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Suspended Solids Size Distribution Determined with the Winged Arm Sampler

Final Report

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Executive Summary

Impairment due to suspended solids pollution is an important 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 during and following a storm event. Automated equipment is also capable of collecting multiple flow-weighted or time-weighted samples during a single or storm event. This can be important for a given monitoring objective 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 by 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 in studies to characterize stormwater particles, as well as for evaluating the performance of stormwater treatment practices. Portable automatic field samplers, however, have been found to overestimate concentrations of coarse silts and sands contained in suspended solids.

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.

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 increases the maximum sediment size where sampling accuracy is within +/- 10% from 62 µm to 256 µm. The new sampling intake performs with a substantial remaining bias for larger sediment sizes. The bias, however, seems to be consistent, such that the true distribution up to 350 µm can be developed when the proper transformation is performed. The new intake thus demonstrates improved sampling accuracy and precision.

Suspended solid samples during runoff from two agricultural watersheds were compared with suspended solid samples from two residential watersheds in the Minneapolis and St. Paul metropolitan area. There was no distinct difference between the watersheds in the particle sizes sampled, probably because the runoff comes primarily from the streets and parking lots during the majority of the storms. It is only the larger storms that will have a runoff contribution from pervious areas.

Chapter 1
Introduction

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, particle size is the primary variable to determine settling velocity. For stormwater BMPs which remove particles via filtration or 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 by 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.

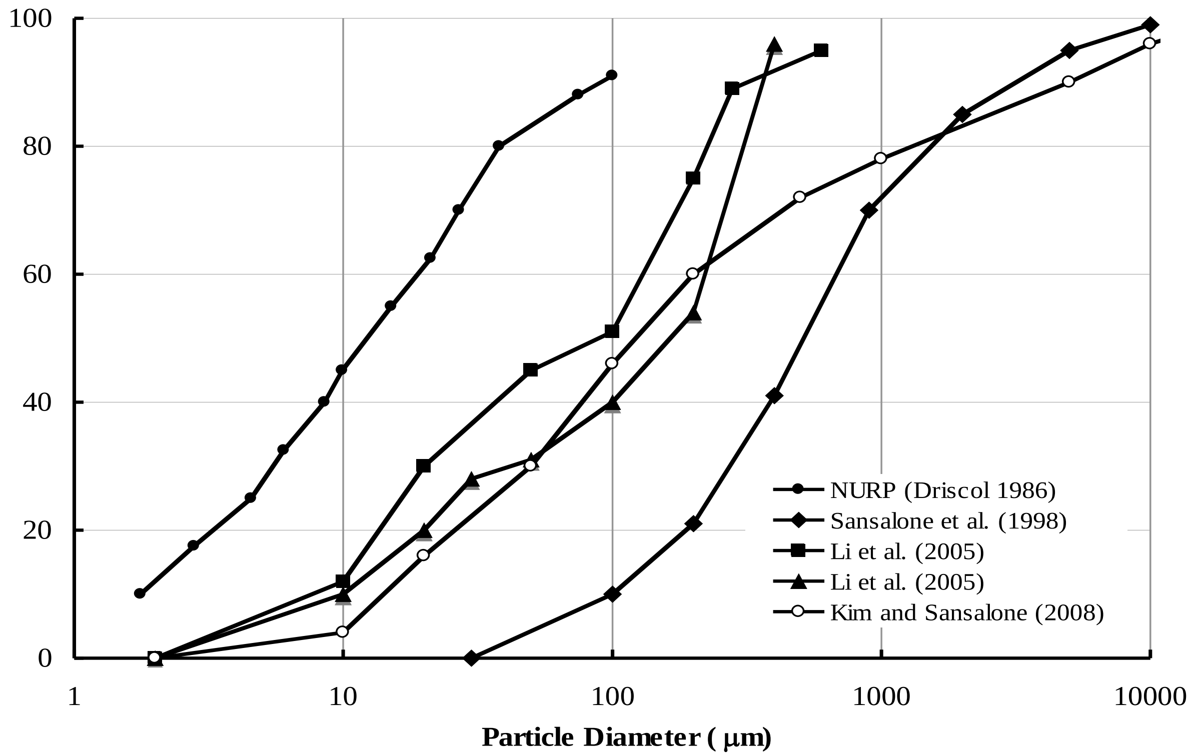

Figure 1. Comparison of cumulative size distributions (percent by mass less than) for the NURP studies and receipt highway runoff studies. The NURP distribution was determined by conversion of measured settling velocity distribution to particle size assuming silica particles.

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 that 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. 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 $u_* = \text{sqrt}(\tau_w/\rho)$, 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 streambed, 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.

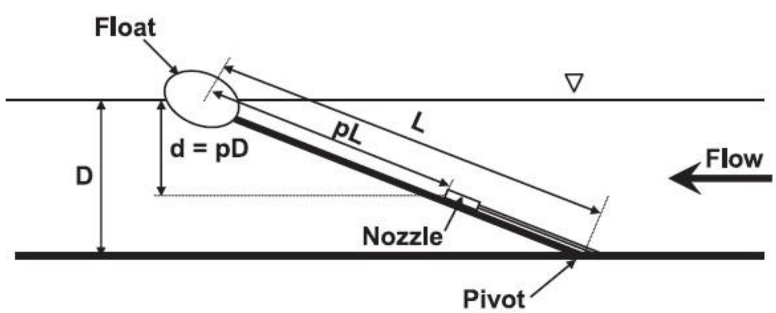

**Figure 2. Eads and Thomas (1983) depth proportional intake device.
Image reproduced from Lecce (2009).**

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.

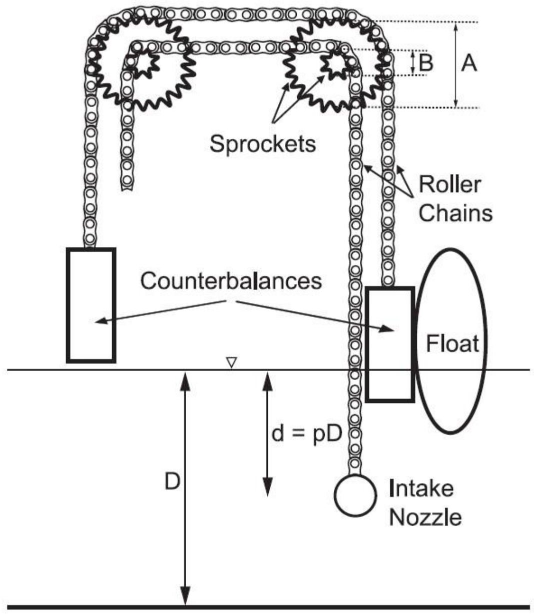

Figure 3. Depth proportional intake device (Lecce 2009)

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.

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

where C is suspended sediment concentration at depth y, measured from the bed, y_0 is a small distance above the channel bed, $C_{average}$ 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.

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. At lower water surface slopes this departure of the ratio occurs at lower particle sizes. 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.

