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Particle Size Distribution of Highway Runoff and Modification Through Stormwater Treatment

by

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CHAPTER 1 INTRODUCTION

1.1 Overview

A significant concern to regulatory agencies and to professionals in the environmental field is nonpoint source pollution. This type of pollution includes the direct or scattered sources of pollution that enter a water system through runoff from agricultural fields as well as urban areas (USGS, 2005). The continuing development of urban activities, *i.e.*, construction and traffic flow, has increased nonpoint source pollution, which promotes the degradation of the quality of the receiving water. The pollutants from these activities then adsorb onto the surface of the fine particles in the runoff. Reducing the amount of fine particles in runoff through various Best Management Practices (BMPs) before the stormwater reaches the receiving water is a typical method for decreasing the adverse impact on water bodies due to nonpoint source pollution. The treatment capabilities of BMPs can be improved by learning about the particle size distribution and particle density of these fine particles.

1.2 Regulatory Framework

Federal and state regulations dictate the handling of stormwater. The Federal Water Pollution Control Act, also known as the Clean Water Act, has significant influence on various water quality concerns. The United States Environmental Protection Agency (USEPA) created the act in 1972 that was amended in 1977. This act formulated the regulatory structure for protecting the surface waters of the United States from pollutant discharge. The regulations put in place water quality standards for all surface waters and required permits to discharge pollutants from point sources. Two sections of the Amendments to the Federal Water Pollution Control Act in 1977 are particularly relevant to highway runoff water quality issues: 303(d) and 404. Section 303(d) of the Clean Water Act declares that, every other year, each state needs to submit to the EPA a list of water bodies within its jurisdiction that do not meet their designated use and/or that are impaired by contaminants. EPA and United States Army Corps of Engineers have jurisdiction over section 404 of the Clean Water Act. This section states that an individual, agency, or company must obtain a permit before placing fill materials in the water bodies (streams, ponds, lakes, and wetlands). The permit is needed for the construction of roads and to lay pipes as well as the development of residential, commercial, and recreational sites. The purpose of the permit is to balance the protection of the water bodies with the need to use filling materials. There are three types of 404 permits: Nationwide Permit, Regional General Permit, and Individual Permit.

Investigating how pollutants are transported in highway stormwater runoff and how efficiently various Best Management Practices (BMPs) operate in treating runoff is crucial to protect ground and surface water.

1.3 Project Objectives

The objective of this project was a documentation of the size distribution and density of particles in stormwater runoff. The objective was achieved through the following approach:

- Operating monitoring devices to collect samples of runoff from bridge approach highway and bridge deck as well as collecting runoff samples from various BMPs (Austin sand filter, extended detention pond, and vegetated filter strip)

- Developing and implementing a reliable method for correctly characterizing highway stormwater runoff

- Calculating average density of particles in the stormwater runoff samples, and comparing the calculated densities to the density of sand

- Analyzing the particle removal efficiency for the stormwater BMP treatment processes

Chapter 2 examines the results of previous research dealing with particle size distribution and with the density of particles in stormwater. The technique and process used in this research to characterize stormwater runoff are described in Chapter 3, and Chapter 4 discusses the analysis of collected data. Lastly, Chapter 5 presents conclusions and an overall discussion of the key findings.

CHAPTER 2   LITERATURE REVIEW

2.1 Introduction

Stormwater runoff is a major contributor to nonpoint source pollution that leads to the deterioration of receiving waters. The particles in runoff and soluble contaminants that adsorb to surfaces of particulate material enter the water body. Urban expansion may cause new highway development and consequent increased nonpoint source pollution from runoff. Thus, urban development has led to concerns about potential declines in water quality and impacts to the health of residents (Barrett *et al.*, 1998). Therefore, research focused on the characteristics of particles in stormwater runoff as well as in the effluent of different types of Best Management Practices (BMPs) used to treat runoff is important to reduce the adverse effects of nonpoint source pollution.

Storm events mobilize particles and enable them to be washed into receiving waters. The density and the size distribution of particles affect the transport of the solids and associated pollutants (Characklis and Wiesner, 1997). Larger particles in stormwater runoff settle out, but smaller particles remain suspended in stormwater runoff and travel greater distances. In addition, decreasing particle size often is correlated with increasing surface area of the particles, allowing for more adsorption of dissolved constituents onto the surface of the particles. Thus, examining the particle size distribution of the particles in runoff aids the understanding of the transportation time of pollutants, the magnitude of the area affected, and the treatability of these particles. The properties of the particles also influence the type of treatment process that is appropriate for removal.

The pollutants on roads and, therefore, also in highway runoff is harmful to receiving waters, so it is important to know the primary sources of this nonpoint source pollution. Young *et al.* (1996) enumerated these primary sources of contaminants. A significant amount of the particulate matter in runoff stems from the wear and tear of the pavement and vehicles both from normal traffic operations and from road maintenance. Sediment disturbance and the atmosphere increase the amount of particulate matter, nitrogen, and phosphorus in highway runoff. The use of fertilizer on highway right-of-ways also impacts nitrogen and phosphorous levels in runoff. Lead and zinc found in runoff is generally produced by the following parts of automobiles: tire, lubricating oil and grease, and wheel bearings. Copper constituents in runoff generally are generated from two sources: automobiles (metal plating, bearing wear, engine parts, and brake lining wear) and chemical substances (fungicides and insecticides).

These harmful pollutants tend to adsorb onto fine sediment in highway runoff; therefore, further information about fine particles must be collected to improve the control measures and to advance the treatment and disposal of highway runoff. Sansalone and Buchberger (1997) stated that the pollutant loads of zinc, lead, and copper with a diameter smaller than 100 μm for the road runoff samples attributed to more than 50% of the cumulative pollutant loads, but only 10% of the total weight (Furumai *et al.*, 2002; Sansalone and Buchberger, 1997). Numerous early studies examined the menace of sewer overflows on receiving waters in terms of biochemical oxygen demand (BOD), total suspended solids (TSS), and total coliform counts, and other commonly studied runoff constituents are chemical oxygen demand (COD), phosphorus, nitrogen, and heavy metals (Palmer 1950, 1963; Characklis and Wiesner, 1997). However, published information about the pollutants adsorbed to the fine particles in highway runoff is limited, so to truly improve stormwater treatment processes of highway runoff, the characteristics and density of the fine particles must be explored and recorded.

2.2 Particle Size Distribution

2.2.1 Methods to Determine Particle Size Distribution

Past research has used several different methods to examine the particle size distribution of stormwater runoff. One common technique used to analyze particle size distribution of runoff is a sieving method, where the sediment is sieved through different sieve sizes to characterize the size distribution. Two methods of sieving exist: wet and dry. The liquid runoff samples are poured directly onto the sieve for the wet sieve technique, and for the dry sieve process, only the sediment from the runoff samples are poured onto the sieve. Both methods produce reliable particle size distribution results and are easy to perform on runoff samples. However, each method has its own disadvantages. Dry sieving can be time intensive if the liquid in the runoff sample must be evaporate to get the road sediment. Some of the fine particles can clump together and act as a larger particle during the evaporation step. Wet sieving, on the other hand, does not have this issue; however during the wet sieve process for the smaller sieve sizes, a mucous layer can form that clogs the sieve holes. Both methods are typically used to characterize the size distribution of the coarse particles, but they can not accurately measure the size distribution of the fine particles.

Some researchers use the sieving process for the larger particles and then use a machine to determine the size distribution of the fine particles since it is difficult to characterize the size distribution of the fine particles when using the sieving method. Different types of machines can be used for this measurement. Two types of instruments include an electrical sensing zone (ESZ) instrument and a Coulter LS 130. The ESZ instrument determines the particle size distribution by measuring the voltage flux between to electrodes caused by the particles, and the Coulter LS 130 quantify the diffraction of a parallel beam of a monochrome laser due to the particles (Andral *et al.*, 1999). More research should be conducted to evaluate these various instruments to establish the most accurate method to determining the size distribution of the fine particles.

Furumai *et al.* (2002) used solely the dry sieving technique to characterize the particle size distribution of collected highway runoff at the inlet of a retention pond in Winterthur, Switzerland. The particle size distribution was determined by sieving the sample first with a 2 mm mesh sieve to remove the large debris and then with sieve sizes ranging from 50 μm to 800 μm. TSS was also measured for each sample. The data collected supported the notion that most of the suspended solids (SS) concentration was associated with the coarser size particles.

Characklis and Wiesner (1997), however, used the electrical sensing zone instrument to explore the particle size distribution of grab samples from the Brays Bayou both before and after storm events. The Brays Bayou is located in the Houston metropolitan area, and the Fort Bend and Harris counties' stormwater drains into it. Their research supported the idea that SS concentrations of runoff increases after a storm event, and they also found an increase in number concentration of particles with a particle diameter below 2.5 μm.

Andral *et al.* (1999) used both the sieving method along with the use of the Coulter LS 130 to determine the particle size distribution for sediment captured in a catchment area off a motorway in Kerault Region, France. The most notable finding from this research was that the particles with a diameter larger than 100 μm settle out of the suspension easily; however, the particles with a diameter less than 100 μm remain in suspension. Thus, the investigators concluded that particles with a diameter less than 50 μm must be studied in order to effectively treat runoff.

Furumai *et al.* (2002), Characklis and Wiesner (1997), and Andral *et al.* (1999) were all able to determine the size distribution of particles in runoff; however, they used different techniques. Since different techniques can yield the same type of data results, it is necessary to investigate the advantages and disadvantages of each method. This method comparison should be recorded to help guide future researchers create a protocol for accurately determining particle size distributions.

2.2.2 Association of Pollutants with Particle Size

Researchers have been examining which particle size range needs to be targeted when designing stormwater treatment systems since the 1970's, so determining the particle size distribution of sediment in highway runoff will enable researchers to then go a step further by associating pollutants with particular particle sizes. Numerous research studies have shown that the treatment systems must be able to effectively remove fine particles in runoff to significantly reduce the pollutant loads. Research on this subject has supported the idea that the urban dust and dirt in the small particle size range is correlated with the higher concentrations of pollutants, *i.e.*, heavy metals (Pitt and Amy, 1973; Woodward-Clyde, 1994; Vaze and Chiew, 2004). The data showed that 75% heavy metal found on road sediment were associated with a particle diameter below 500 μm, and approximately half of the heavy metal found on road sediment was adsorbed on particles with a diameter between 60 μm to 200 μm. High concentrations of copper, zinc, and phosphorus were found on sediment with a particle diameter between 74 μm and 250 μm (Dempsey *et al.*, 1993; Vaze and Chiew, 2004). Characklis and Wiesner (1997) found that particles with a particle diameter below 2.5 μm did not account for a large portion of the total mass; however, it impacted the total surface area, allowing for more pollutants to adsorb onto the surface of the particles. Thus, the concentration of metal, zinc for example, in terms of total percent of stormwater solid mass increased as the particle size decreases. Metals, like zinc and iron, may not be effectively treated with sedimentation, which only removes larger particles efficiently.

Vaze and Chiew (2004) concluded that treatment systems must reduce fine particles in runoff, but they stated that it is necessary to remove particles that are larger than 53 μm, but preferably 11 μm, in order to decrease the amount of particulate matter that has total phosphorus (TP) and total nitrogen (TN) adsorbed onto it. This conclusion was based on their research project in Melbourne, Australia. Dry solids as well as stormwater grab samples were collected from a street that had an average traffic volume of 3,000 vehicles/day. The perpendicular street had an average traffic volume of 30,000 vehicles/day. Once dry and stormwater samples were collected, their nutrient loads were analyzed. More TN was adsorbed to the fine sediment in the stormwater samples compared to the wet sieved samples. Twenty to fifty percent of TN was dissolved in the stormwater grab samples. However, the amount of TP dissolved in the stormwater and wet sieved samples were similar. More than 60% of the TP was attached to sediment with a diameter between 11 μm and 150 μm, and 40-50% of the attached TP was adsorbed onto particles with a diameter between 11 μm and 53 μm. Similar to TP, the majority of the TN was attached to particles in the size range of 11 μm to 150 μm. However, only a small amount of TP and TN adsorbed onto particles with a diameter between 4.5 μm and 11 μm. Thus, these investigators concluded that treatment facilities should be designed to remove particles with a diameter greater than 11 μm. Overall, previous studies support the idea that it is crucial to remove the fine particles in stormwater runoff in order to reduce the pollutant concentrations.

2.3 Density of Particles in Stormwater Runoff

Knowing the density of particles in stormwater runoff is critical because the density impacts the water quality. The particle density also influences the behavior in advective transport, sedimentation, filtration, coagulation/flocculation, and reentrainment. Frequently, the density of particles is considered to be equivalent to the density of sand, which is 2.65 g/cm^3, and the actual particle density is seldom determined in terms of a function of particle diameter (Allen, 1990; Cristina *et al.*, 2001). Many treatment designs, such as those for highway runoff settling basins, are developed by using the concept of minimum trapping efficiency. This trapping efficiency is related to the settling velocities of the particles, which are strongly influenced by particle density (Cristina *et al.*, 2001).

