide channel. This represents the two-dimensional model discussed above. For a given sediment size and flow condition, the sediment distribution can be calculated and the point of the mean concentration,

$y_{\bar{c}}$, can be computed. This point is also the centroid of mass of the particles and is represented by a target on the figure.

If we extend this conceptual model to a circular pipe, we end up with a distribution that looks approximately like Figure 17 (right). The particle concentration is greater in the regions closer to the walls and the bottom of the pipe. This has the effect of increasing the magnitude of $y_{\bar{c}}$, again represented by a target on the figure. In other words, the distribution of sediment in a circular pipe leads to a mass distribution with a higher centroid.

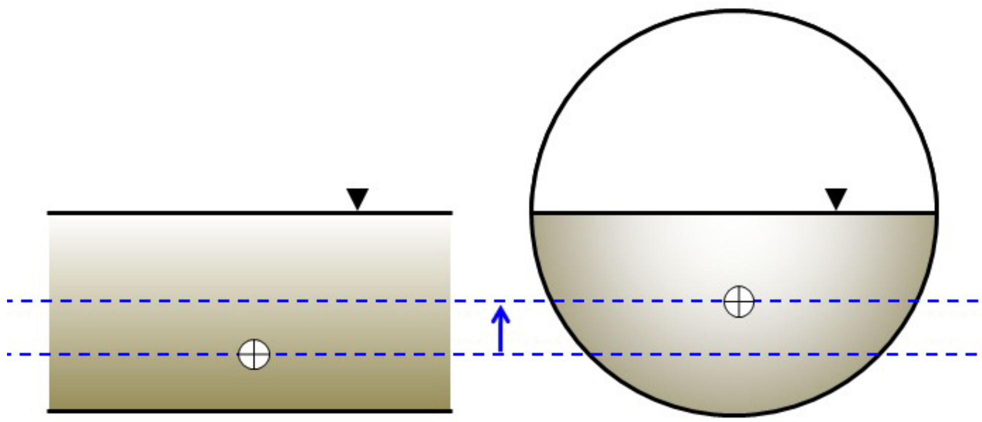

Figure 17. Centroid shift effect from wide channel (left) to circular pipe section (right).

It can also be observed that $y_{\bar{c}}$ increases more significantly as the distribution of sediment becomes more pronounced towards the channel bottom. The increase in $y_{\bar{c}}$ for circular pipe flow can be seen in the plots of observed and modeled data above. As the sediment size increases (increasing the ratio of of v_s to u_*) this effect becomes more pronounced.

The geometric layout of the sampling device can also lead to differences between calculated and measured concentration. The base of the sampling device consists of an anchoring component which holds the lower ends of the sampling tubes in place. The frame arm extends from the center of this anchoring component, and the tubes are arranged around the frame arm. Figure 18 shows how this configuration leads to sampling tube openings which are slightly offset from the axis of rotation of the sampling device. This offset causes variations in the locations of the tube openings for different angular positions of the sampling device. As such, the ends of the sampling tubes may be above or below the theoretical positions of $1/8^{th}$, $3/8^{th}$, $5/8^{th}$ and $7/8^{th}$ of the total flow depth.

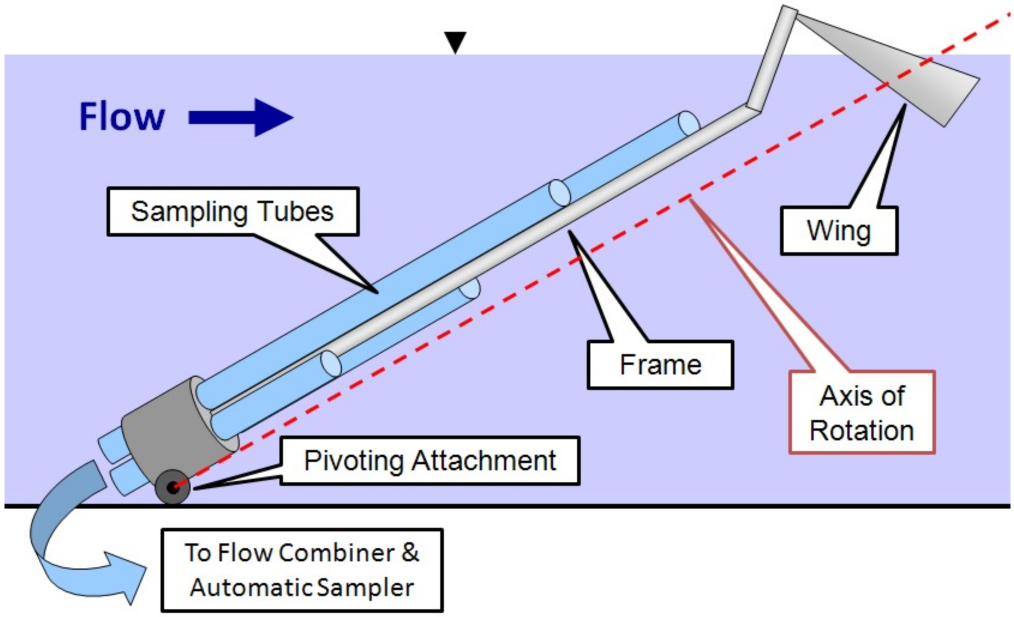

Figure 18. Position of intake tube openings relative to axis of rotation.