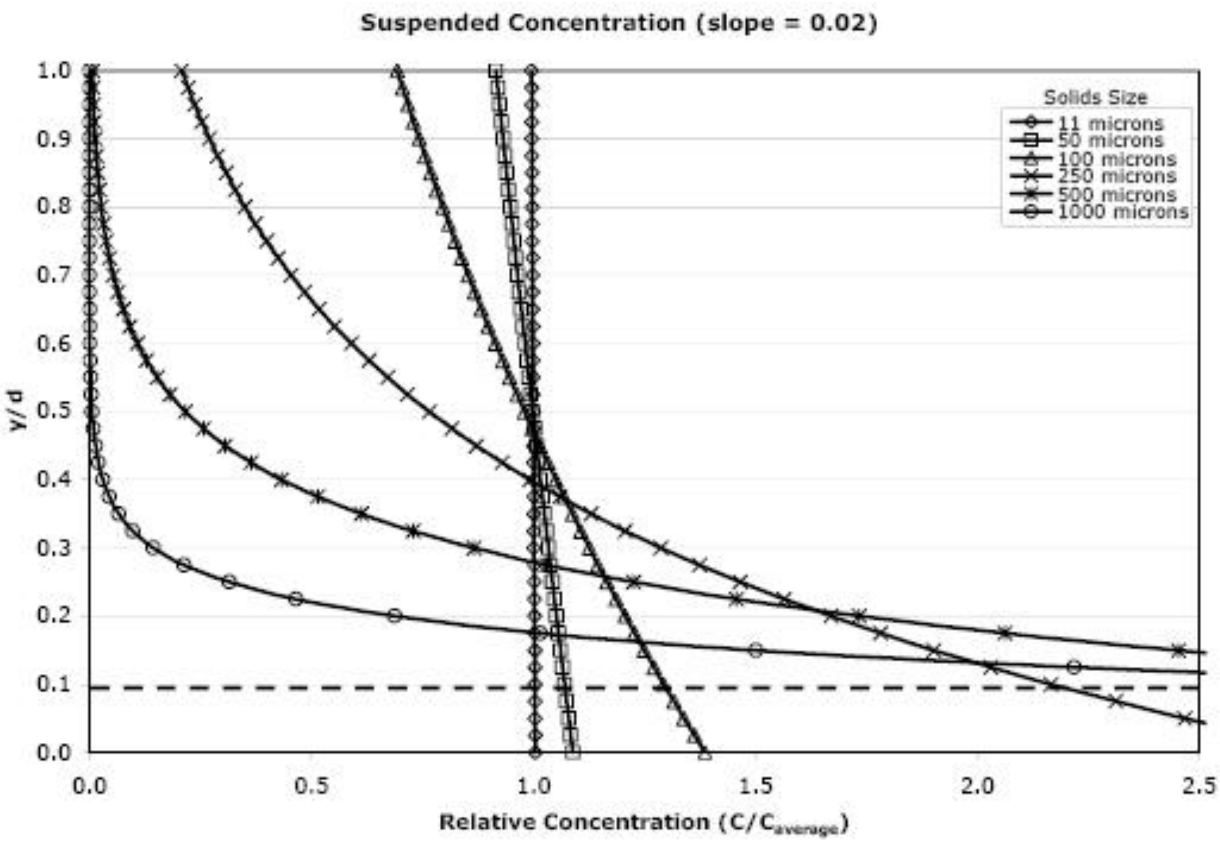

Figure 4. Suspended solids concentration as function of depth for fully developed flow in a wide duct with a water surface slope of 0.02. (Gulliver et al. 2010).

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 that collect both the dissolved and suspended fractions include manual (or grab) sampling, isokinetic sampling, and tube sampling for automatic samplers.

Chapter 3
Accuracy of Current Sampling Methods

In a previous study, 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., 2010). 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 **Error! eference source not found.**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 on 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.

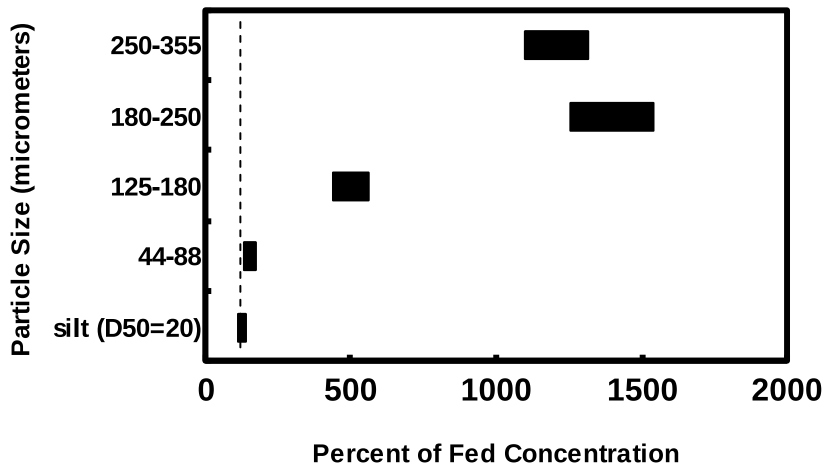

Figure 6. Percent of fed concentration versus particle size for sampling tube facing downstream, each bar represents 95% confidence interval of the mean percent of fed concentration.

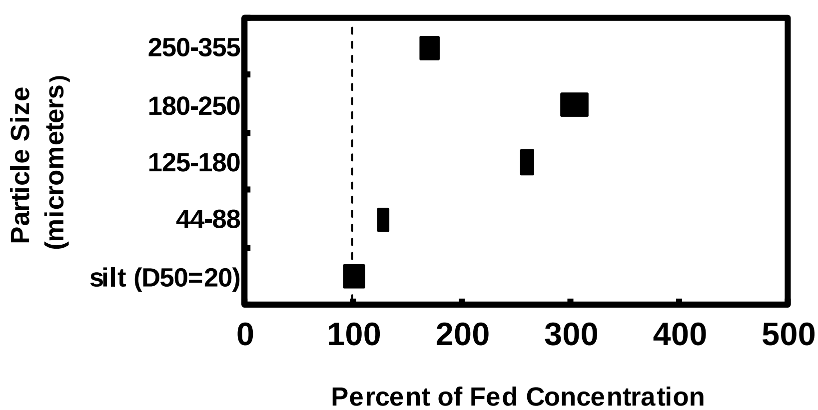

Figure 7. Percent of fed concentration versus particle size for sampling manifold in the fixed configuration, each bar represents a 95% confidence interval of the mean percent of fed concentration.

It was observed that current sampling technology substantially overestimates the concentration of 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: Development of the Winged Arm Sampler

To improve sampling accuracy, a new sampler was designed using the same experimental setup described in Chapter 3. Different sampling methods were pursued, and 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, and 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.

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 winged arm sampler is illustrated in Figure 8. Photos detailing the wing attachment are shown in Figure 9. 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.

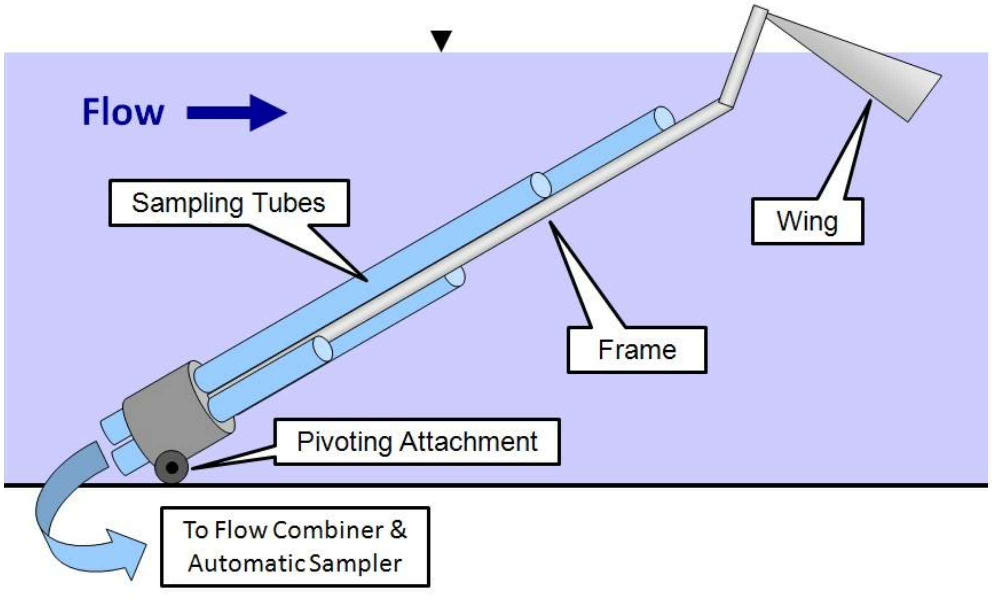

Figure 8. Sketch of winged arm sampler.

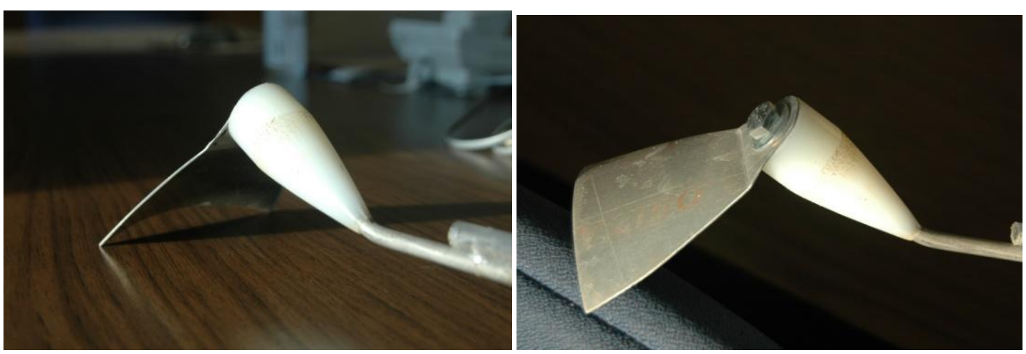

Figure 9. Photos of wing attachment.

A short distance from the frame, the four tubes enter a flow combiner. Figure 10 shows an external schematic of the flow combiner. Figure 11 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 12 shows these parts in streamwise view (top) and in cross-sectional profile view (bottom).