Cristina *et al.* (2001) investigated the particle size distribution and density of anthropogenic particulate matter carried in highway snow and snowmelt in Cincinnati, Ohio. The particle size distribution was determined by using the common method of dry sieving. The sieve sizes ranged from 25-4750 μm. A hydrometer was then employed to analyze the particles with a diameter less than 75 μm. The density was measured using an inert gas pycnometer. The inert gas was an ultra-high pure He. The mean density values of the coarse and fine particulate matter were 2.86 g/cm^3 and 2.75 g/cm^3, respectively.

Sansalone and Triboullard (1999) also studied sediment on Cincinnati roads using similar particle size distribution methods and density analysis as Cristina *et al.* (2001); however, their research examined the particulate matter accumulated on the pavement of highways instead of snowmelt runoff. This particulate matter would be mobile once a storm event occurred. The sediment was collected by using a conventional wet-dry vacuuming technique. The large particles were easier recovered compared to the fine particles because the small particles got caught in the cracks and joints of the pavement. The densities ranged from 2.70 to 3.01 g/cm^3 for the sediment found for all gradations, and the larger densities were associated with the particles in the size range of 850 to 1400 μm. The data suggested that the fine particles, such as tire material, were deposited beyond the pavement and shoulder areas because the abraded tires possess a density between 1.5-1.7 g/cm^3 with a particle diameter less than 20 μm (Kobriger and Geinopolos, 1984; Sansalone and Triboullard, 1999). Sansalone and Triboullard (1999) also stated that abraded vehicular matter has a larger range in density and particle diameter. The density and particle diameter range are 1.6-4.0 g/cm^3 and 1-104 μm, respectively. Thus, the densities of the road sediment seemed to be affected by the abraded vehicular matter when looking at the magnitude of the density values.

Kobriger and Geinopolos (1984) stated that vehicular-infrastructure abrasion is the primary source of particulate matter, which was supported by Sansalone and Triboullard (1999). Vehicular-infrastructure abrasion includes tire-pavement interaction as well as abrasion between metallic vehicular parts. The abraded pavement accounts for 40-50% of the total particulate mass, and abraded tires account for 20-30% of the total particulate mass. Thus, previous research implied that the particulate matter on highways was primarily inorganic due to the fact that organic materials have a lower density values compared to the values that were recorded.

Exploring how the density of road sediment and snowmelt compares to the density of particles in stormwater runoff would be a significant advancement to the stormwater treatment field, since these data could improve the design of the treatment systems. Evaluating the data variance between the usage of an inert gas pycnometer and a Coulter Counter for density measurements would also add insight to the field. Currently, a limited amount of data exists on the density of particles in stormwater runoff and how it varies between storm events. A summary of the recorded density values of highway particulate matter is displayed in Table 2.1.

Table 2.1 Summary of Reported Sediment Density Values

Reference	Location	Source	Density (g/cm^3)
Cristina *et al.*, 2001	Cincinnati, OH	Snowmelt: Coarse Fraction	2.86
Cristina *et al.*, 2001	Cincinnati, OH	Snowmelt: Fine Fraction	2.75
Jacopin *et al.*, 1999	Bordeax, France	Detention Basin: stormwater sewer	2.20 & 2.27
Jacopin *et al.*, 1999	Bordeax, France	Detention Basin: combined sewer	2.24
Bachoc, 1992; Referenced by Jacopin *et al.*, 1999	France	Stormwater sewers	2.19-2.56
Bulter *et al.*, 1992	London, England	Street Surface Sediment	2.10-2.51
Zanders, 2004	Hamilton, New Zealand	Road Sediment	2.14 (d_p<32μm)
Zanders, 2004	Hamilton, New Zealand	Road Sediment	2.15 (32<d_p<63μm)
Arthur and Ashley, 1998	Dundee, Scotland	Inorganic Particles: combined sewer	1.000-1.998 (9<d_p<1100μm)
Fan *et al.*, 2003	-	Sewer Sediment	2.4-2.6 (40<d_p<900μm)
Li *et. al.,* in press, a	Los Angeles, California	Highway Runoff	1.30-1.42* (d_p<0.45μm)
Allen, 1990; Cristina *et al.*, 2001	-	Sand (Typically assumed runoff density)	2.65
Cristina *et al.*, 2001	-	Typical Highly Organic Solids	1.1

* Wet Specific Gravity

The data in the table illustrate that the particle density in runoff ranged from 1.00-2.86 g/cm^3. The snowmelt density was slightly larger than the density of road sediment, street surface sediment, and detention basin samples. Also, the smaller particle range had a lower density compared to the samples that incorporated the small, medium, and large particle size ranges in the density measurements.

2.4 Particle Treatment

Particle treatment plays a vital role in removing pollutants from highway runoff. Various Best Management Practices are commonly used to treat stormwater runoff; therefore, optimizing their treatment efficiency is crucial. These treatment systems include detention basins, sand filters, ponds, wetlands, and vegetated controls. Kang *et al.* (2005) stated that it is important that BMPs operate efficiently with minimal supervision. BMPs must also be able to manage a variation in pollutant concentration and flow rate. Rainfall characteristics, daily traffic flow, and period of dry days affect the characteristics of the runoff. Details about extended detention ponds, vegetated filter strips, and Austin sand filters are presented in this section.

2.4.1 Extended Detention Pond

Extended detention ponds are a widely used type of Best Management Practice for pollution reduction. They treat the stormwater by a sedimentation process; thus the particles settle to the bottom of the pond over time. The detention pond temporarily holds the water for a storm event with a minimum detention time of 24 hr. Longer detention times increase the amount of particulate matter that settles to the bed of the pond, which enhances the particle removal efficiency. They are also easy to integrate into multi-chamber stormwater treatment systems (Connecticut Stormwater Quality Manual, 2004).

Jacopin *et al.* (1999) examined the particle removal efficiencies of detention tanks in Bordeaux, France as a method to effectively treat runoff. This research studied two detention ponds: Perinot (underground, off-line, combined sewer system) and Bourgailh (grassed sides and bottom, separate stormwater sewer system). The combined sewer system (Perinot) captured a larger amount of organic particulate matter compared to the separate stormwater sewer system (Bourgailh). In addition, the percentage of fine particles increased when the basin was filled more frequently; however, the size distribution of the collected particles from the detention pond traps still varied. The number percent of particles with a diameter below 100 μm varied between 58% and 91%, and the median diameter range was 22 μm to 75 μm. The size of the particles was correlated to two factors: the characteristic of the runoff and the trap submersion depth when the basin was filled during a storm event. The solids that settled out of the runoff formed a deposit layer on the bottom of the basin; fortunately, the migration of the pollutants, including hydrocarbons and heavy metals, into the soil was only limited to the superficial layer of soil (0 cm to 10 cm). Jacopin *et al.* concluded that the detention basins have the potential to treat fine particles if they are operated and designed properly.

2.4.2 Vegetated Filter Strips

Vegetative controls are effective treatment processes for removing pollutants from highway runoff. They are also adaptable to site conditions and are one of the least expensive techniques for handling highway runoff (Dorman *et al.*, 1996). One commonly used type of vegetative control is vegetated filter strips, also known as buffer strips. The stormwater is treated as the filter strips receives the highway runoff as overland sheet flow (Barrett *et al*., 2004). The primary mechanisms that vegetated filter strips use to treat highway runoff are sedimentation, adsorption, infiltration into the soil, and biological/chemical activity of the grass and soil media. This type of BMP is designed with relatively smooth and dense vegetation areas with moderate slope, which is typically less than 5% (Young *et al.,* 1996; Barrett *et al*., 2004).

Vegetated filter strips, like all BMPs, have both advantages and disadvantages. Zanders (2005) stated that vegetated filter strips decreased the amount of pollutant accumulation that can lead to pollutant loads in stormwater compared to kerb and gutter systems (Zanders, 2005). Barrett *et al.* (2004) also verified that this type of BMP was effective at pollutant removal for highway runoff. They concluded that vegetated filter strips were consistently effective at decreasing the suspended solid and total metal concentrations in highway runoff. This BMP also reduced the dissolved metal concentration when the edge of pavement concentration was high. However, the buffer strips did not treat the nitrogen and phosphorus in the runoff, and the concentration of organic carbon and of dissolved solids actually increased as the stormwater flowed along the grassy strips. If the vegetation coverage of the buffer strips was below 80%, the performance of the BMP reduced drastically (Barrett *et al.*, 2004). Another debatable issue deals with small particle removal efficiencies because fine particles tended to have densities below 2.2 g/cm^3, which reduces the predicted trapping efficiencies. In addition, these fine sediment particles may enter the BMP through aerial deposition instead of stormwater runoff (Zanders, 2005). Both the advantages and disadvantages of vegetated filter strips should be considered before implementing this type of BMP on site; therefore, gaining more information about buffer strips ability to treat fine particles in runoff allows the designer to make a more informed decision.

2.4.3 Austin Sand Filters

Austin sand filters are another example of a commonly used BMP to treat highway runoff. This type of BMP consists of two to three different chambers. The first chamber is a sedimentation basin, also known as an extended detention basin. The heavy sediment settles out of the stormwater in this section. The sedimentation basin is followed by a filtration chamber, where the stormwater percolates through a sand bed. Next, the water flows through a discharge chamber to either a storm drainage system or surface water. Figure 2.1 displays the typical design of an Austin sand filter.

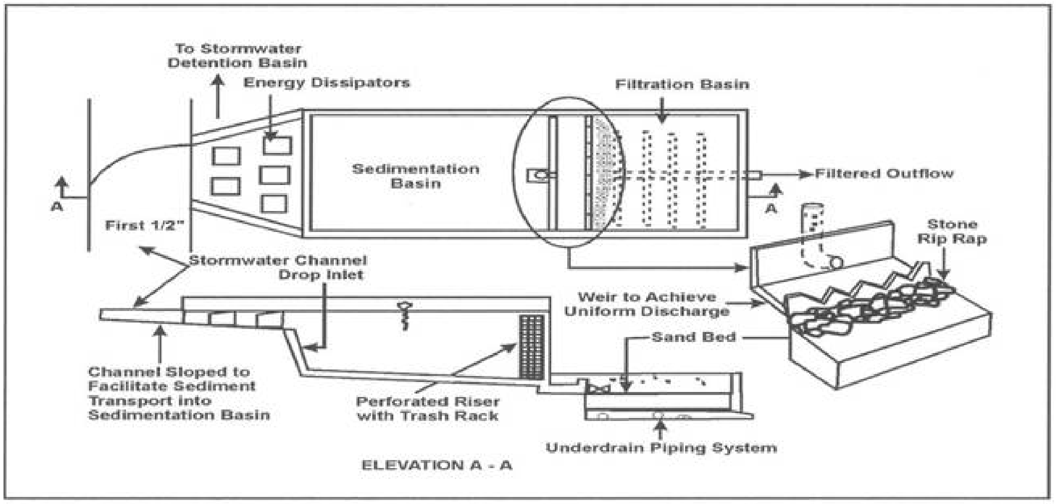

Figure 2.1 Typical Austin Sand Filter (Shaver, 1991; USEPA, 1999)

Austin sand filters are beneficial because they can be installed in highly developed sites. They also effectively reduce sediment, biochemical oxygen demand, and fecal coliform bacteria concentrations (USEPA, 1999). A study by Barrett (2003) showed that the effluent concentration of the discharge from the Austin sand filter was independent of the influent runoff concentration. Therefore, the system consistently decreased the TSS of the runoff to 7.8 mg/L. Unfortunately, Austin sand filters can be limited to climate condition because it has not been proven yet that this BMP can efficiently operate in cold weather where freezing may occur. Austin sand filters can only handle small drainage area, and other BMPs may cost less than an Austin sand filter (USEPA, 1999). The Austin sand filter can effectively treat stormwater runoff; however, it is important to weigh the advantages and disadvantages of each BMP when choosing which one to implement at a particular site.

2.5 Summary

Additional work needs to be conducted to gain information about the treatability of the fine particles in stormwater runoff by various types of Best Management Practices. The fine particles possess a large surface area, which enables pollutants to adsorb onto them. Learning more about the size distribution of particles in runoff helps researchers to understand the characteristics of highway runoff. Thus, correlating size distribution of particles with suspended sediment concentration would lead to more information about the density of the particles in highway runoff. Estimating the density of particles in highway stormwater runoff is crucial when designing and operating BMPs because most BMPs incorporate the sedimentation process, which is influenced by particle density. These density values need to be published and recorded to make advancements in designing stormwater treatment processes.

CHAPTER 3 MATERIALS AND METHODS

3.1 Overview

This study examined the characteristics of stormwater runoff. The particle size distribution and suspended sediment concentration were measured for each collected runoff sample, and then the average particle density was calculated. The runoff samples were collected from five sites throughout Austin, TX.