No specific design recommendations are given for the size of the wing. The wing developed here measures approximately 4 inches (10 cm) in length and 5 inches (13 cm) in width. In instances where the design has been modified, a larger wing may be needed to provide sufficient lift to position the device across the water column. Examples of such modifications may include devices with longer – and therefore heavier – lift-arms for larger diameter pipes, or devices with lift-arms of larger material gage for greater strength. Practitioners may also choose to place a shroud along the upstream side of the lift-arm, enclose the sampling tubes within a larger tube, or use a different material, such as metal, for the sampling tubes. Minimum velocity to provide lift generally need not be considered as site locations with such low flow velocities will have correspondingly low shear velocities, making them unsuitable for obtaining accurate sampling results because of the high value of v_s/u_*.

Chapter 7. Application to Urban Runoff

For small particles the need to improve sampling performance has not been pressing, as large errors have not been encountered with present sampling methods. However, the accuracy of sampling larger particles such as coarse silts and sands has been a vexing problem. In addition to being difficult to accurately sample, these particles have been found to comprise a significant portion of the total mass and surface area of solids associated with urban and highway runoff (Lin et al., 2008).

Common urban runoff applications for automatic samplers include establishing existing pollutant conditions, monitoring the effectiveness of mitigation efforts, and evaluating the performance of stormwater BMPs – both in the field and in a laboratory setting. Inaccurate sampling has implications for these applications. These implications are discussed here in two examples.

Example 1: Stormwater BMP Assessment

Monitoring is performed at sites upstream and downstream of a newly installed settling BMP. For sake of simplicity the particle size distribution entering the stormwater BMP is bimodal: large particles are settled out and small particles pass through the BMP.

Due to the use of inaccurate sampling methods discussed in Section 3, the large particles are oversampled. Or, if fixed height intakes are kept off of the pipe bottom the bias may be toward the smaller particles. This leads to overestimation (or underestimation if using a fixed height location) of solids removal efficiency. The end result is the stormwater BMP is determined to be more effective (or less effective for smaller particles with a fixed height sample site) at removing particle load than is actually the case.

Figures 18 and 19 illustrate this example. Small particles are represented by lightly shaded boxes. Large particles are represented by darkly shaded boxes. Each box represents the same amount of mass collected. The mass removed by the stormwater BMP is estimated by subtracting the measured outflow from the measured inflow.

In Figure 19, the small particles are accurately sampled, but the large particles are oversampled by 300%. The oversampled mass is represented by the boxes labeled “OS”. These boxes can be thought of as fictitious – they are solely the result of inaccurate sampling methods.

In Figure 20 both particle sizes are accurately sampled. Computing removal efficiency yields 75% for Figure 19, but only 50% for Figure 20. Accurate sampling reveals that the stormwater BMP has lower removal efficiency than established with previous sampling methods.

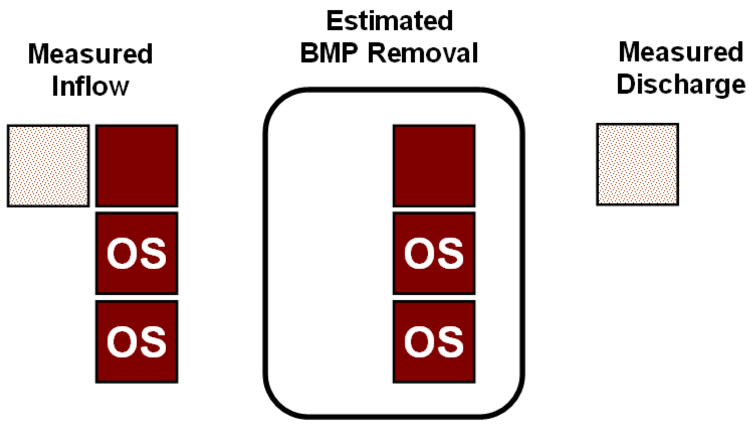

Figure 19. Inaccurate sampling yields estimated removal efficiency of 75%. Lightly shaded boxes represent small (non-settleable) particles and dark boxes represent large (settleable) particles. Oversampled mass is represented by boxes labeled "OS".