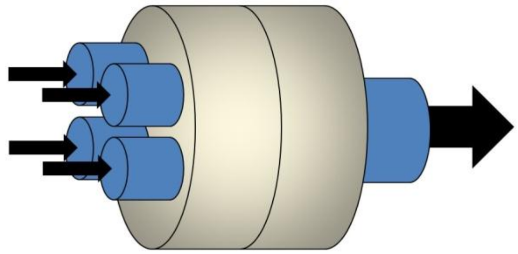

Figure 10. Flow combiner schematic.

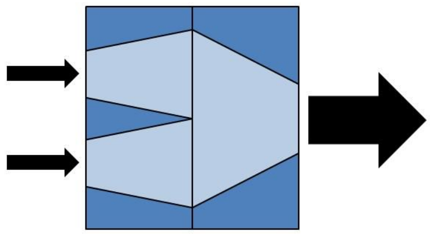

Figure 11. Flow combiner in cross section profile view.

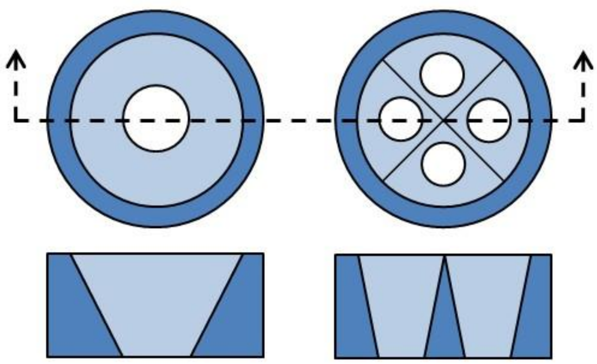

Figure 12. Flow combiner components in streamwise view (top) and cross section profile view (bottom).

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 within 2% of equal.

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 winged arm sampler are given in Tables 1 and 2, with the results shown in Figure 13. River water was used for the experimental runs. The background suspended solid concentration was subtracted from the sampled suspended solids concentration to result in a concentration that is directly compared to the fed sediment concentration. 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).

Figure 13 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. High flow runs with the winged arm sampler.

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
Mean of sampled*/fed (%)	93	111	59	36
95% confidence interval of sampled*/fed ** (%)	85 to 102	100 to 121	46 to 72	10 to 61

**Background-adjusted mean*

Table 2. Low flow runs with the winged arm sampler

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
Mean of sampled*/fed (%)	108	108	64	20
95% confidence interval of sampled*/fed (%)	98 to 117	96 to 121	49 to 79	13 to 27

* *Background-adjusted mean*

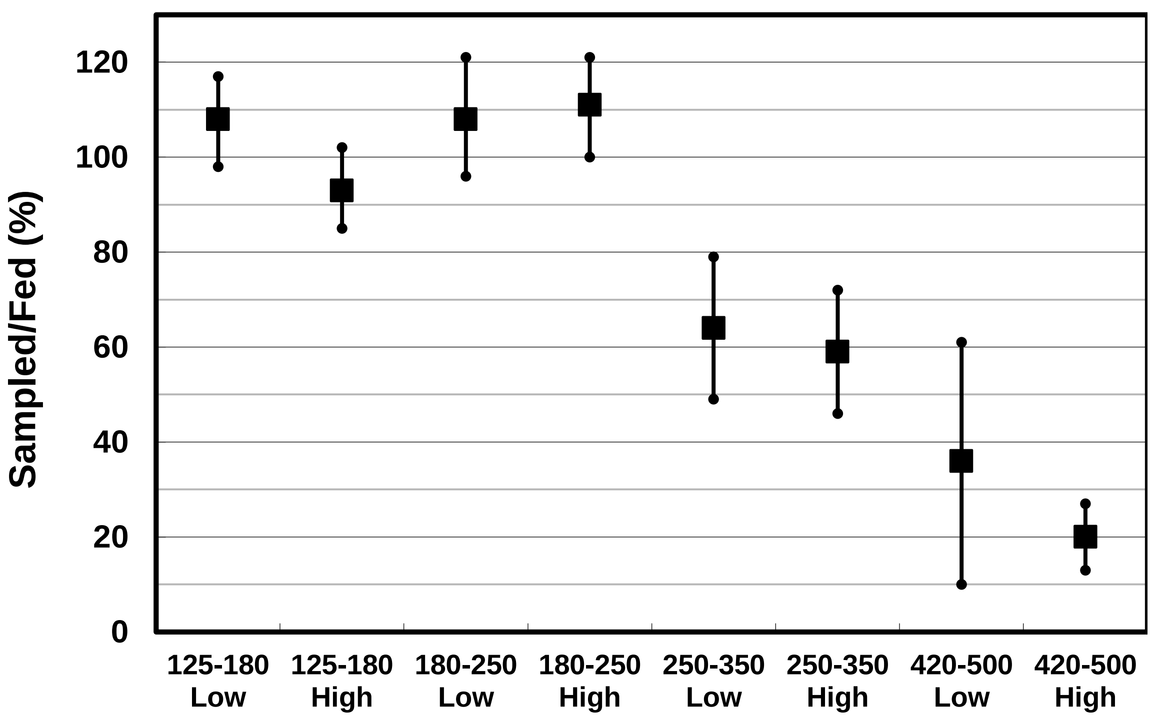

Figure 13. Results for winged arm sampler, with particle diameters given in micrometers. 95% confidence intervals of the mean are shown.

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.

One of the most important determinants of settling velocity is particle size; the larger the particle, the faster the settling velocity. Particles with high settling velocity are settler fast, and therefore are unlikely to be evenly distributed throughout the column of water. This causes a high concentration of larger sized particles near the bottom of the water column. Since the manufacturer recommended manifold sits of the bottom of the pipe, and only collects samples at the bottom of the pipe, it most likely over samples the concentration of larger particles. Thus, the old manifold does not take into account the range of settling velocities of different sized particles and assumes constant distribution of particles of all sizes throughout the column, hence the oversampling of sediments greater than 500 μm. The winged arm sampler corrects for this deficiency by sampling at four points across the depth of the flow. The wing assures that the sampler will be elevated across the depth.

Chapter 5
Field Verification Methods

The two samplers, the manufacturer-recommended strainer (recommended by ISCO) and the winged arm sampler were used simultaneously at four different storm water outfall sites in Minneapolis and in St. Paul to collect stormwater samples. Samples were collected at two outfalls along Minnehaha Creek, and two outfalls on the University of Minnesota St. Paul Campus. At each site, the samplers were installed side by side in sewer pipes near the outfall, with both sampling devices attached to the bottom of the pipe, approximately ten to fifteen feet into the pipe (see Figure 15). The samplers were attached to the pipes during dry periods, so as to ensure the samplers would stay in place. The arm samplers were attached to the concrete pipe using concrete nails at first. Later the samplers were held in place by drilling into the pipe, and caulking the nails into the holes to prevent the equipment from washing out. Plastic tubing ran from the samplers to the containers, which collected the samples via two ISCO automatic samplers, placed above the outfall.

In order to protect the equipment (in particular the batteries and flowmeter), the flow meter, batteries, piping and one of the ISCO samplers, were stored in a large metal box, as shown in Figure 15. This minimized the effects of animals, insects and weather on the equipment.

Figure 14. Strainer or manifold (right rear) and winged arm sampler (left front) installed in outfall

Figure 15. Equipment set up at Commonwealth Site in St. Paul, MN with two automatic samplers and a protective metal box.

At each site, the flow meter needed to be set to different minimum water levels for collection, as well as different volume of water intervals at which to collect samples. The minimum flow level and volume of water interval should be set according to a typical flow volume for the outfall. In this study, outfalls with low flow (on the order of hundreds of cubic feet per storm event) were typically set to sample at a minimum water level of approximately .2 inches, and to sample at an interval of every five to ten cubic feet. This was done to ensure the maximum number of samples would be collected from the site. For sites with higher flows (on the order of 30-100 thousand cubic feet of flow per storm), the flow meter would be set to sample at a minimum water depth of about two inches, and at a sample interval of five to ten thousand cubic feet of flow.

The slope of the pipes was obtained from the pipe design drawings. Roughness was also taken to be 0.012 (since the pipes were concrete). This data was entered into the flowmeter prior to each storm event. We did not use head when calculating the flow, instead it was assumed that flow through the pipes was non-pressurized, open channel flow through a circular pipe, and the Manning's Equation was used to calculate flow in the flowmeter.

Initially, the sampling devices were attached to the outfall pipes via cement nails. However, this method of attachment proved ineffective, as both the manufacturer-recommended strainer and the winged arm sampler could wash out of the pipe during heavy rainfalls and high flows through the pipes. In this case, samples either were not collected at all, or only a small amount of water was collected (depending on when the samplers were washed out of the pipe). To fix this problem, a small hole was drilled into the pipe. The pipe was then caulked in order to hold the screw in place. This method proved more effective for keeping samplers in place.