The locations of all of the sites are shown in Figure 3.1. Four of the sites were located on Loop 360, which is a 14-mile state highway located on the western side of Austin; it is also know as the Capital of Texas Highway. It extends from the south side of Austin near the Barton Creek/Mopac area to the north side at Highway 183. Two adjacent filter strip sites were located on the northbound shoulder at 1905 South Loop 360, which is north of the Loop 360 and Loop 1 intersection. The bridge deck site was located one mile east of Loop 1 and west of South Lamar Blvd. on Loop 360. The bridge approach highway site was the stretch of the Loop 360 highway from the bridge deck site to the peak of the South Lamar overpass. A full sedimentation sand filter was in place at this site. Another sand filter was located on Anderson Mill Road near Parmer Lane, but because of design and construction flaws it is operated as an extended detention basin.

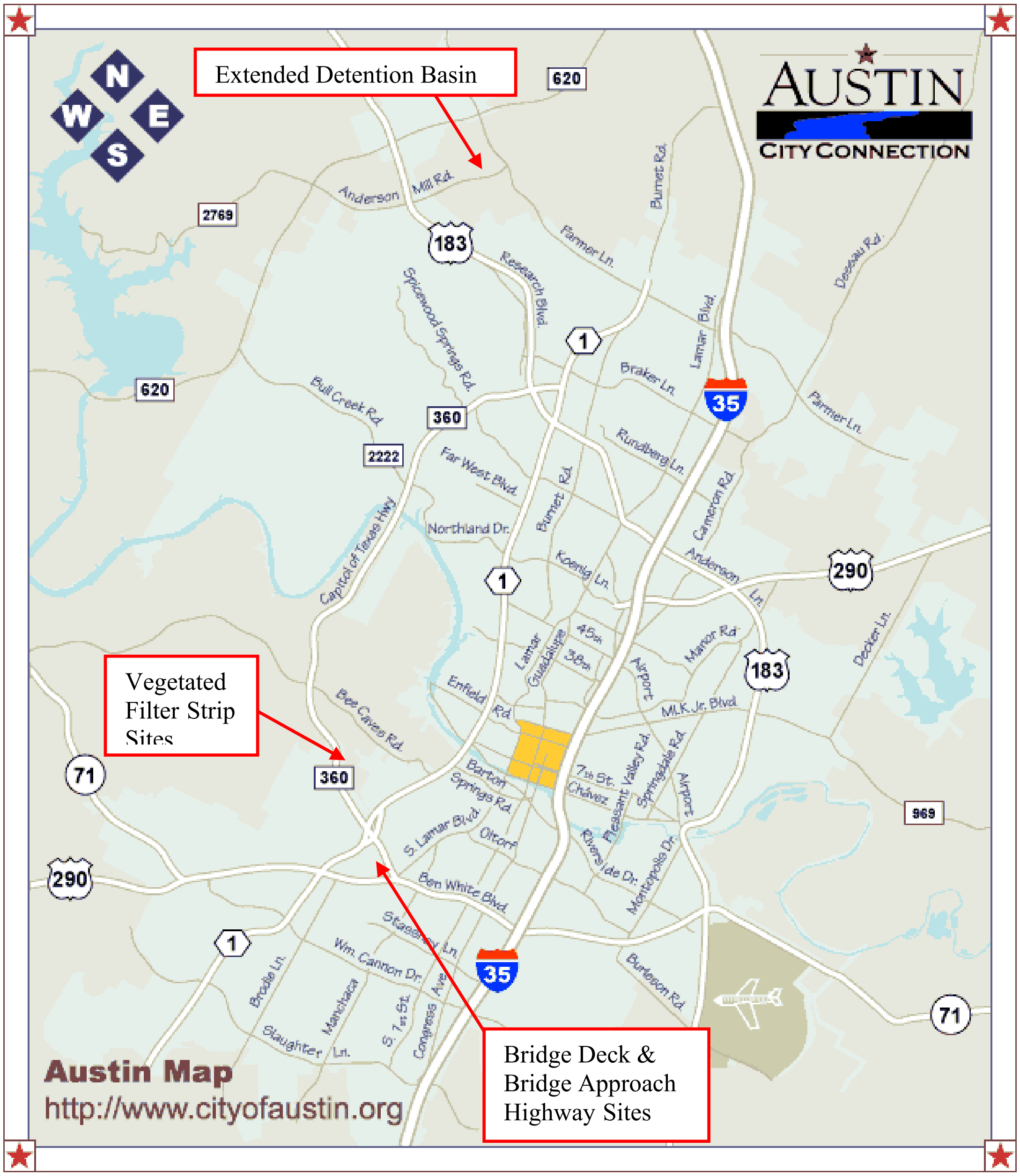

Figure 3.1 Map of Austin with Site Locations (Austin City Connection, 2005)

3.2 Subdivision of Runoff Samples

The stormwater samples were collected and brought to the laboratory within 24 hours after a storm event. These samples were immediately placed into a 4°C refrigerator until they were subdivided. Each sample was split by using a Dekaport Cone Sample Splitter (Rickly Hydrological Company, http://www.rickly.com/sai/dekaport.htm), which is displayed in Figure 3.2.

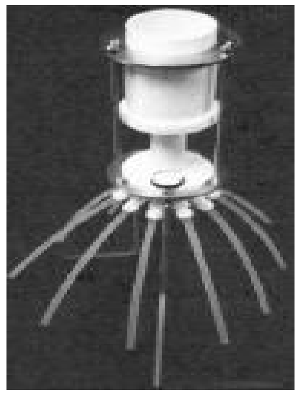

Figure 3.2 Photograph of a Dekaport Cone Sample Splitter (Rickly Hydrological Company, 2004)

The sample splitter is designed to overcome the issue of dividing the main sample into representative sub-samples. It is difficult to split the main sample because it contains sand, grit, and other large particles which are all highly settleable. This splitter has a cone that is 26 in deep with a diameter of 4 in. Filling the cone to the top with the water sample is important to maintain a substantial head above the exit, and it allows the head loss to be equal in all of the tubes, which enables the sample to be divided evenly. The problem with the rapid settling particles is overcome when the entire sample is poured through the splitter. It is vital to note that proper operation of the sample splitter is required so that the main sample is divided into representative sub-samples.

The sample splitter was used to divide the main stormwater sample into ten sub-samples with relatively equal volumes and concentration of suspended particles. If the sample was between 5 L and 10 L, each tube of the cone splitter was connected to a 1 L bottle; however, if the sample was less than 5 L, two adjacent of the tubes were connected to each of five 1 L bottles. In the rare instance that the sample was larger than 10 L, the first and last 5 L of the sample were poured through the cone splitter. In all cases, two of the sub-divided samples were then poured back into the cone splitter with each tube connected to a 250 mL bottle. Double splitting the samples was necessary because the SSC work needed to use runoff samples that were approximately 200 mL. The sub-divided samples were then placed back into the 4˚C refrigerator until they were needed for analysis.

3. 3 Solid Concentration Measurements

3.3.1 Comparing TSS and SSC

The first step in creating an experimental protocol to calculate the particle density in runoff was to determine the best technique for measuring the suspended solids concentration: total suspended solids (TSS) or suspended sediment concentration (SSC). These two measures are performed quite similarly. In both cases, a know volume of the sample is passed through a standard filter paper. This filter is dried at 105˚C, brought to room temperature in a desiccator, and weighed both before and after the sample is filtered. The difference in the weight of the two measurements is the mass of sediment captured on the filter. The difference in the two measurements is in how the sample to be measured is obtained. The sub-sample is taken from the suspension with a pipette and then is dispensed onto filter paper to gather the sediment for TSS (Standard Methods, 1995). For SSC, the whole sample is poured onto the filter paper to catch the sediment (Gray, 2000). The reason that the SSC technique is considered by many to be the preferred method for runoff samples is that it is difficult to get a representative sample into a pipette. The stormwater runoff samples have particles with high settling velocities. These particles settle rapidly to the bottom of the container, so it is difficult for them to be pulled up by the pipette.

Experiments were performed using SIL-CO-SIL suspensions to establish which technique would best determine the sediment concentration of the stormwater runoff. SIL-CO-SIL is ground pure silica. It is an inert, white, low moisture substance that is at least 99.4% SiO_2. SIL-CO-SIL 49 was used in these experiments, where the number means that approximately 98% by weight of the particles are less than 49 μm in diameter (U.S. Silica, 1998). Known concentrations of SIL-CO-SIL suspensions were made; and then, both TSS and SSC measurements were made on these suspensions. Table 3.1 displays the TSS and SCC for the known concentrations of the SIL-CO-SIL suspensions.

Table 3.1 Comparison of Known Concentrations of SIL-CO-SIL Suspensions and their Corresponding TSS and SSC

Concentration (mg/L)	SSC (mg/L)	TSS (mg/L)
500	494	283*
100	79	36*

* represents the average TSS

The SSC for the 500 mg/L SIL-CO-SIL suspension was close to the actual concentration of the suspension. However, the SSC for the 100 mg/L suspension was lower than the expected concentration of the suspension. It is important to note that the 100 mg/L suspension was made by diluting a 500 mg/L suspension using a pipette method. If the pipette method is biased against the large particles, which seems to be a valid conclusion, the actual concentration of the 100 mg/L SIL-CO-SIL suspension could have been lower than desired. The TSSs were all lower than the actual concentration of the suspensions. The TSS results supported the notion that the pipette process, which was used in TSS, was partial against the large particles in a suspension because these particles had significant settling velocities. It was difficult for these large particles to turn 180º to be pulled into the pipette. The data collected in this experiment supported U.S. Geological Survey's (USGS) belief that SSC is a more accurate measurement of suspended sediment concentration than TSS (Gray, 2000). For this reason, the SSC technique was used to measure the suspended solids concentration in this research.

3.3.2 Sieving Sub-samples

The runoff sub-samples were wet-sieved before SSC measurements were made to determine the mass of particles between certain diameter ranges. For each runoff sample collected, one sub-sample was sieved through a 75 μm sieve, and another sub-sample was poured through a 125 μm sieve. For some of the runoff samples, a sub-sample was also sieved through a 105 μm sieve, but the dry particle mass difference between the samples sieved through a 105 μm sieve and a 75 μm was small. There also was only a small difference in the solids content of samples sieved through 105 μm and 125 μm sieves, so, the 105 μm sieve was eliminated from the process. The wet-sieving set-up is illustrated in Figure 3.3.

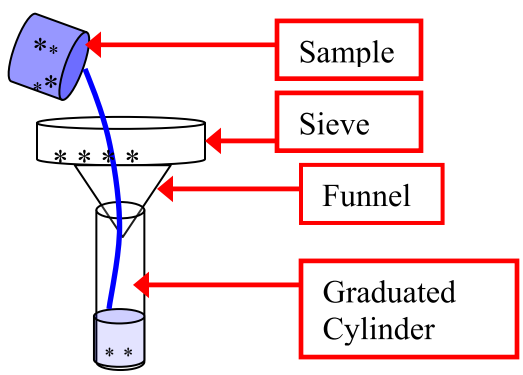

Figure 3.3 Experimental Setup for Sieving the Samples

The sieve was placed on top of a plastic funnel, which was attached to a graduated cylinder. The graduated cylinder was tested to make sure that its volume was accurate before it was used. The sample was mixed in its container, and then the entire sample was poured onto the sieve. The water/sediment suspension that passed through the sieve was captured in the graduated cylinder, where its volume was measured. Once the volume was recorded, Millipore water was used to rinse any remaining particles out of the container onto the sieve. Millipore water was also poured on the sieve to make sure that none of the particles with a diameter smaller than the sieve size remained on the sieve. The sample was then ready for the suspended solids work.

3.3.3 SSC Measurements

SSC measurements were made on the collected runoff samples. The SSCs were determined for particles with a diameter less than 75 μm, less than 125 μm, and for all of the particles in sample. The procedures followed were similar to the procedures described in ASTM's Method D 3977-97 (ASTM, 2002):

1. Place a vacuum filter apparatus on a flask with a side nozzle, which is attached to the laboratory vacuum by a plastic tube
2. Insert a Whatman 934-AH microfiber filter paper into the vacuum filter apparatus
3. Rinse the filter paper with approximately 200 mL of Millipore water to remove dissolved solids on the paper; discard the water
4. Place the filter paper in an aluminum weighing container and set it in a desiccator
5. Transfer the filter paper and container to a 105°C oven for 60 min (For volatile suspended solids (VSS), ignite for 15 mins in a 550°C oven)
6. Set the filter paper and container in a desiccator for 30 min, while the items cool to room temperature
7. Measure the mass of the filter paper and the container
8. Reinsert the clean filter paper into the vacuum apparatus
9. Shake and pour an entire runoff sample with a known volume onto that filter paper
10. Rinse the sample container with Millipore water and pour the water onto the filter paper
11. Place the filter paper and collected sediment back onto the aluminum container in a desiccator

12. Put the filter paper/container back in a 105°C oven for 60 min (For VSS, ignite for 20 mins in a 550°C oven)
13. Remove these items and set them in a desiccator for 30 min
14. Weigh the items

The initial mass of the filter paper, the mass of the filter paper/sediment, and the volume of the sample were needed to solve for SSC. Equation 3.1 is the formula used to solve for this value.

$$SSC\left(\frac{mg}{L}\right)=\frac{\left[X_{fp+r}(g)-X_{fp}(g)\right]*\left[10^{3}\left(\frac{mg}{g}\right)\right]*\left[10^{3}\left(\frac{mL}{L}\right)\right]}{V_{s}(mL)} \qquad \textbf{Equation 3.1}$$

In the equation, X_{fp+r} is the mass of the filter paper plus residue, X_{fp} is the initial mass of the filter paper, and V_s is the volume of the sub-sample.