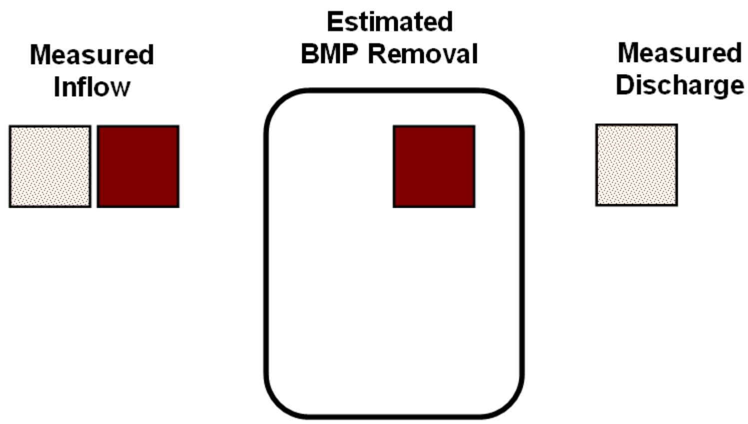

Figure 20. Accurate sampling yields estimated removal efficiency of only 50%. Lightly shaded boxes represent small (not-settleable) particles and dark boxes represent large (settleable) particles.

Example 2: Stormwater BMP Selection

A load-estimating model is used to design watershed improvements. Monitoring is performed with portable automatic field samplers in order to determine an appropriate particle size distribution. Due to inaccurate sampling methods, larger particle sizes are oversampled. This particle data is then used with the load-based model during the design process.

While the attempt to establish an accurate particle size distribution for the watershed is certainly well-intentioned, the inaccurate distribution which was obtained yields the selection of a settling BMP which is much smaller than required.

Figures 20 and 21 illustrate this example. In Figure 21 an accurate particle size distribution is used to size the settling BMP. The BMP is thus properly sized and functions as intended. In Figure 22 the particle size distribution used – represented by the dashed line – is skewed towards larger particle sizes due to inaccurate sampling methods. The subsequent design process assumes particles which settle much more quickly. The end result is a BMP which is undersized and ineffective at treating the actual particle size distribution.

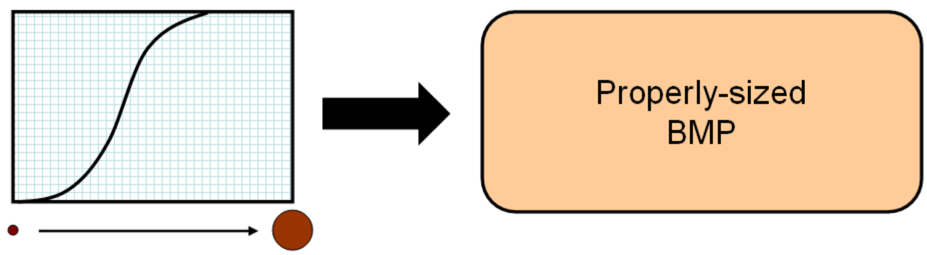

Figure 21. Accurate particle size distribution data yields properly designed settling BMP.

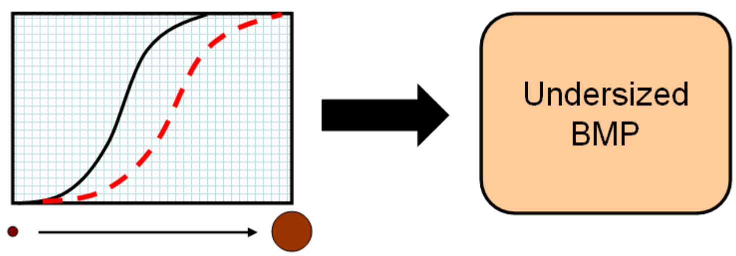

Figure 22. Inaccurate particle size distribution (due to oversampling large particles) yields undersized BMP.

The examples above are two of many scenarios where inaccurate sampling can lead to (1) significantly overestimating stormwater BMP performance and (2) encouraging the use of under-designed BMPs.

Chapter 8. Conclusions

Accurate data concerning particle size and composition is necessary for the proper selection and design of stormwater BMPs as well as for accurate assessment of BMP performance over time. However, previous studies of particle size distribution have indicated wide variations in particle size ranges attributed to monitoring artifacts. The purpose of this series of research has been to refine sampling/monitoring techniques so as to provide better data and reduce sources of sampling bias that have been introduced into particle size assessments. The difficulty with sampling suspended sediments in flowing water has been known for some time (Rouse, 1937). The main difficulty in sampling suspended solids arises from the behavior of these particles in turbulent flow in that sediment particles are not uniformly distributed with depth in the water column. Additionally, particle size data can exhibit more variation between storm events at each site than between different sites themselves (USEPA, 1983).

Automatic sampling inaccuracy is primarily attributable to these varied distributions of particles in the flow column. Sampling with a single intake opening does not necessarily capture a sample that is representative of the mean concentration. Sampling with multiple intake openings also may not capture a representative sample unless a sufficient number of equal-volume sub-samples are taken across the water column. The multiple intake sampling device developed here improves the accuracy of automatic samplers by collecting sub-samples of equal volume from multiple locations in the water column and across a range of flow conditions

The improvement in automatic sampling achieved here is a critical step in the advancement of knowledge concerning stormwater particles. Improved automatic sampling data should be collected and analyzed carefully. Improved sampling is needed over a longer period of time and in coordination with the collection and analysis of other pertinent data (e.g. rainfall depth, intensity, frequency; land use and other anthropogenic factors) to build meaningful conclusions for stormwater regulation and practice.

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