Flow was measured using an ISCO 4230 Bubble Flow Meter. The bubbler tube for the flow meter was secured inside the pipe in the same fashion as the sampling devices. A flow meter was also attached to the inside of the pipe, and used to measure the total volume of water through the pipe in a storm event, and to alert the sampler of when to sample during a storm. The flow meter was set to alert the sampler at specific intervals during a storm event that changed according to the site—the intervals between samples would be larger for sites that typically saw more flow, and smaller for sites with less water flow. The intervals were determined after seeing typical flow values for each site, to find a reasonable volume interval for the sampling at the site.

Samples were collected as soon as possible after each storm event. The samples were preferably collected within twenty-four hours. The samples were then taken back to the lab and either refrigerated or analyzed. Analyzing the samples included a process of wet sieving, driving and massing for larger particles; and using the Beckman Coulter counter to analyze particles smaller than 63 microns. Samples were sieved according to the following sizes, >500 microns, 250-500 microns, 180-250 microns, 125-180 microns, 88-125 microns, and 63-88 microns. After the wet sieving process, six grab samples were taken—three 100 mL grab samples, and three 30 mL samples. The 100 mL samples were sieved using paper filters to filter out particles <63 microns. The 30 mL samples were kept to be analyzed by the Coulter counter. After collection, samples were dried at 104° C, in order to obtain a dry solids mass for each particle size category in a sample. This data was used to create a particle size distribution by which compared results of the two sampling devices.

The Coulter counter was used create a suspended solids concentration for particles below 63 microns (using the 30 mL grab samples), and to create a particle size distribution for the small particles in the water.

Chapter 6
Field Verification Results

The focus of this project was to determine whether or not the suspended solids concentration taken with the winged arm sampler proved to be substantially different from the manufacturer-recommended manifold sampling device in the field. The sampler was to be tested at sites varying in geographic makeup, and location. The project would also begin to create a particle size distribution for each watershed and connect this distribution to the sites particular geographic make up.

The sampling devices were tested at four sites in Minneapolis and St. Paul; two outfalls were on the University of Minnesota St. Paul Campus and two outfalls along Minnehaha Creek.

The first site sampling site was located on the University of Minnesota's St. Paul Campus Sheep Pasture. It was around 210 acres, and was predominantly agricultural runoff. The site typically saw relatively high flows, on the order of a hundred thousand or more cubic feet per flow.
The second sampling site was in Minneapolis, located at Penn Ave. on Minnehaha Creek, and was predominantly residential runoff. This site is assumed to have a small watershed, due to the small flow volumes during each storm event. A single storm would see up to 300 cubic feet of flow—drastically different from the other sites.

The third site was located at 12th Ave South and Minnehaha Parkway East in Minneapolis. This site typically saw ten to twenty thousand cubic feet of water per storm event, and was also residential runoff. The Minneapolis sites were within about three miles of each other.

The final site was located on the St. Paul Campus at the University of Minnesota, at the cross section of Commonwealth and Transit Way. This outfall saw high flows, similar to the St. Paul Sheep Pasture site. Again, this site had high flow volumes, on the order of hundreds of thousands of cubic feet per flow, and flows originated from fifty percent agricultural land and fifty percent urban land.

All storm water outfalls had twenty four-inch diameter tunnels, with the exception of the site at Penn Avenue, which had an eighteen-inch diameter.

Typical results are shown in Figure 16. These results were taken from the Minneapolis site at 12th Ave S and Minnehaha Parkway E. Data from the manufacturer-specified strainer/manifold is shown in Table 3, and data from the winged arm sampler is shown in Table 4.

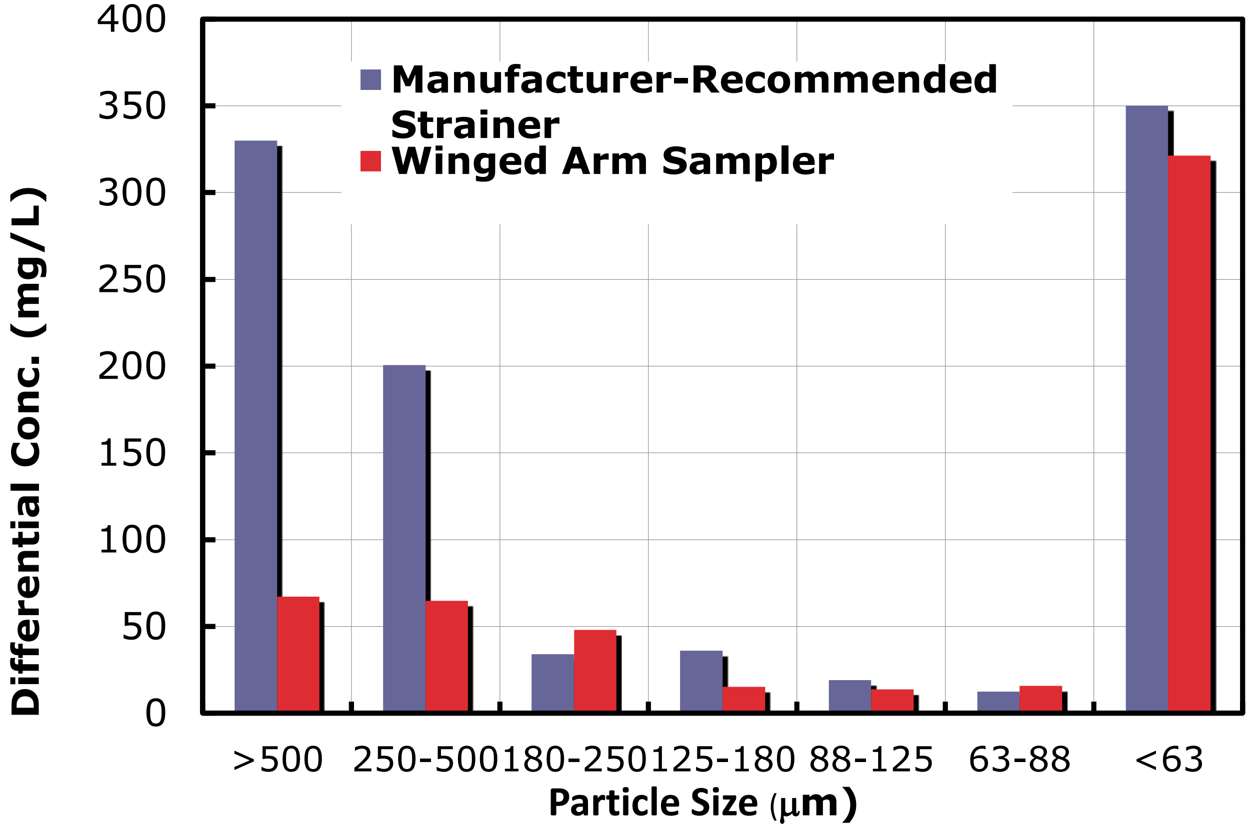

Figure 16. Results from the June 28, 2010 storm in St. Paul.

This data set shows significantly greater concentrations of particles greater than 250 μm using the manufacturer-recommended manifold/strainer. Although the actual concentrations of sediment in the storm water are unknown, it can be posited that the larger size particles are being overestimated in the manifold/strainer due to sitting on the bottom of the pipe (and not measuring across the water column).

Tables 3-22 contain the full results for the four sites from June through October 2010. The cumulative concentrations, masses and percentages refer to the quantity of dried material after the sample water was filtered. The percent cumulative concentration was used to graphically compare the samplers. The tables are arranged by sampling site. The measured precipitation and total volume of flow that passed the flow meter for each storm event, when available, is recorded above the table. The total precipitations were obtained from Weather Underground at wunderground.com—Rain quantities for the two St. Paul sites were collected from Villa Park Overlook, in Roseville, Minnesota, which is approximately two miles from the sampling sites. The rainfall totals from Minneapolis came from Tangletown Minneapolis—the neighborhood in which the sampling sites were located. The size range column refers to the size of the particle, whereas sieve size refers to the size of the sieve being used. The results for particles less than 63 micrometers were generally disregarded because the uncertainty in the measurements was greater than the mass collected.

Tables 3 through 22: Comparison of particle size determined by two sampling techniques.