3. 4 Coulter Counter Measurements

3.4.1 Coulter Counter Description

A Beckman Coulter Multisizer 3 was used to measure the particle size and the particle count distributions of the runoff samples for this research; a picture of the instrument is in Figure 3.4, along with a schematic of the central measuring zone. This technology is based on the electrical sensing zone principle (ESZ). A steady electrical current is maintained between two electrodes, one inside an aperture tube and the other immersed in the sample being measured. The suspension is pulled through an aperture at a steady rate. As each particle is pulled through the small aperture, it increases the resistance between the electrodes. This resistance changes the voltage between the electrodes. The voltage fluctuation is proportional to the volume of the particle. The sorting of the voltage pulses into size bins yields the number concentration of particles in a large number of size increments, *i.e.*, the particle size distribution. The Beckman Coulter Multisizer 3 can size and count particles in the size range of 0.4 to 1200 μm.

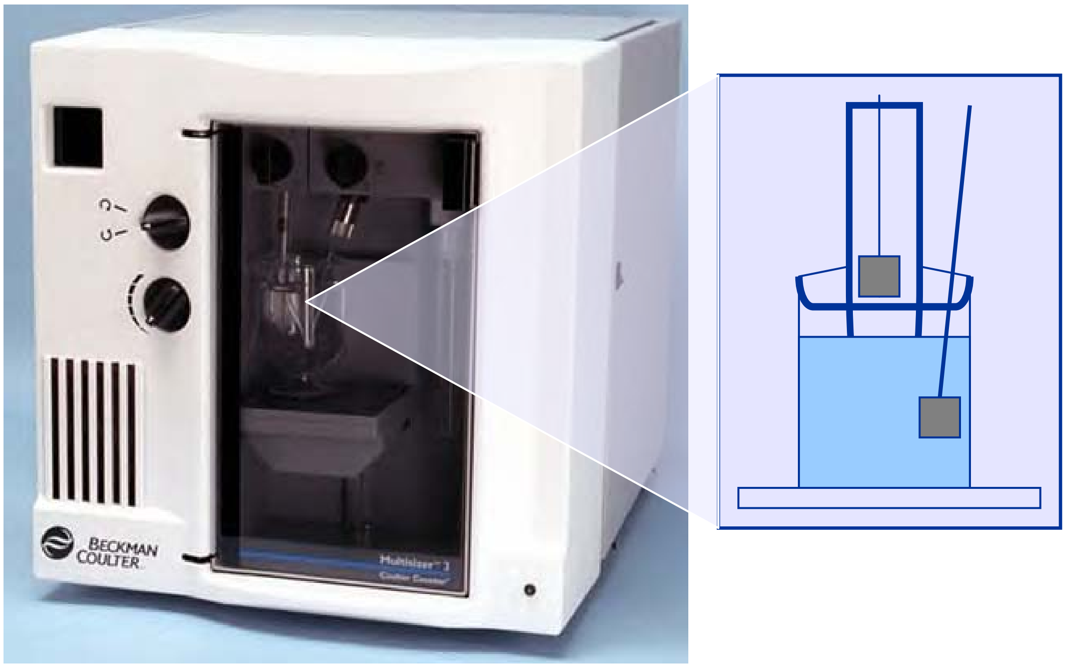

Figure 3.4 Photograph of the Beckman Coulter Multisizer 3

The Coulter Counter is operated through a PC by running the Beckman Coulter's Multisizer 3 software. The raw data were displayed immediately on the computer screen since the technology used digital pulse measurements. The data were saved to a disk for further processing. The collected data were then exported to an Excel file to convert the results into the number distribution, volume distribution, and particle size distribution function. Refer to the Beckman Coulter's Multisizer 3 operation's manual for more detailed information about the Coulter Counter (Multisizer 3 Operator's Manual, 2002).

3.4.2 Sample Preparation for the Coulter Counter

Diluting the runoff sample with an electrolyte solution was necessary when measuring the particles in a runoff sample on the Coulter Counter. The Coulter Counter could not measure the sample directly because the stormwater samples were too concentrated for the machine. At the same time, it is necessary to have enough of the stormwater sample measured by the Coulter Counter because high conductance solution is needed for the electrical sensing to work. Thus, mixing the appropriate proportion of sample and electrolyte solution to get a particle count in the count range for the aperture tube used was essential. The desired count range for each aperture size is shown in Table 3.2.

Table 3.2 Desired Count Range in Relationship to Aperture Size

Aperture Size (μm)	Particle Size* (μm)	Desired Count Range (#/μL)
30	$d_p < 30\ \mu$m	200 - 360
100	$d_p < 100\ \mu$m	55 - 80
400	$d_p < 400\ \mu$m	0.15 - 0.23

* It is important to note that the each aperture can technically have particles with a diameter below the aperture size pass through the aperture hole; however, if the particle diameter is above 75 μm, the settling velocity will be so great that the particle will settle to the bottom of the container instead of passing through the aperture.

Making sure that the mixture of electrolyte solution and runoff sample was within the desired count range was an integral part of the Coulter Counter work. If the suspension was too concentrated, the Coulter Counter could have counted several little particles as one large particle or the aperture hole would have clogged. If there were too few particles, the certainty that the data were a representative measurement of all of the particles in the runoff sample was low. Typically, for the 30 μm and 100 μm apertures, 40 mL of electrolyte solution was mixed with 0.6-15 mL of runoff sample, which depended on the concentration of the stormwater sample. The 30 μm aperture needed more of the runoff sample compared to the 100 μm aperture. The 400 μm aperture was generally run with a suspension of 80-100 mL of electrolyte solution and 1-20 mL of runoff sample. Compared to the other aperture sizes, the 400 μm aperture consumed a significant amount of the suspension. Since the 400 μm aperture drew in such a large volume of suspension, it used the vacuum meter to pull in the suspension, instead of the meter pump that the 30 μm and 100 μm apertures used. The 400 μm aperture was also more sensitive to substantial count jumps. These jumps come from a large clump temporally clogging the aperture, and this clump creates a lot of false electrical signals. When this occurs, the data are not reflective of the real particles going through the aperture, so the data are flawed. If the values had sudden, large count peaks, the run was redone.

The electrolyte solution used for experimentation was either 2% $NaCl_2$ + 0.1% NaN_3 or 0.01 M $CaCl_2$ + 2% $NaCl_2$ + 0.05% NaN_3, which was dependent on the needs of the other researchers in the laboratory. The electrolyte solution was filtered successively through 0.22 μm and 0.05 μm filter papers continuously for 48 hours before it was used for the Coulter Counter work. Figure 3.5 shows the apparatus set-up for the filtering of the electrolyte solution.

Figure 3.5 Electrolyte Filtering Set-up

This filtering setup has a pump which is on the top shelf. The pump pulls electrolyte solution from the bottom 4 L jar and pushes it through the filters which discharge to the top 4 L jar. When the top jar reaches a certain height, a siphon is automatically started, and the collected electrolyte solution is drained to the bottom jar.

3.4.2 Particle Size Distributions

The data for each run from the Coulter Counter were imported into a calibrated excel spreadsheet for the particular electrolyte solution being used. The data from the three aperture sizes were placed in the same excel file so that the data overlaid each other. Figure 3.6 displays the particle size distribution function for a 100 mg/L SIL-CO-SIL suspension.

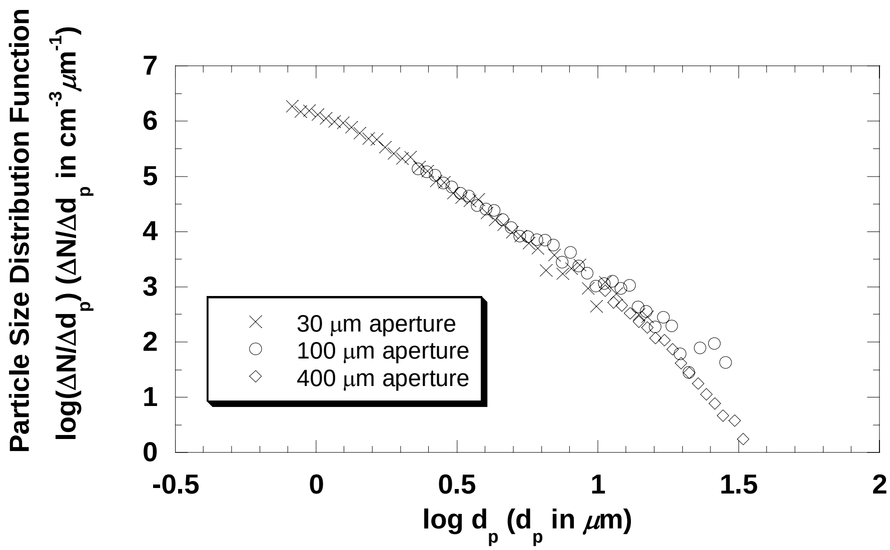

Figure 3.6 Original Particle Size Distribution Function for a SIL-CO-SIL Suspension

These data were then cleaned up so that there was a smooth transition in particle sizes between the different aperture sizes. It was important that the data did not overlap so that double counting of particles would not occur. If this occurred, the volume concentration determined, which was used to calculate the average particle density, would be larger than the actual volume concentration. The volume concentration was calculated by summing the volume concentrations for each aperture size. The area under the volume distribution curve was also equal to the cumulative volume concentration for the suspension. Figure 3.7 shows the particle size distribution function, number distribution, and volume distribution for the SIL-CO-SIL suspension after the data were adjusted to prohibit overlapping.

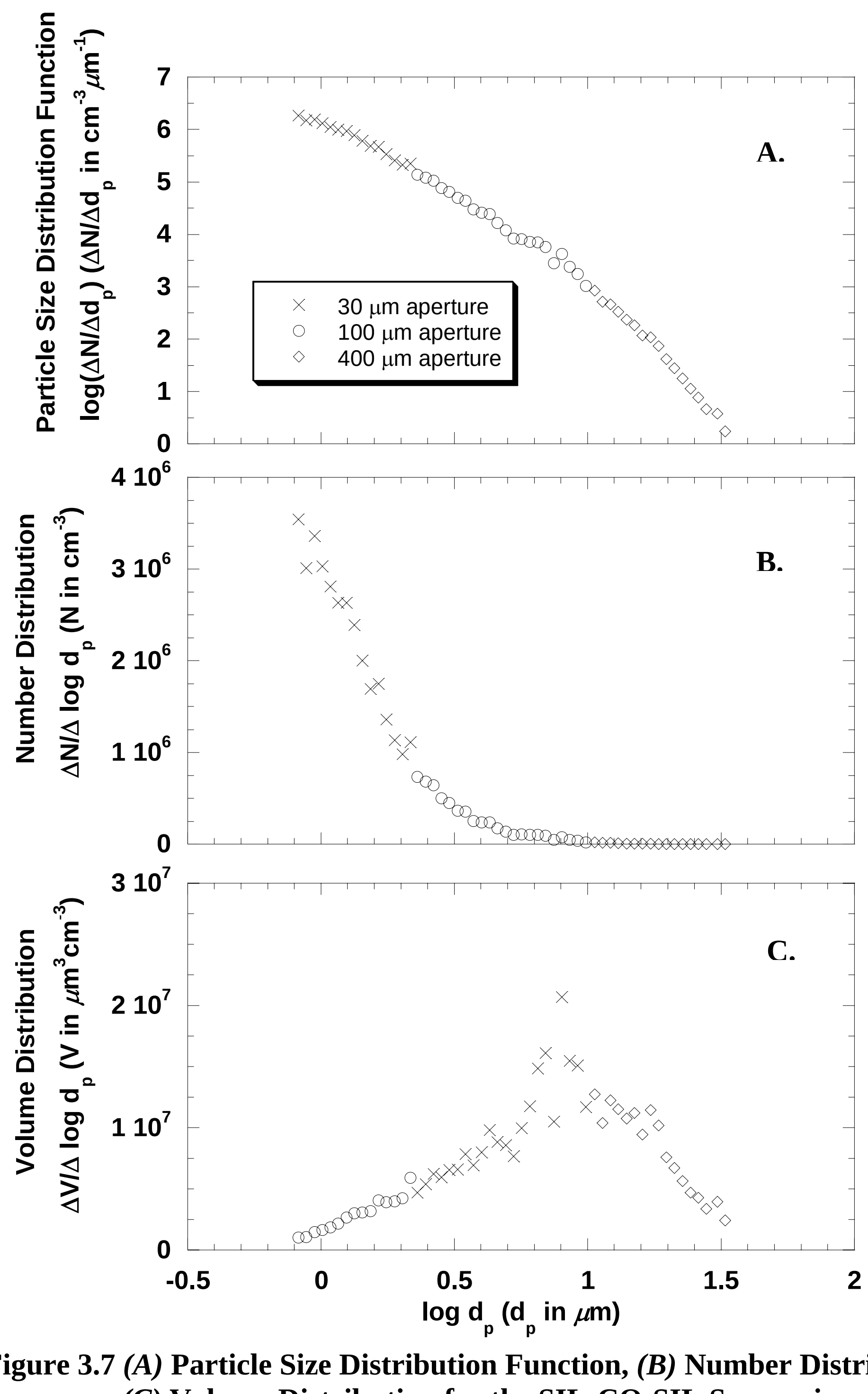

Figure 3.7 ***(A)*** **Particle Size Distribution Function,** ***(B)*** **Number Distribution, and** ***(C)*** **Volume Distribution for the SIL-CO-SIL Suspension**