St. Paul Sheep Pasture Site (Tables 3 – 10):

Table 3. **6/11/10** Precip = 2.2 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	9.03	470.39	100.00	7.8	353.7	100.0	>500
250	6.63	345.54	73.46	6.7	304.5	86.1	250-500
180	5.73	298.40	63.44	6.2	281.4	79.6	180-250
125	5.20	270.80	57.57	5.8	264.7	74.8	125-180
88	4.88	254.01	54.00	5.6	255.7	72.3	88-125
63	4.30	223.93	47.61	5.4	244.6	69.2	63-88
<63	4.03	209.75	44.59	5.1	231.7	65.5	<63

Table 4 **6/22/10** Precip = 0.03 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	0.89	75.11	100.00	0.9	55.6	100.0	>500
250	0.70	58.85	78.34	0.8	50.0	89.8	250-500
180	0.62	52.30	69.62	0.7	46.3	83.2	180-250
125	0.58	48.92	65.12	0.7	44.1	79.2	125-180
88	0.55	46.38	61.75	0.7	42.2	75.9	88-125
63	0.53	44.69	59.50	0.7	40.9	73.5	63-88
<63	0.51	43.00	57.25	0.6	40.0	71.9	<63

Table 5 **6/26/10** Precip = 0.75 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (μm)	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	8.53	474.12	100.00	1.6	90.2	100.0	>500
250	6.08	337.77	71.24	1.2	65.4	72.5	250-500
180	0.66	36.68	7.74	0.4	19.6	21.7	180-250
125	0.32	17.82	3.76	0.2	12.1	13.4	125-180
88	0.12	6.68	1.41	0.1	6.6	7.3	88-125
63	0.05	2.85	0.60	0.0	2.3	2.5	63-88
<63	0.00	0.00	0.00	0.0	0.0	0.0	<63

Table 6 **6/28/10** Precip = 0.10 cm, Runoff =0.11 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	20.62	981.79	100.00	11.5	545.7	100.0	>500
250	13.69	651.85	66.39	10.0	478.5	87.7	250-500
180	9.48	451.29	45.97	8.7	413.7	75.8	180-250
125	8.76	417.33	42.51	7.7	365.8	67.0	125-180
88	8.01	381.39	38.85	7.4	350.6	64.3	88-125
63	7.61	362.32	36.90	7.1	337.0	61.8	63-88

Table 7 **6/29/10** Pecip = 0.10 cm, Runoff = 0.06 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cum Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	5.24	374.13	100.00	1.8	116.5	100.0	>500
250	4.09	292.19	78.10	1.6	106.0	91.0	250-500
180	2.15	153.28	40.97	1.1	72.1	61.8	180-250
125	1.83	130.55	34.89	1.0	62.5	53.6	125-180
88	1.70	121.64	32.51	0.9	57.6	49.4	88-125
63	1.63	116.41	31.12	0.8	54.6	46.9	63-88
<63	1.56	111.33	29.76	0.8	52.0	44.6	<63

Table 8 **7/3/10** Precip = 0 cm St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	5.38	352.59	100.00	1.8	116.5	100.0	>500
250	4.23	277.37	78.66	1.6	106.0	91.0	250-500
180	2.29	149.84	42.50	1.1	72.1	61.8	180-250
125	1.97	128.97	36.58	1.0	62.5	53.6	125-180
88	1.84	120.80	34.26	0.9	57.6	49.4	88-125
63	1.77	116.00	32.90	0.8	54.6	46.9	63-88
<63	1.70	111.33	31.58	0.8	52.0	44.6	<63

Table 9 **7/4/10** Precip = 3.58 cm, Volume = 0.09 cm July 4 & 5 combined
St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	0.76	94.80	100.00	0.8	86.0	100.0	>500
250	0.66	82.57	87.10	0.7	75.8	88.2	250-500
180	0.61	76.12	80.30	0.7	71.3	82.9	180-250
125	0.60	74.70	78.80	0.7	69.6	81.0	125-180
88	0.58	72.76	76.75	0.6	66.9	77.8	88-125
63	0.55	68.91	72.69	0.6	64.5	75.0	63-88
<63	0.52	65.33	68.92	0.6	63.0	73.3	<63

Table 10 **7/5/10** Precip = 3.58 cm, Volume = 0.09 cm July 4 & 5 combined
St. Paul Sheep Pasture Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	12.37	1832.75	100.00	5.0	720.2	100.0	>500
250	3.52	521.13	28.43	2.8	403.9	56.1	250-500
180	1.98	293.76	16.03	2.2	314.6	43.7	180-250
125	1.84	272.84	14.89	2.1	298.2	41.4	125-180
88	1.63	241.01	13.15	1.9	275.3	38.2	88-125
63	1.49	220.67	12.04	1.8	261.3	36.3	63-88
<63	1.40	207.00	11.29	1.7	244.5	33.9	<63

Minneapolis 12th Ave. and Minnehaha Parkway Site (Tables 11 – 13)

Table 11 **8/02/10** Precip = .05 cm. Minneapolis 12th Ave. & Minnehaha Parkway Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	19.24	793.43	100.00	10.9	508.7	100.0	>500
250	9.52	392.42	49.46	8.0	371.1	73.0	250-500
180	6.47	266.95	33.64	4.9	229.4	45.1	180-250
125	5.53	227.86	28.72	3.7	172.8	34.0	125-180
88	5.11	210.78	26.57	3.3	153.4	30.2	88-125
63	4.61	190.28	23.98	2.6	123.2	24.2	63-88
<63	4.27	176.20	22.21	2.3	105.1	20.7	<63

Table 12 **8/12/10** Precip = 3.95 in. Minneapolis 12th Ave. & Minnehaha Parkway Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	8.66	962.70	100.00	5.3	531.9	100.0	>500
250	4.22	469.21	48.74	3.9	388.9	73.1	250-500
180	2.52	280.29	29.11	2.8	279.0	52.4	180-250
125	2.26	251.00	26.07	1.6	158.3	29.8	125-180
88	1.91	212.70	22.09	1.4	136.0	25.6	88-125
63	1.69	188.21	19.55	1.2	118.3	22.2	63-88
<63	1.57	174.33	18.11	1.1	106.3	20.0	<63

Table 13 **9/28/10** Precip= 0.56 cm Minneapolis 12th Ave. & Minnehaha Parkway Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	5.36	382.67	100.00	62.3	3115.7	100.0	>500
250	3.26	232.79	60.83	29.4	1472.2	47.3	250-500
180	2.21	157.89	41.26	9.5	473.0	15.2	180-250
125	1.81	129.06	33.73	3.5	174.3	5.6	125-180
88	1.45	103.68	27.09	2.3	114.4	3.7	88-125
63	1.31	93.54	24.44	1.6	78.8	2.5	63-88
<63	1.18	84.50	22.08	1.3	64.7	2.1	<63

Minneapolis Penn Ave. Site (Tables 14 – 21)

Table 14 **7/4/10** Precip = 0.05 cm Vol. ~ 0 cm July 4 & 5 combined; MPLS Penn Ave. Site

	Manufacturer Recommended Strainer			**Winged Arm Sampler**			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	2.17	255.55	100.00	2.0	234.0	100.0	>500
250	1.88	220.67	86.35	1.6	188.2	80.4	250-500
180	1.17	137.85	53.94	1.0	123.5	52.8	180-250
125	1.03	121.67	47.61	1.0	112.1	47.9	125-180
88	0.92	107.69	42.14	0.9	104.4	44.6	88-125
63	0.82	96.92	37.93	0.8	95.0	40.6	63-88
<63	0.78	91.33	35.74	0.8	90.7	38.7	<63

Table 15 **7/5/10** Precip = 0.05 cm Vol. ~ 0 cm July 4 & 5 combined; MPLS Penn Ave. Site

	Manufacturer Recommended Manifold			**Winged Arm Sampler**			
Sieve Size (mm)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (µm)
500	1.01	119.06	100.00	0.35	39.2	100.0	>500
250	0.91	107.56	90.34	0.25	28.3	72.3	250-500
180	0.86	101.49	85.24	0.20	22.6	57.6	180-250
125	0.85	100.15	84.11	0.19	21□3	54.4	125-180
88	0.84	98.32	82.58	0.18	19.6	50.0	88-125
63	0.80	94.70	79.54	0.15	16.2	41.3	63-88
<63	0.78	91.33	76.71	0.12	13.0	33.2	<63

Table 16 **7/8/10** Precip = 2.46 cm, Volume = 226 cubic feet MPLS Penn Ave. Site

	Old Manifold			**Winged Arm Sampler**			
Sieve Size (µm)	Cum□lative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (µm)
500	1.45	290.19	100.00	3.14	348.6	100.0	>500
250	0.96	191.75	66.08	2.18	241.9	69.4	250-500
180	0.63	125.59	43.28	1.39	154.7	44.4	180-250
125	0.60	119.29	41.11	1.24	137.4	39.4	125-180
88	0.54	108.11	37.26	1.09	120.6	34.6	88-125
63	0.48	96.43	33.23	1.01	112.0	32.1	63-88
<63	0.43	86.33	29.75	0.96	106.3	30.5	<63

Table 17 **7/12/10** Precip = 3.68 cm MPLS Penn Ave. Site

	Manufacturer Recommended Manifold			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	1.45	290.19	100.00	3.1	348.6	100.0	>500
250	0.96	191.75	66.08	2.2	241.9	69.4	250-500
180	0.63	125.59	43.28	1.4	154.7	44.4	180-250
125	0.60	119.29	41.11	1.2	137.4	39.4	125-180
88	0.54	108.11	37.26	1.1	120.6	34.6	88-125
63	0.48	96.43	33.23	1.0	112.0	32.1	63-88
<63	0.43	86.33	29.75	1.0	106.3	30.5	<63

Table 18 **7/27/10** Precip = .28 cm MPLS Penn Ave. Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	1.98	495.90	100.00	0.2	231.9	100.0	>500
250	1.13	281.45	56.76	0.1	185.1	79.8	250-500
180	0.58	145.28	29.30	0.1	157.1	67.7	180-250
125	0.46	114.50	23.09	0.1	138.3	59.6	125-180
88	0.29	71.70	14.46	0.1	112.4	48.5	88-125
63	0.23	57.95	11.69	0.1	91.2	39.3	63-88
<63	0.18	44.30	8.93	0.1	66.9	28.9	<63

Table 19 **7/28/10** Precip= 0.03 cm MPLS Penn Ave. Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	6.77	501.25	100.00	1.2	242.1	100.0	>500
250	3.69	273.51	54.57	1.0	197.7	81.7	250-500
180	1.47	109.11	21.77	0.8	157.1	64.9	180-250
125	1.04	77.26	15.41	0.7	141.0	58.3	125-180
88	0.81	60.27	12.02	0.6	122.7	50.7	88-125
63	0.65	48.39	9.65	0.5	98.3	40.6	63-88
<63	0.59	43.75	8.73	0.4	79.3	32.7	<63

Table 20 8/8/10 Precip= 1.22 cm MPLS Penn Ave. Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	15.30	1912.74	100.00	10.8	1541.4	100.0	>500
250	6.91	864.14	45.18	5.5	787.1	51.1	250-500
180	3.28	409.73	21.42	2.9	421.4	27.3	180-250
125	2.70	337.68	17.65	2.3	324.4	21.0	125-180
88	2.22	278.02	14.53	1.9	275.9	17.9	88-125
63	1.86	231.95	12.13	1.6	222.1	14.4	63-88
<63	1.65	205.67	10.75	1.4	197.0	12.8	<63

Table 21 **8/12/10** Precip= 10.03 cm MPLS Penn Ave. Site

	Manufacturer Recommended Strainer			Winged Arm Sampler			
Sieve Size (um)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Size Range (um)
500	0.29	116.24	100.00	2.0	280.7	100.0	>500
250	0.26	102.04	87.78	1.0	142.7	50.8	250-500
180	0.23	92.60	79.66	0.6	79.1	28.2	180-250
125	0.22	88.44	76.08	0.5	67.9	24.2	125-180
88	0.21	82.72	71.16	0.4	60.5	21.6	88-125
63	0.19	74.56	64.14	0.4	56.5	20.1	63-88
<63	0.17	67.00	57.64	0.4	52.3	18.6	<63

St. Paul Commonwealth and Transit Way Site (Table 22 only)

Table 22 **10/26/10** Precip = 2.60 cm St. Paul Commonwealth and Transit Way Site

	Manufacturer Recommended Strainer			New Manifold			
Sieve Size (mm)	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	Cumulative Mass (g)	Cum Conc. (mg/L)	Cumulative %	
500	5.56	327.18	100.00	6.5	326.7	100.0	>500
250	2.50	146.85	44.89	3.5	173.4	53.1	250-500
180	0.58	33.91	10.36	1.5	77.4	23.7	180-250
125	0.54	31.53	9.64	1.5	75.4	23.1	125-180
88	0.46	26.99	8.25	1.4	71.6	21.9	88-125
63	0.38	22.37	6.84	1.4	67.6	20.7	63-88
<63	0.33	19.67	6.01	1.3	65.3	20.0	<63

The data from all locations and all sample dates was combined to create a graph for each size range comparing sampled concentrations of both samplers. These data were fit by a least squares line without intercept for a direct comparison. These data and least squares fits are given in Figures 17 through 21.

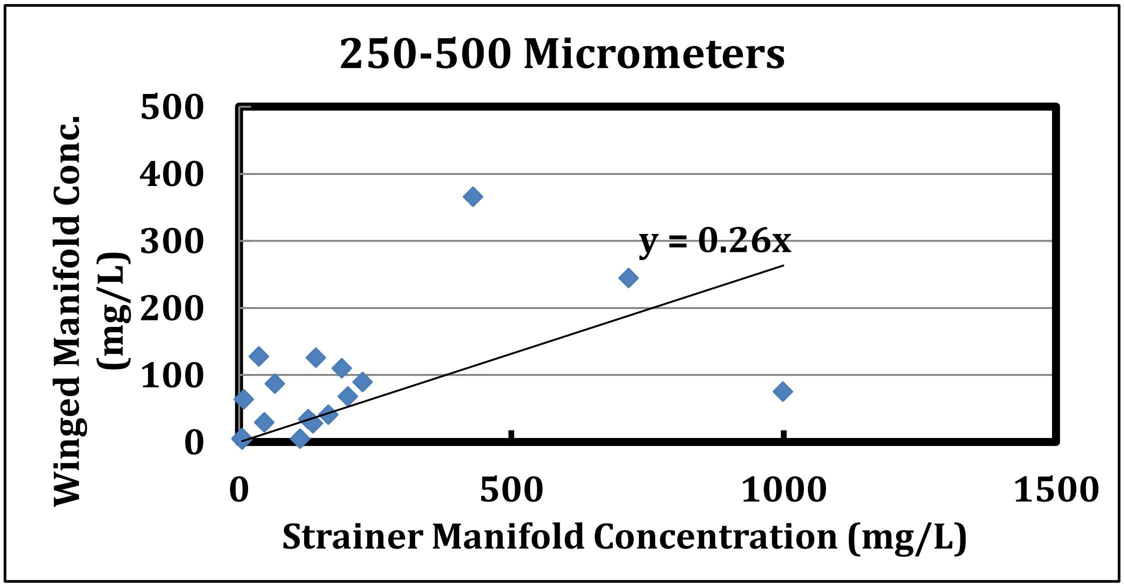

Figure 17. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles greater than 500 micrometers.

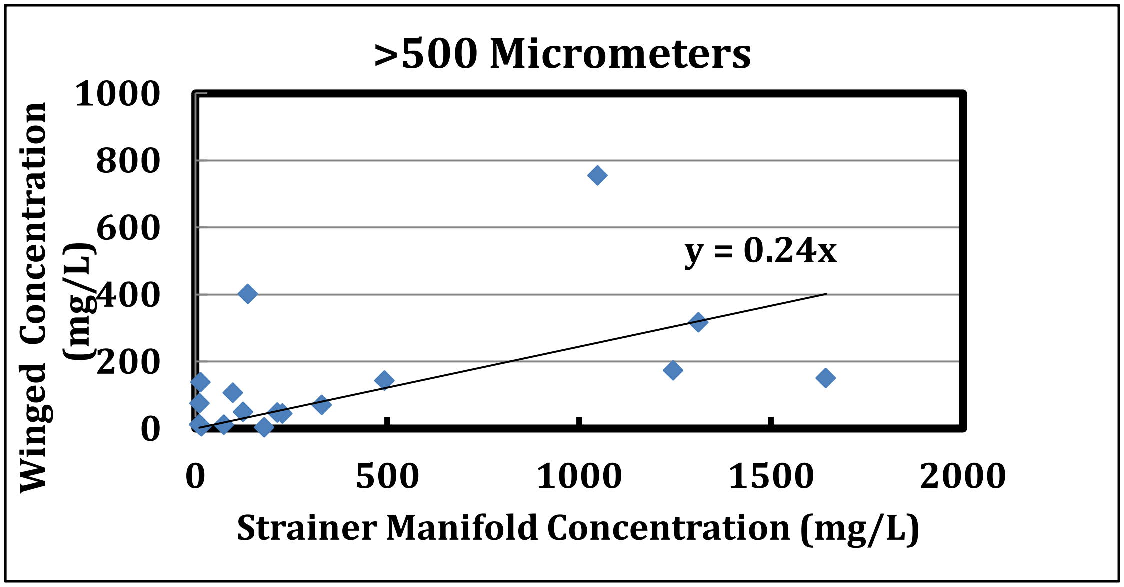

Figure 18. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles between 250 and 500 micrometers