The particle size distributions were all normalized with a logarithmic scale to give better resolution to the data. Figure 3.7 A is the particle size distribution function. The y-coordinate for this figure is the logarithm of the arithmetic change in number of particles for a small increment divided by the arithmetic change in diameter size. This distribution is typically used for flocculated suspension (Lawler, 2004). Figure 3.7 B is the number distribution. It divides the change in number of particles in a small increment that is correlated to the logarithmic increment in particle diameter. The area under the curve yields the number concentration. This distribution is also useful because it visually displays the size range that contains the most particles and shows the spread of the particle size distribution (Lawler, 2004). Figure 3.7 C is the volume distribution. This distribution graphs the volume concentration for a small increment divided by the logarithmic increment in particle diameter. The total area under the curve is equaled to the total volume concentration, and this value is needed to solve for the particle density of the runoff.

Figure 3.7 also shows that each aperture size measures a different size range of particles. The 30 μm aperture could not count particles with a large diameter because these particles could have not fit through the aperture hole. In addition, the 400 μm aperture was not as sensitive to the smaller particles that could have been measured by the 30 μm aperture. Table 3.3 displays the typical size range of the particles measured by each aperture size.

Table 3.3 Comparing the Aperture Size Needed in Relationship to Particle Diameter

Aperture Size (μm)	Particle Diameter Range (μm)
30	0.8 – 2
100	2 – 10
400	10 – 75

3.5 Density Calculations

The density of the particles in the runoff samples was calculated after the SSCs and volume concentrations from the Coulter Counter work were collected. The SSCs used were the SSC measurements for the samples that were sieved through the 75 μm sieve, because it was assumed that the Coulter Counter was only counting the particles that were smaller than 75 μm. The particles that were larger than 75 μm had such a high settling velocity that they fell to the bottom of the container before they were pulled through the aperture tube. The average particle density was calculated using Equation 3-2.

$$\text{Density}\left(\frac{\text{g}}{\text{cm}^3}\right) = \rho_p = \frac{(SSC, \text{mg/L})\left(10^{12}\,\dfrac{\mu\text{m}^3}{\text{cm}^3}\right)}{\left(V_p, \dfrac{\mu\text{m}^3}{\text{mL}}\right)\left(1000\,\dfrac{\text{mL}}{\text{L}}\right)\left(1000\,\dfrac{\text{mg}}{\text{g}}\right)} \qquad \textbf{Equation 3.2}$$

The densities for the collected samples were then compared to the density of sand, to the density of highly organic materials, and to the densities found in the literature review to add insight about the runoff characteristics.

CHAPTER 4 RESULTS AND ANALYSIS

The data collected in this research are presented and interpreted in this chapter. The suspended sediment concentrations, particle size distributions, and densities of the particles in the runoff samples are compared for the different storm events and site locations. The treatment capability of Austin sand filters and of vegetated filter strips are discussed in the light of the data.

4.1 Suspended Sediment Concentration

Suspended sediment concentration measurements were taken for all of the gathered runoff samples. In preparation for this measurement, the collected samples were subdivided. Sub-samples from each storm event were sieved through different sieve sizes. Initially, the samples were sieved with a 75 μm and 105 μm sieves, but after analysis of the SSCs for the first few storm events, the future samples were also sieved with a 125 μm sieve in order to better characterize the particle size distribution. However, the mass difference between the samples that were sieved through a 105 μm sieve and the other two sieve sizes were small, so the 105 μm sieve size was removed from the sieving process. Table 4.1 illustrates the SSCs for the untreated runoff at each location: bridge approach highway, bridge, vegetated filter strip, and extended detention basin.

Table 4.1 Suspended Sediment Concentration and Density of Particles less than 75 μm in Untreated Highway Runoff

		SSC (mg/L)				% of Total Mass		
Date	Location*	Total	d_p <125μm	d_p <105μm	d_p <75μm	d_p <125μm	d_p <105μm	d_p <75μm
11/1/2004	Bridge	26	-	12	11	-	45	43
11/15/2004	Bridge	27	-	17	13	-	63	48
1/27/2005	Bridge	76	-	32	30	-	42	39
1/4/2005	BHA	104	-	87	77	-	84	74
1/27/2005	BHA	702	-	268	249	-	38	35
3/26/2005	BHA	2803	141	-	129	5	-	5
5/8/2005	BHA	1007	129	-	111	13	-	11
1/27/2005	VFS1	289	-	-	176	-	-	61
5/28/2005	VFS2	193	113	-	76	59	-	39
7/27/2005	EDB	114	58	-	42	51	-	37
8/5/2005	EDB	605	28	-	16	5	-	3
8/8/2005	EDB	60	26	-	15	43	-	25

* BHA = Bridge Approach Highway; VFS 1 = Vegetated Filter Strip Site 1; VFS 2 = Vegetated Filter Strip Site 2; EDB = Extended Detention Basin

The suspended sediment concentration for a runoff sample was dependent on the particular storm event; in addition, the percent of total mass under a certain particle size varied for each storm, suggesting that the intensity of the storm caused differences in the relative size distributions. The percent of total mass with a particle diameter below 125 μm ranged from 5% to approximately 59%, and the percent of total mass with a particle diameter below 75 μm ranged from 5% to 61%. For the two samples collected on January 27, 2005, the bridge deck sample had a far lower SSC compared to the bridge approach highway sample. This occurrence could have been due to the fact that the bridge approach highway runoff flowed a greater distance along the road, which enabled it to pick up more sediment, compared to the bridge deck runoff.

While the data set is small, it appears that storm events that cause very high total SSCs have only a small fraction of the mass in the small particles. Even though the total suspended sediment concentrations was dramatically different for the bridge approach highway samples collected on March 26th and May 8th of 2005, a similar amount of mass was caught between the 75 μm and 125 μm sieves for these samples.

The total SSC for the extended detention basin also varies significantly. The largest SSC was 605 mg/L from the storm event on August 8, 2005, and the lowest SSC was 60 mg/L from the storm event on August 5, 2005. The SSC for the particles with a diameter below 75 μm were relatively similar, even though the total SSCs varied notably. The storm event on July 27, 2005 has a total SSC of 114 mg/L; however, it had a much larger SSC for the particles with a diameter below 75 μm, which was 42 mg/L, compared to the other extended detention basin runoff samples.

4.2 Coulter Counter Measurements

The Coulter Counter was used to find the size distribution of the particles in the runoff samples. Figure 4.1 displays the particle size distribution function and volume distribution of the particles in the bridge approach highway sample collected on January 27, 2005. The other individual particle size distribution functions and volume distributions for the bridge approach highway and bridge deck samples are shown in Appendix B. They are also combined and discussed subsequently in the chapter.

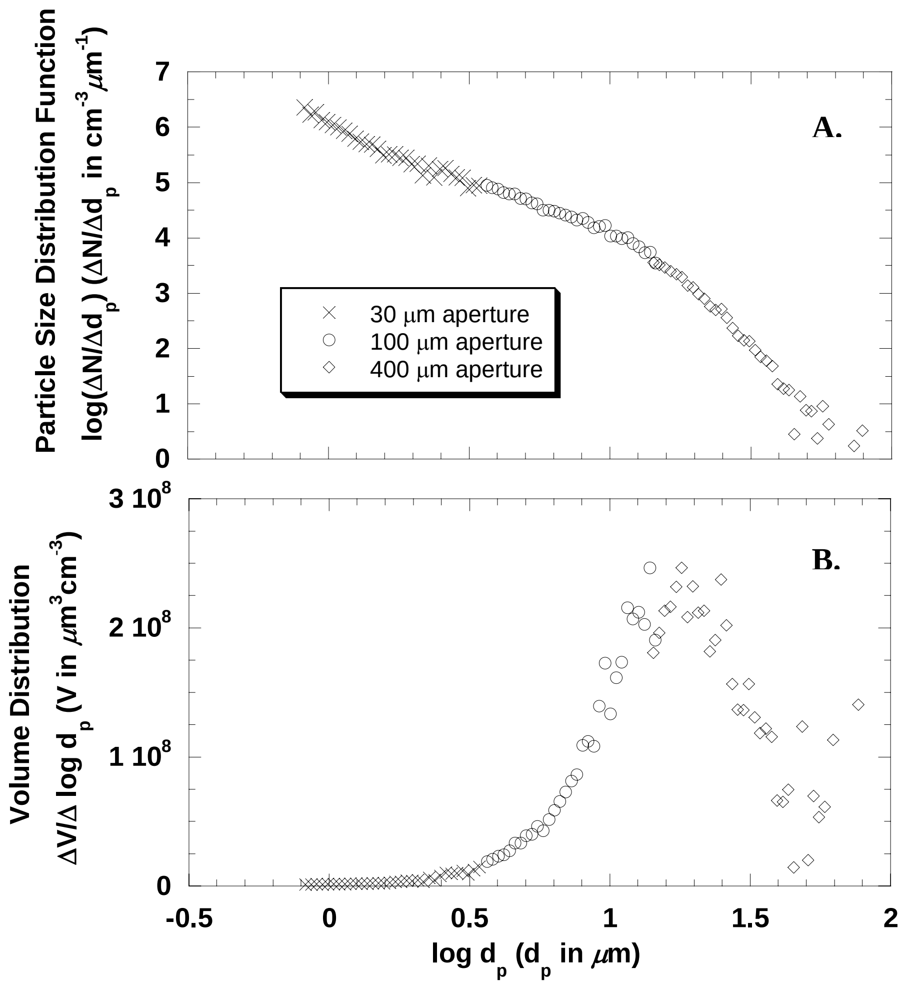

Figure 4.1 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution in the Bridge Approach Highway Runoff Sample from January 27, 2005**

The graph shows that the 30 μm aperture measured the particles with a diameter between 0.8 μm to 3 μm ($-0.1 < \log d_p < 0.5$). The 100 μm aperture assessed the particles with a diameter between 3 μm to 16 μm ($0.5 < \log d_p < 1.2$), and the 400 μm aperture analyzed the particles with a diameter between 16 μm to 75 μm ($1.2 < \log d_p < 1.9$). The particle size distribution function, shown in Figure 4.1 A, illustrated that, on a number basis, more particles were in the size range measured by the 30 μm aperture compared to the

400 μm aperture. However, the volume distribution (Figure 4.1 B) showed that the majority of the total particle volume concentration came from the large particles, and the small particles only contributed a small amount to the overall volume. When plotted as shown, the area under the volume distribution is the total particle volume concentration; this value was used in the density calculations.

4.3 Density Calculations

The average density of the particles in the stormwater runoff samples was calculated from the Coulter Counter and SSC data. The bridge approach highway sample from January 27, 2005 is analyzed in detail here to explain the density calculations. The SSC of the sample was 249 mg/L, and the volume concentration of the sample was $1.46*10^8$ μm^3/mL, or $146*10^6 \frac{\mu m^3}{mL}\left(\frac{mL}{cm^3}\right)\left(\frac{cm^3}{10^{12}\,\mu m^3}\right) = 146\frac{\mu m^3}{10^6\,\mu m^3} = 146\ ppm_V$.

$$\text{Density} = \frac{\left(249\frac{mg}{L}\right)\left(10^{12}\frac{\mu m^3}{cm^3}\right)}{\left(1.46*10^8\frac{\mu m^3}{mL}\right)\left(1000\frac{mL}{L}\right)\left(1000\frac{mg}{g}\right)} = 1.71\frac{g}{cm^3} \qquad \textbf{Equation 4.1}$$

These values yielded a particle density of 1.71 g/cm^3. Table 4.2 displays the SSCs, volume concentrations, and densities for the particles in the bridge approach highway, bridge, and vegetated filter strip samples.

Table 4.2 Average Particle Densities in Various Runoff Samples

Date	Location[a]	SSC (mg/L)	Volume (ppm_v)[b]	Density (g/cm^3)
1/27/2005	Bridge Deck	30	23	1.31
1/4/2005	BHA	77	67	1.17
1/27/2005	BHA	249	164	1.71
3/26/2005	BHA	129	64	2.00
5/8/2005	BHA	111	46	2.42
1/27/2005	VFS1 0m	176	125	1.41
5/28/2005	VFS2 0m	76	64	1.19
5/28/2005	VFS2 2m	56	73	0.76
5/28/2005	VFS2 4m	30	45	0.67
5/28/2005	VFS2 8m	22	27	0.81
7/27/2005	EDB inlet	42	15	2.80
8/5/2005	EDB inlet	16	12	1.33
8/8/2005	EDB inlet	15	11	1.36

[a] BHA= Bridge Approach Highway; VFS1 = Vegetated Filter Strip Site 1; VFS2 = Vegetated Filter Strip Site 2; EDB = Extended Detention Basin
[b] 1 $ppm_v = 10^6\ \mu m^3/mL$

These densities are the densities of the particles with a diameter less than 75 μm. The particles with a diameter larger than 75 μm were not measured by the Coulter Counter due to their high settling velocities. These particles dropped to the bottom of the container, which made it impossible for them to be pulled through the aperture tube. The calculated density of the particles in the runoff samples ranged from 0.81 g/cm^3 to 2.80 g/cm^3. Clearly, the density of the particles is not likely to be below 1 g/cm^3. The low densities could have been measured lower than in reality due to the fact that the density calculation, which includes two mass measurements and three Coulter Counter measurements (three separate apertures), had compounded error. Many investigations have assumed that the density of the particles in stormwater runoff is that of sand, 2.65 g/cm^3; however, almost all of the calculated average densities were below the density of sand.

Since typical organic materials possess a density of approximately 1.1 g/cm^3, the presence of organic material may have impacted the density of the particles in the runoff samples, which caused the average particle density of the samples to be lower than the density of sand (Cristina *et al.*, 2001). Thus, the low densities found for the bridge deck site, for vegetated filter strip sites, and for two of three inlet samples at the extended detention basin site suggested that these samples contained a significant amount of organic material. The vegetated filter strip samples from site 2 had visible grass and insects in the runoff, which is organic material. The runoff samples could have also collected rubber from tires and asphalt from the road. These materials have densities of 1.5-1.7 g/cm^3, which would lower the average particle density of the runoff (Kobriger and Geinopolos, 1984; Sansalone and Triboullard, 1999). The calculated densities still supported the idea that the particles in highway runoff do not have a density equivalent to sand even though error existed in the values.

The bridge approach highway sample collected on 1/4/05 had a noticeably lower density compared to the other bridge approach highway samples; thus it is possible that the level of organic material in the runoff may vary notably between storm events. The bridge approach highway samples collected on 3/26/05 and 5/8/05 had a density in a similar range compared to the literature review values for detention basins, stormwater sewers, and street surface sediment. The larger densities seemed to be correlated with the larger SSCs, which suggested that the fraction of inorganic material such as sand was higher for these samples. The runoff sample from the inlet to the extended detention basin on July 27, 2005 had the highest average particle density because its SSC was relatively high compared to its small volume concentration; it seems possible that the SSC is erroneously high. To reiterate the most significant finding, almost all of the stormwater runoff samples collected had an average particle density below the density of sand.

4.4 Relative Distribution by Mass

The relative distribution by mass was calculated from the Coulter Counter data and SSCs. The procedure was to convert the volume distribution to a cumulative basis and then scale it according to the relative mass in the $SSC_{75\mu m}$ versus SSC_{total} samples. Figure 4.2 shows the relative distribution by mass for the bridge approach highway and bridge deck samples collected on January 27, 2005.

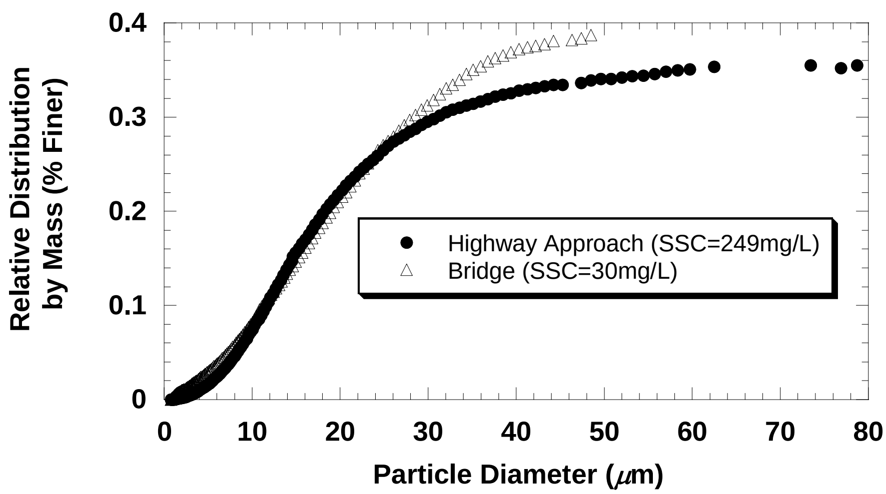

Figure 4.2 Comparison of the Relative Distribution by Mass

The figure illustrates that only 35-40% of the total mass in the stormwater runoff samples were measured by the Coulter Counter. Even though the SSCs were significantly different for the bridge deck and bridge approach highway samples, the fraction of suspended particles measured by the Coulter Counter was comparable. However, the bridge deck sample had a slightly larger percentage of its particles by mass measured by the Coulter Counter ($d_p < 75$ μm). The relative distribution by mass must be bimodal, since the curves leveled out around 40% instead of elevating towards 100% in Figure 4.2. Another significant increase in mass must occur at a larger particle size so that the relative distribution by mass reaches 100%.

4.5 Comparing Bridge Approach Highway Samples

The SSCs and particle size distributions for the bridge approach highway samples collected on four different dates were compared. The SSCs varied from 77 mg/L to 249 mg/L, which was a notable difference between storms. The particle size distribution functions of these samples are displayed in Figure 4.3. The sample collected on January 4, 2005, which also had the lowest SSC, contained more small particles ($d_p < 1.8$ μm or $\log d_p < 0.25$) compared to the other samples. Also, the sample collected on January 27, 2005, which had the highest SSC, had more particles in the mid-size range (1.8 μm $< d_p <$ 25 μm or $0.25 < \log d_p < 1.4$), comparatively. All of the samples had a similar particle size distributions for the large particles (25 μm $< d_p <$ 75 μm or $1.4 < \log d_p < 1.9$). Thus, it seems that the small particles did not affect the SSCs; however, the particles with a diameter in the mid-size range, as well as those larger than 75 μm, were primarily responsible for the differences in the SSCs.

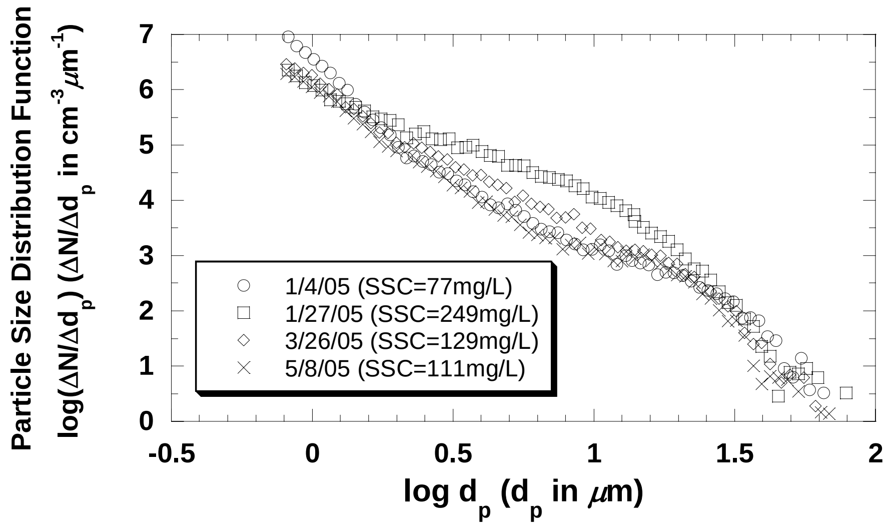

Figure 4.3 Particle Size Distribution Function of the Bridge Approach Highway Samples

4.6 Before and After Treatment

4.6.1 Full Sedimentation Sand Filter

Two samples were gathered at the bridge approach highway site on January 27, 2005: bridge approach highway runoff and effluent of the full sedimentation sand filter. This type of full sedimentation sand filter is commonly referred to as an Austin sand filter. It is an extended detention basin followed by a sand bed filter. The particle size distribution functions and volume distributions for these coupled samples are displayed in Figure 4.4. The SSC for the effluent sample was drastically lower than the SSC for the bridge approach highway runoff. The effluent sample's suspended sediment concentration was too small to measure for the sieved sample, and the sample that was not sieved had a SSC of 2.9 mg/L. The SSC for the bridge approach highway sample that was sieved with a 75 μm sieve was 249 mg/L, and the total SSC was 702 mg/L. Between the inflow and outflow samples, the particle size function distributions shows an efficient removal of particles with a diameter larger than 1 μm (log $d_p > 0$), and the volume distributions illustrates a significant decrease in volume for the particles with a diameter larger than 2.5 μm (log $d_p > 0.4$). The information gathered supported the notion that the full sedimentation sand filter treatment process dramatically improved the bridge approach highway stormwater runoff.

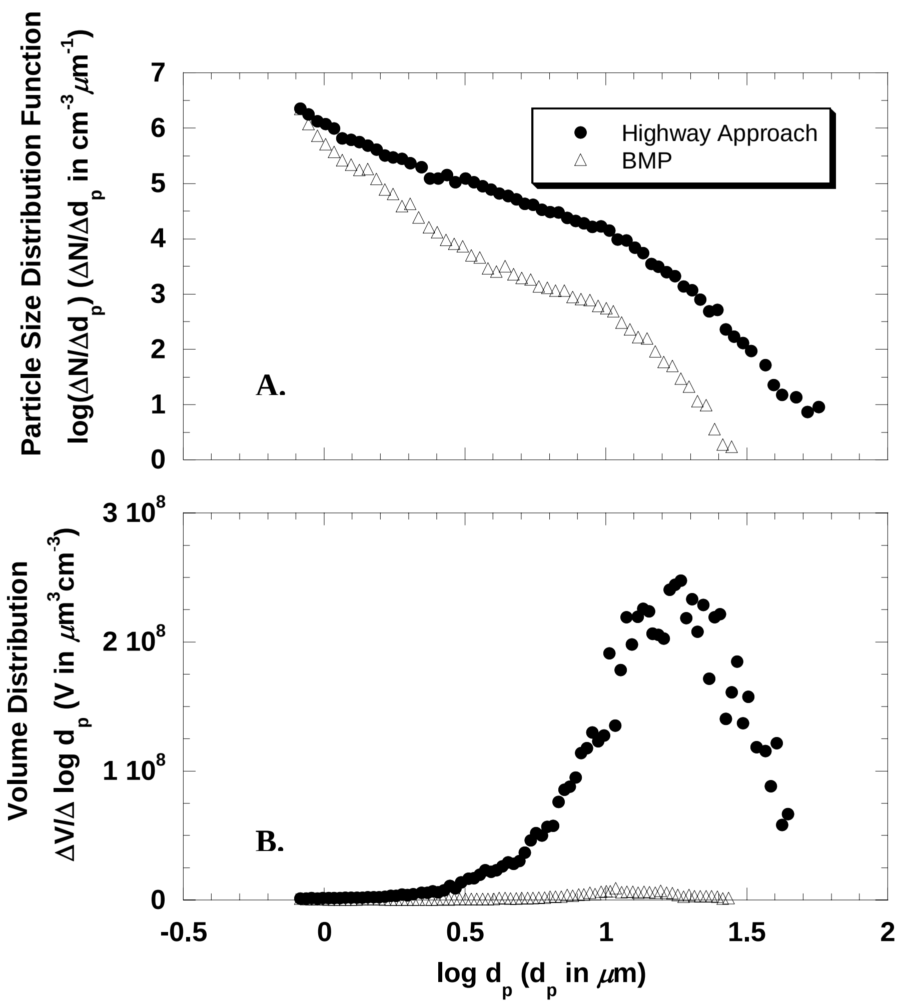

Figure 4.4 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution Before and After Treatment with an Austin Sand Filter for Samples Collected on January 27, 2005**

4.6.2 Extended Detention Basin

The Anderson Mill Basin site has an extended detention basin installed to treat the runoff. Three runoff samples were gathered at the inlet and outlet of the extended detention basin as well as three grab samples of the water within the basin. Figure 4.5 displays the inflow and outflow particle size distributions for the samples collected from the storm event on July 27 and 28, 2005. The particle size distributions for the other samples are located in Appendix B and show similar trends.