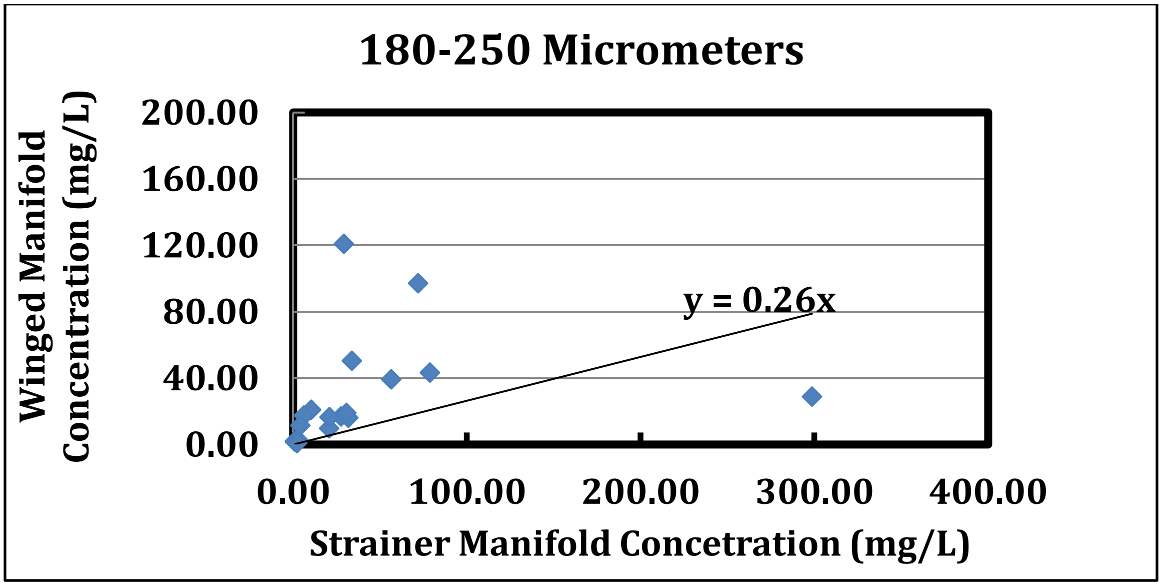

Figure 19. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles between 180 and 250 micrometers.

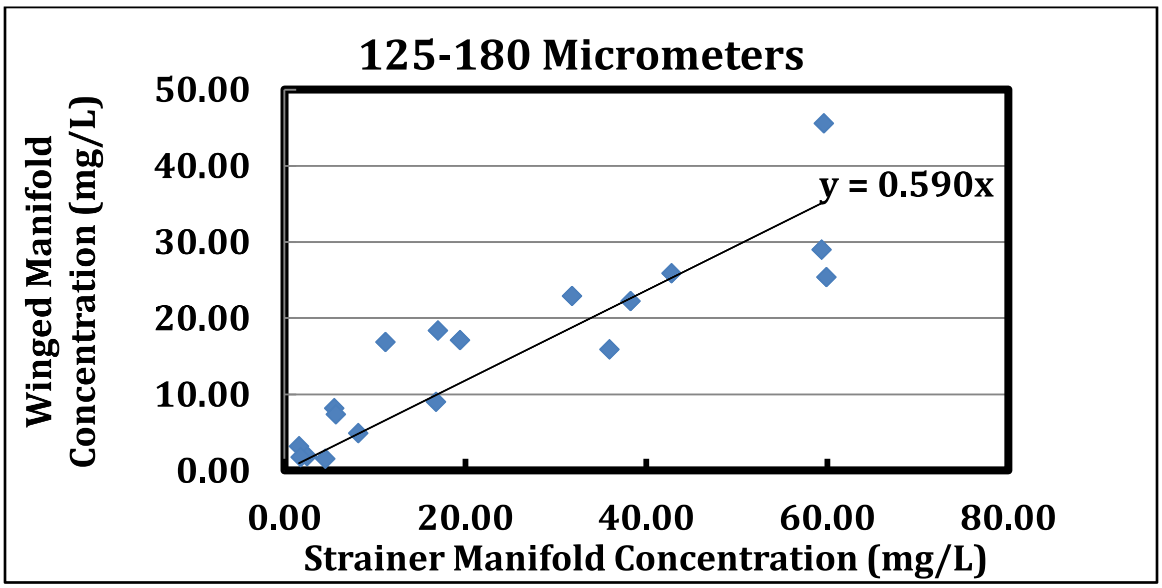

Figure 20. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles between 125 and 180 micrometers.

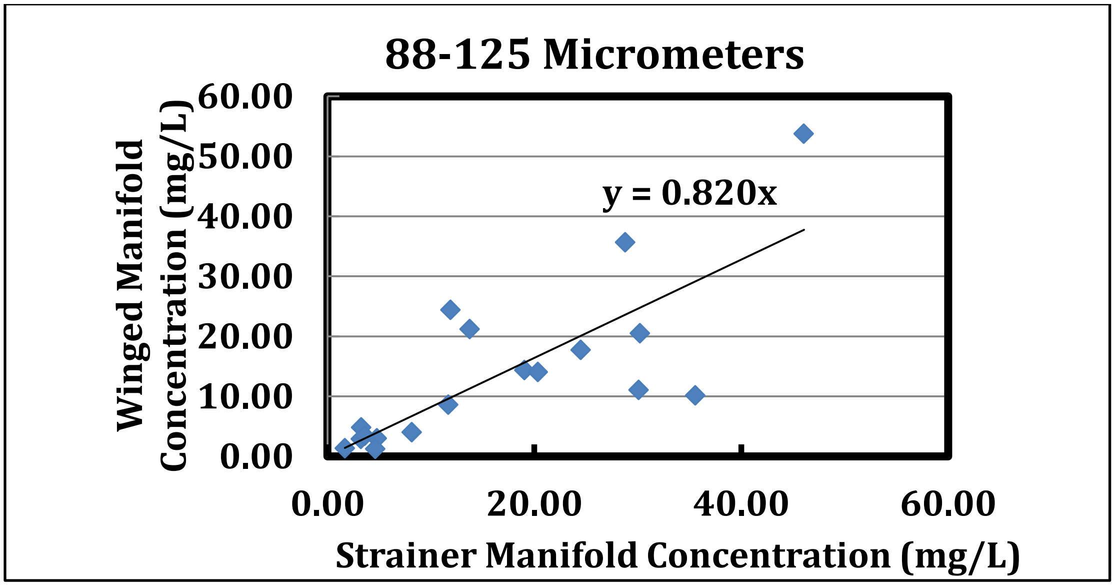

Figure 21. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles between 88 and 125 micrometers.

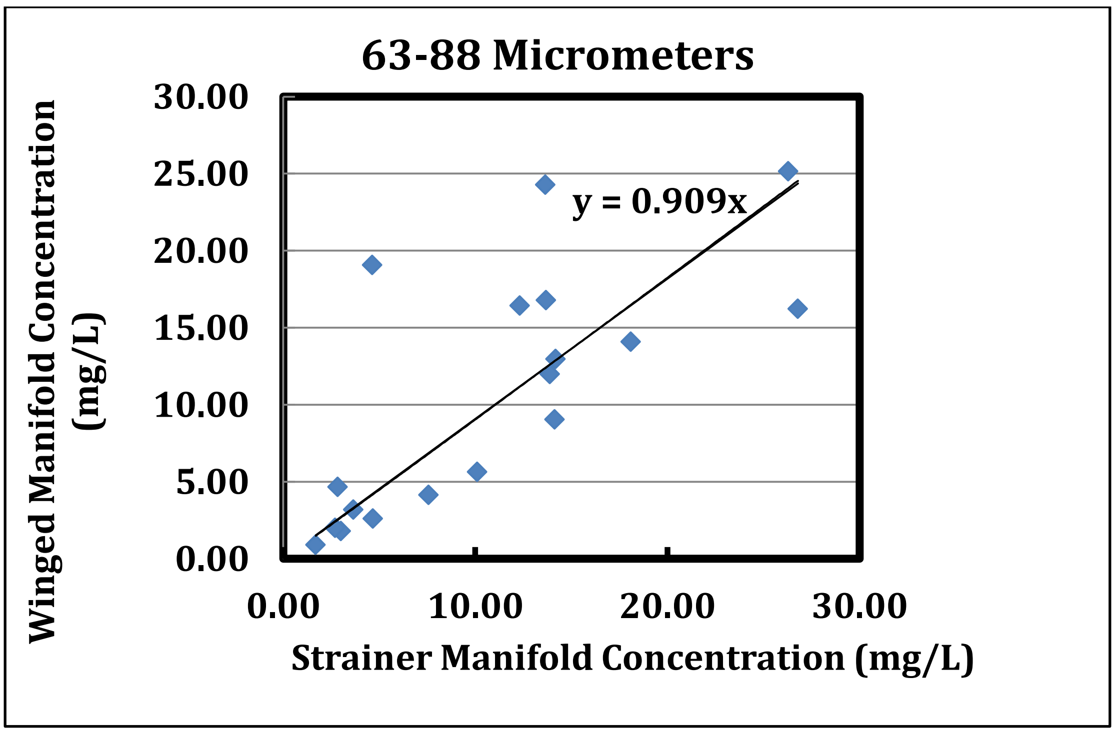

Figure 22. Concentration sampled by the winged arm versus the manufacturer-recommended manifold for particles between 63 and 88 micrometers.