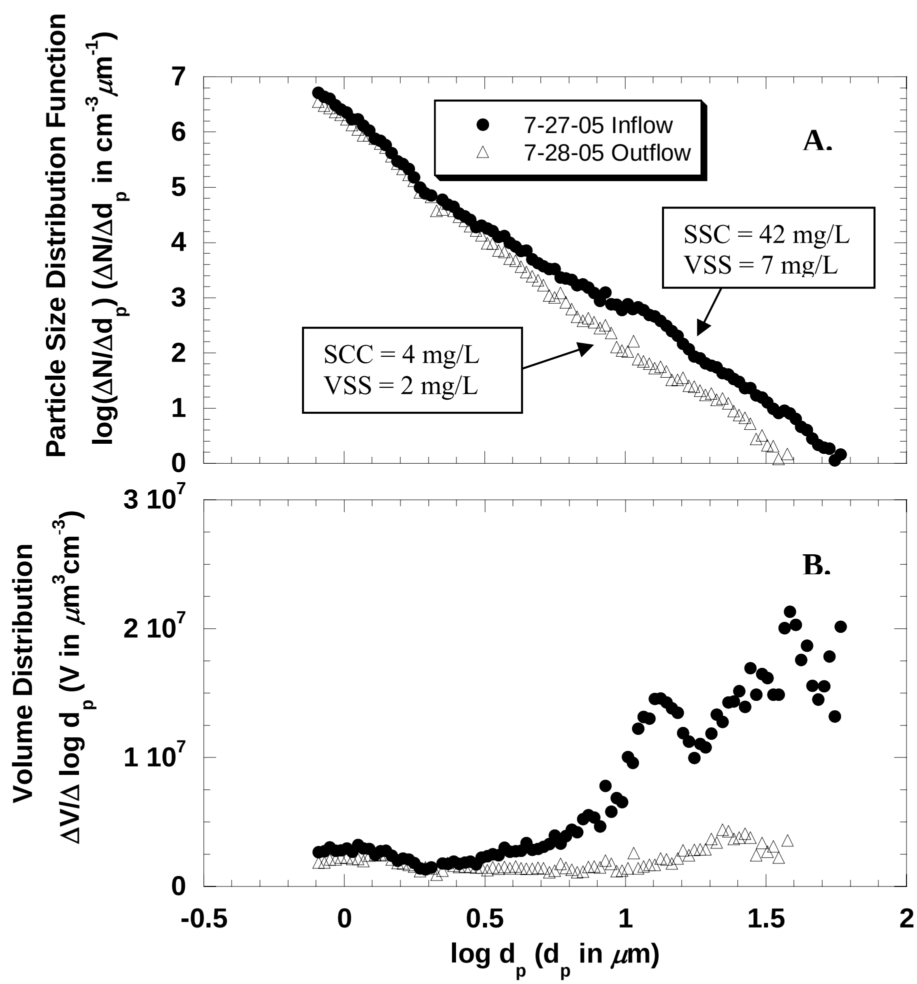

Figure 4.5 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution Before and After the Extended Detention Basin of Samples Collected on July 27 & 28, 2005

Figure 4.5 shows a reduction in particles with a diameter larger than 3 μm (log $d_p > 0.5$) between the inlet and outlet of the BMP for this particular storm event; all the data shown are samples that had been sieved through the 75 μm sieve. The particle volume concentration decreased between the inlet and outlet samples as well; from a value of 15 ppm_v for the inlet to 3 ppm_v for the outlet, for particles with a $d_p < 75$ μm (log $d_p <$ 1.9). The SSC decreased from 42 mg/L to 4 mg/L, and the VSS reduced from 7 mg/L to 2 mg/L by treatment. A significant portion of the suspended sediment in the outflow sample was volatile. Unfortunately, the density of the particles in the outflow sample could not be calculated because the suspended sediment concentration was too low. A slight error in the SSC could drastically affect the calculated density. Refer to Appendix A for additional SSC and VSS data.

This research supported the treatment process theory that a sand filter basin plus an extended detention basin has a better treatment capability compared to solely an extended detention basin. The extended detention basin alone does not reduce the particle volume as efficiently as the full sedimentation sand filter that was discussed in the prior section. It also did not remove particles with a diameter between 1 μm and 3 μm while the Austin sand filter did reduce those particles; however, this detention basin did remove larger particles quite well. The excellent removal of large particles could be due in part to the nature of the storm. The system seems to work well when all of the runoff in the basin can sit undisturbed for several hours so that batch sedimentation is efficient. The duration of the storm event on July 27, 2005 was 3 hours, and the total rainfall was 1.02 in. The short storm event allowed for effective particle removal due to batch sedimentation. A storm with a longer duration might not work as well because the runoff will be going into the basin at the same time it is leaving. The outflow valve could be shut to hold the runoff in the basin longer to maximize the treatment efficiency.

4.6.3 Vegetated Filter Strip

Highway stormwater runoff samples were collected at the vegetated filter strip site 1 on January 27, 2005. This storm event has 1.5 inches of rainfall over approximately 16 hours (Wunderground, 2005). The collected samples were analyzed with the Coulter Counter to examine the alteration in particle size distribution from 0 m to 8 m across the grassy shoulder, which can be seen in Figure 4.6.

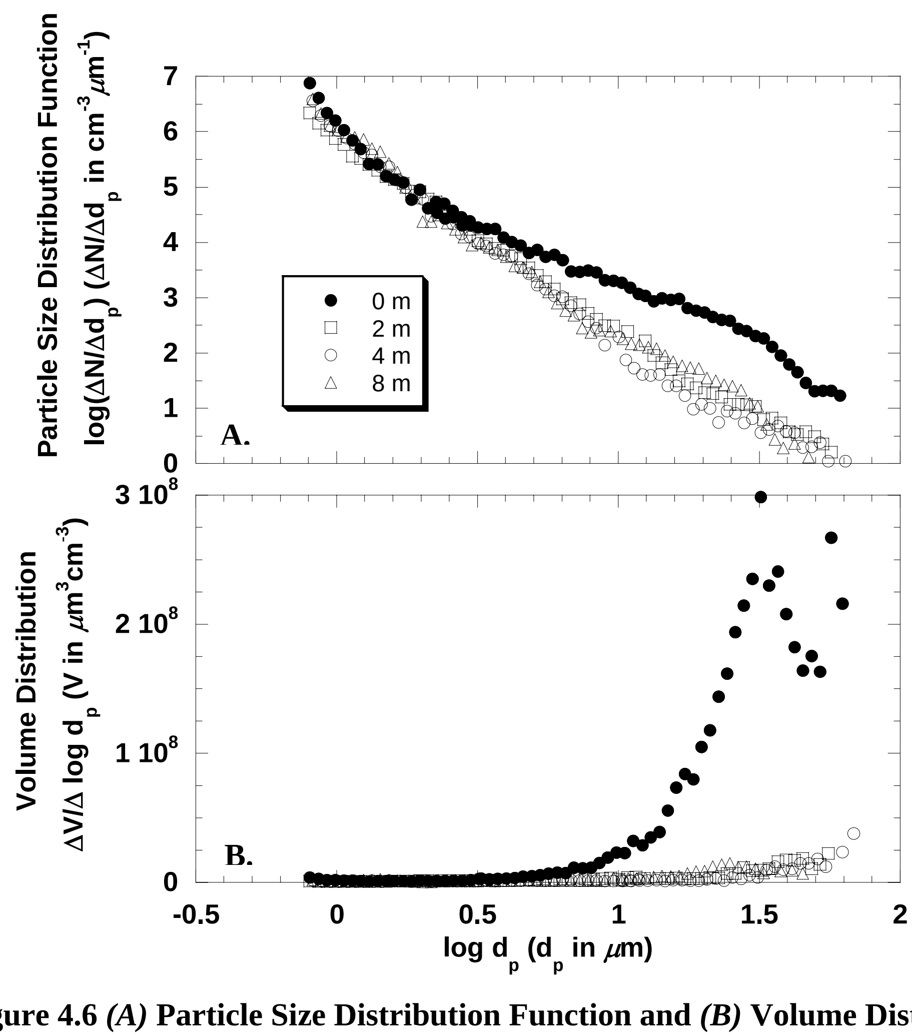

Figure 4.6 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of the Samples Collected Along the Buffer Strip at Site 1 on January 27, 2005

Figure 4.6 demonstrates that most of the particles in the highway runoff were removed between 0 m and 2 m along the vegetated filter strip. A significant volume concentration reduction occurred for the particles with a diameter larger than 8 μm (log $d_p > 0.9$) from 0 m to 2 m. All four samples had nearly identical size distributions for particles less than 2 μm (log $d_p < 0.3$), although the 2 m samples seemed to have the fewest particles. For large particles (log $d_p > 0.5$, or $d_p > 3.2$ μm), the three samples at 2 m, 4 m, and 8 m were quite similar, though the 4 m sample had the fewest particles in that range. It is possible that particles in this size range were scoured by the flowing water between 4 m and 8 m to increase the concentration as shown. Overall, the grassy shoulder showed effective removal of particles with a diameter larger than 2.5 μm, and the majority of the particle treatment happened between 0 m and 2 m along the buffer strip. Refer to Table 4.3 to look at the correlated SSCs.

Table 4.3 SSCs for Samples Collected from the Storm Event on January 27, 2005

Location	Sieve Size	SSC (mg/L)
0m	75 μm	176
0m	None	285
0m	None	292
2m	None	20
2m	None	17
4m	None	14
4m	None	16
8m	None	4
8m	None	6

Table 4.3 shows that a significant reduction in SSC occurred between 0 m and 2 m along the grassy shoulder. The total SSCs for the particles in the runoff samples continued to decrease down the filter strip; however the decrease in concentration was not as pronounced as it was from 0 to 2 m. Thus, the SSCs supported the Coulter Counter work and the conclusion that notable particle removal occurs between 0 m and 2 m along the buffer strip.

Samples were also collected at the second vegetated filter strip site after a storm event on May 28 and 29 of 2005. The particle size distributions of the samples collected at 0 m and 8 m along the vegetated filter strip are illustrated in Figure 4.7. Refer to Appendix B to see the particle size distributions of the samples collected at 2 m and 4 m along the buffer strip. The particle size distributions for 0 m, 2 m, 4 m, and 8 m were relatively similar.

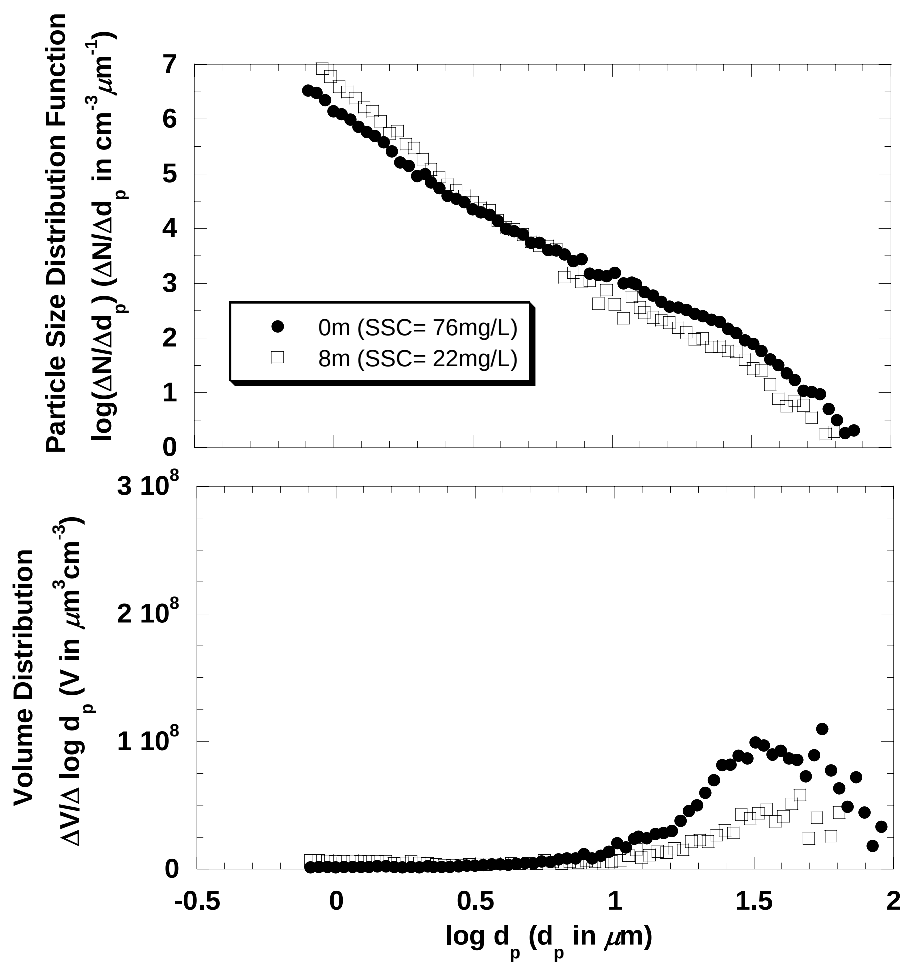

Figure 4.7 (A*)* Particle Size Distribution Function and *(B)* Volume Distribution of the Samples Collected Along the Buffer Strip at Site 2 on May 28 and 29, 2005

Figure 4.7 suggests an increase in particles with a diameter below 5 μm (log $d_p < 0.7$) from 0 m to 8 m along the vegetated filter strip, and the volume concentration also increased for this size range. However, the particles with a diameter between 5 μm and 75 μm ($0.7 < \log d_p < 1.9$) decrease both in number and volume concentration from 0 m to 8 m down the buffer strip. It is possible that the Coulter Counter sample, which was only a few milliliters of the whole sample, was not representative of the overall 0 m sample. The particle size distributions of the samples shows that the vegetated filter strip was not effective at treating all of the particles with a diameter below 75 μm; however, the SSCs reduced from 76 mg/L to 22 mg/L from 0 m to 8 m down the grassy shoulder. It seemed as if the heavier particles with a diameter below 75 μm settled-out of the suspension, but the runoff collected more particles that had low densities and small diameters.