Correlations of Size Distribution with Rainfall and Watershed Characteristics

Attempts were made to correlate sediment size distribution with rainfall and watershed characteristics. The St. Paul sites had a mixed road and agricultural watershed, and the Minneapolis sites had a residential usage. Both sites were approximately 50% impervious. No correlation with watershed characteristics could be discerned between the St. Paul and Minneapolis sites. Part of the reason could be that insufficient data was analyzed. When comparing monitoring data, 20 storms are not sufficient due to the uncertainty associated with each measurement. Another reason could be that the predominant factor in watershed runoff is the impervious area because only the largest storms will have substantial runoff from pervious areas. The impervious areas in the Minneapolis and St. Paul sites are similar. In fact, most impervious areas have a similar type of usage for cities. One difference in sediment size distribution could be the result of drainage from construction sites; however, none of the four watersheds had an active construction area during the monitoring.

Table 23 displays the coefficient of the equations for each size range. A general increase in slope is observed from large to small size ranges. As the particles get smaller, the concentration sampled should be approach to a 1:1 ratio, representing a y=x equation (slope of one). A slope less than 1 represents a higher concentration of larger particles sampled by the strainer manifold, and an oversampling by the strainer manifold likely causes this trend. As with all monitoring data, there is substantial scatter in the results. For that reason, the median ratio of the concentration collected by the winged arm sampler over the manufacturer-recommended manifold was also computed, as shown in Table 23. The results indicate a similar trend to the linear coefficient, where the median ratio increased as the size was reduced, until it was close to one at the smallest size range.

Table 23. Linear coefficients for fit of winged arm sampler versus manufacturer-recommended manifold samplers.

Size (um)	Linear Coefficient	Median Ratio of Winged/Strainer
>500	Y=.0.244x	0.32
250-500	Y=.0.263x	0.57
180-250	Y=0.264x	0.74
125-180	Y=0.590x	0.73
88-125	Y=0.820x	0.75
63-88	Y=0.909x	0.82

The sampled concentrations depicted in the graphs above confirm the belief that sampling from a single point in the column of water leads to an unrealistic particle size distribution of suspended particles. Since the manufacturer-recommended strainer sits on the bottom of the pipe, it tends to oversample larger particles, particularly those greater than180 micrometers, as larger particles are found in higher concentrations lower in the water column due to increased settling velocity. The winged arm sampler is assumed to be more successful in collecting a representative sample by sampling across the water column.

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 23 and 24 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 23, 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 24 both particle sizes are accurately sampled. Computing removal efficiency yields 75% for Figure 23, but only 50% for Figure 24. Accurate sampling reveals that the stormwater BMP has lower removal efficiency than established with previous sampling methods.

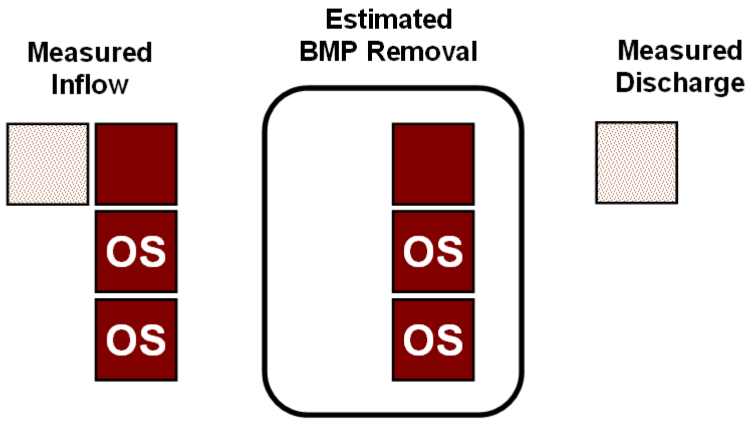

Figure 23. Inaccurate sampling yields estimated removal efficiency of 75%. Lightly shaded boxes represent small (non-settleable) particles and dark boxes represent large (settleable) particles. Oversampled mass is represented by boxes labeled "OS".

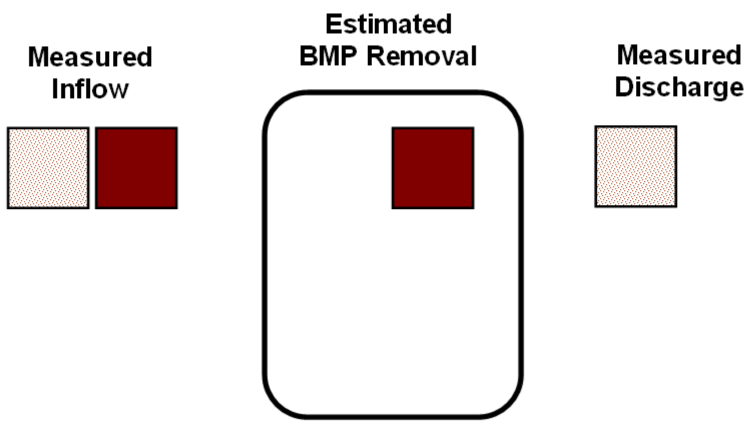

Figure 24. Accurate sampling yields estimated removal efficiency of only 50%. Lightly shaded boxes represent small (not-settleable) particles and dark boxes represent large (settleable) particles.

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 19 and 20 illustrate this example. In Figure 19 an accurate particle size distribution is used to size the settling BMP. The BMP is thus properly sized and functions as intended. In Figure 20 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.

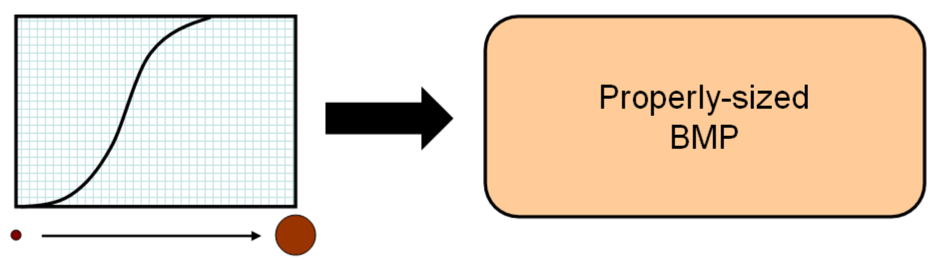

Figure 25. Accurate particle size distribution data yields properly designed settling BMP.

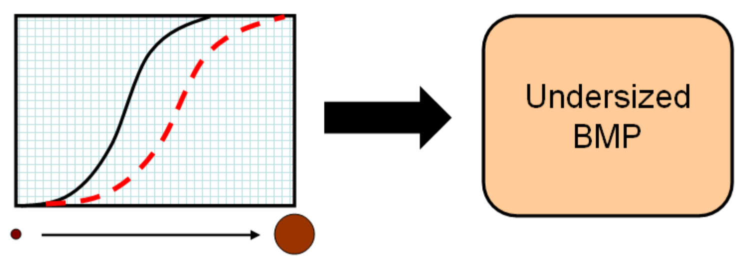

Figure 26. Inaccurate particle size distribution (due to oversampling large particles) yields undersized BMP.

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 indicated wide variations in particle size ranges. These are partially attributed to monitoring artifacts. The purpose of this 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 which 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, called a winged arm sampler, 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 winged arm sampler tested in this study shows significant sampling improvements, particularly for the sampling of larger particles. This improvement is most likely due to the ability of the arm sampler to sample across the entire column of water. By collecting samples from several points along a arm sampler, the sampler is able to collect a more representative depiction of particle concentrations in the water.

The most important parameter in determining the particle size distribution was he intensity of the storm. Other factors, like watershed usage, were difficult to correlate against particle size distribution with the quantity of data available in this study. More data, however, may be able to distinguish whether a relationship exists between particle size distribution and other parameters besides storm intensity.

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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