As mentioned in the density section of this chapter, compounded error most likely occurred with either the volume concentration or SSC measurements which led to a low calculated density for the sample at 8 m. The SSC for the 8 m sieved sample was only 29% of the SSC of the 0 m sieved sample. Since the density of organic material is approximately 1.1 g/cm^3, the SSC of the 8 m sieved sample would have had to been 30 mg/L to get that density, using the same volume concentration (27 ppm$_v$). If the SSC was 30 mg/L, the 8 m sieved sample would have been 40% of the SSC at 0 m. The volume concentration data support the notion that the SSC could have been lower than the actual concentration because the volume concentration of the 8 m sieved sample was 42% of the volume concentration for the 0 m sieved sample.

The total SSCs for the 0 m and 8 m samples were 193 mg/L and 255 mg/L, respectfully, so it appears that the total SSC of the samples increased along the buffer strip. As the runoff progressed along the vegetated filter strip, the runoff collected particulate matter. This occurrence could have been due to high velocity flow or flooding. The National Weather Service recorded that Austin had approximately 1.5 inches of rainfall for this storm event, and the storm event lasted for about a day and a half with several peaks in rainfall (NWSF, 2005; Wunderground, 2005), as shown in Figure 4.8. A significant amount of rain for one event or long storm duration could reduce this BMP's efficiency; also, a sudden downpour would produce high velocity runoff and decrease the effectiveness of the BMP compared to a long slow rain event.

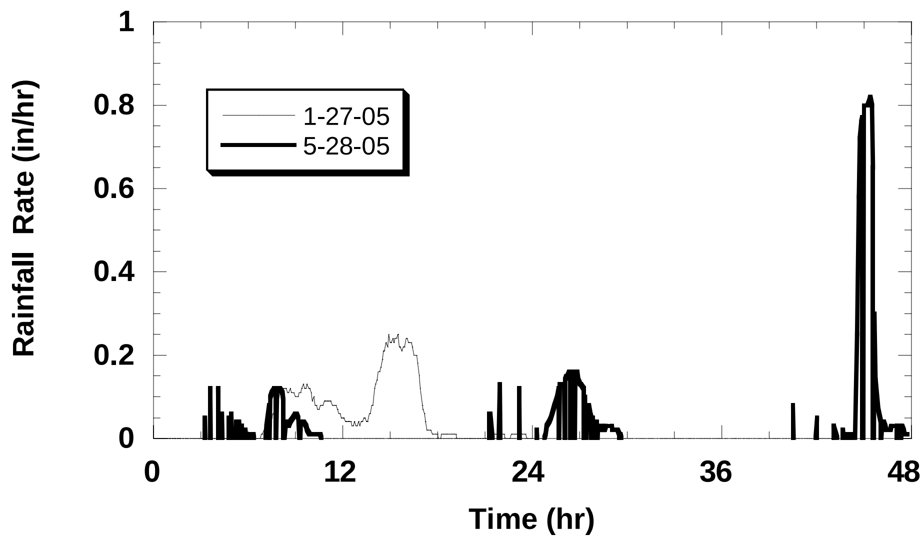

Figure 4.8 Rainfall Rate of the Storm Events on January 27th and May 28th of 2005

Figure 4.8 illustrates that the storm event on May 28, 2005 had periods with high intensity rainfall. The storm event on January 27, 2005 had a more constant rainfall amount that did not reach the same intensity as the storm on May. The duration of the storm event in January was also much shorter than the storm event in May. Thus, the intensity and duration of the storm seemed to impair the vegetated filter strips capability to remove the particles in the runoff.

Seasonal change, in addition to possible flooding, affected the BMP's treatment efficiency because the samples collected at 2 m, 4 m, and 8 m down the shoulder possessed grassy seeds and other vegetation. To examine the seasonal influence on the samples, the volatile suspended solid (VSS) concentrations were measured on these samples. Table 4.4 displays the SSC and VSS concentrations of the collected samples.

Table 4.4 SSCs and VSS concentrations for the samples collected May 2005

Location	Sieve Size	SSC (mg/L)	VSS (mg/L)
0 m	None	193*	48
8 m	None	255*	50
0 m	75 μm	76*	15
8 m	75 μm	22*	8

* represents the average SSC

The VSS concentrations reduced from 15 mg/L to 8 mg/L along the grassy shoulder for the 75 μm sieved samples. However, a tiny change in measured weight of the residue and/or filter paper could significantly affect the VSS concentration, so the actual VSS concentration for the 8 m sieved sample could have been closer to 15 mg/L. The 8 m sieved sample had a larger ratio of the volatile suspended solids to the total suspended solids compared to the 0 m sieved sample, but the compounded error in the value should still be taken into consideration. Organic vegetated matter swept into the runoff impacted the suspended solid concentration and the particle size distribution of the samples collected along the grassy shoulder.

A possibility also exists that the difference in SSCs at 0 m and 8 m is an accurate representation of the values at those locations. Other outside factors, such as fire ant mounds near the collection pipes or build up of debris in the pipes at the beginning of the storm event due to irregular maintenance, should not be completely eliminated. The phenomenon was only observed once and only at one location.

In conclusion, the SSCs suggested that the vegetated filter strips effectively removed the heavy particles with a diameter below 75 μm in the highway runoff through settlement; however, the particle size distributions showed that this treatment method was not consistently effective at removing the less dense particles. The total SSCs increased, so the BMP was not efficient at removing the total amount of suspended solids in the runoff. Runoff treatment efficiencies may vary between storm events, and this occurrence can be caused by storm intensity or seasonal change.

4.6.4 Comparison of BMP Outflow samples

All of the BMPs examined did treat the highway runoff; however, their optimal capability to treat the stormwater runoff varied. Table 4.5 illustrates the percent removal of SSC and volume concentration by the different BMPs.

Table 4.5 Comparison of BMP Treatment Efficiencies

	VFS1	VFS2	ASF	EDB	EDB	EDB
Storm Date	1/27/05	5/28/05	1/27/05	7/27/05	8/05/05	8/08/05
SSC $_{total\ in}$ (mg/L)	288	193	702	114	605	60
SSC $_{total\ out}$ (mg/L)	5	255	3	3	2	5
% Removal $_{SSC\ total}$	98%	-32%	>99%	97%	>99%	92%
SSC $_{(dp<75\mu m)\ in}$ (mg/L)	176	76	249	42	16	15
SSC $_{(dp<75\mu m)\ out}$ (mg/L)	-	22	-	2	1	4
% Removal $_{SSC\ (dp<75\mu m)}$	-	71%	-	95%	94%	73%
Volume $_{(dp<75\mu m)\ in}$ (ppm_v)	125	64	146	15	12	11
Volume $_{(dp<75\mu m)\ out}$ (ppm_v)	7	27	4	3	2	8
% Removal $_{Volume\ (dp<75\mu m)}$	94%	58%	97%	80%	83%	27%

VFS1 = Vegetated Filter Strip at Site 1; VFS2 = Vegetated Filter Strip at Site 2; ASF = Austin Sand Filter; EDB = Extended Detention Basin; Volume = Volume Concentration

The BMP with the worst treatment efficiency was the vegetated filter strip at site 2. Although the vegetated filter strip at site 1 showed effectively particle treatment, site location and conditions should be examined closely when determining whether to implement a buffer strip because the seasonal change and storm intensity can notably impact this BMP’s treatment efficiency. The extended detention basin reduced both the

SSC and volume concentration of the particles in the runoff. The low percentage of volume concentration reduction is not due to this BMP's inefficiency. This value is low because the influent runoff had a significantly lower volume concentration of particles compared to the influent samples at the other sites. The extended detention basin and Austin sand filter had similar total SSC out and volume concentration out ($d_p < 75$ μm) values, which were all lower than the values for the vegetated filter strip sites. The Austin sand filter had high removal efficiencies, and in a previous section, the particle size distributions showed that this BMP treated particles with a diameter above 1 μm. The other BMPs could not treat particles with a diameter below 3 μm, which was also discussed in the previous sections.

Overall, all of the BMPs work for runoff treatment, and more data should be collected to be able to differentiate more between the different types of BMPs. After analyzing the limited data from this research, it was concluded that the Austin sand filter seemed to be the most effective BMP at removing the particles in runoff, and the vegetated filter strip BMP was the least efficient treatment process. It is important that future work is conducted to support or disprove this conclusion since the results were data limited. Additionally, it is necessary to compare the price of construction and maintenance of each type BMP for a particular site when deciding which BMP to implement.

4.7 Summary

The most notable finding from this research was that the average particle density for almost all of the collected runoff samples was less than the density of sand. BMPs are typically designed according to the surface overflow rate theory, and the associated calculations are based on the particle density. If a laboratory experiment is performed using particles with density of 2.65 g/cm^3, the controlled treatment experiments could yield high efficiencies for particle removal. This same treatment system placed in the field could yield lower treatment efficiencies if particle density for highway runoff was overestimated.

This research also supports the idea that the Austin sand filter was the most efficient treatment process at removing particles from the highway runoff compared to the vegetated filter strips and extended detention basins, but more research should be conducted to support this conclusion. This conclusion makes logical sense because an Austin sand filter is an extended detention basin followed by a filter. It is necessarily better than a comparable extended detention basin alone. Vegetated filter strips depend considerably on the design, *i.e.*, slope and degree of vegetation, and could easily be overwhelmed in a large storm event. However, research should be continued on this subject to analyze how the characteristics of the storm event influence these BMPs' treatment capabilities.

CHAPTER 5 SUMMARY AND CONCLUSIONS

The project objective of this research was an analysis of suspended sediment concentrations (SSCs) and particle size distributions of stormwater runoff samples in order to calculate and to document the average particle densities. Runoff samples were also examined before and after three treatment systems. These treatment processes included a full sedimentation sand filter, extended detention basin, and vegetated filter strip. The particle size distribution is correlated to the surface area of the particulate matter in runoff. Since pollutants sorb onto the particles, understanding the particle size distribution of runoff is important so that advancements can be made in designing treatment systems. A limited amount of published articles exist that address the issue of particle size distribution and density of particles in stormwater runoff, so the key findings from this research added essential information to the field to improve the design of BMPs.

5.1 Conclusions

The evaluation of the data collected in this research led to the following conclusions:

1. Suspended sediment concentration (SSC) was a better technique than total suspended solids (TSS) when measuring concentrations of particulate material in stormwater runoff because TSS measurements often fail to include large particles.

2. SSCs in stormwater runoff varied significantly between storm events as well as location. Mid-size particles (1.8 μm < d_p < 25 μm) affected the SSC, but small particles (d_p < 1.8 μm) did not have much impact. Large concentrations of small particles contribute little to the particle volume (mass) in the overall sample.

3. Almost all of the densities of the particles in the collected runoff samples were less than the density of sand ($\rho = 2.65$ g/cm^3).

4. The full sedimentation sand filter effectively treated the stormwater runoff and removed particles with a diameter larger than 1 μm. The extended detention basin was less effective at removing the smallest particles, but did provide substantial treatment of the runoff.

5. The vegetated filter strip decreased the SSC and VSS of runoff as the stormwater progressed along the grassy shoulder. This system, however, did not consistently reduce the volume concentration of the particles in the runoff, because the runoff could pick up organic particles. Seasonal change and storm intensity also influenced treatment efficiency of this BMP.

6. The full sedimentation sand filter was the most effective of the three BMPs studied at decreasing particles in runoff based on the limited data of this research. This result is consistent with treatment process theory. However, additional data should be obtained to verify this conclusion.

Laboratory experiments are often performed with particles having a density of sand, and designs of real systems often incorporate the assumption that the density of the particles in stormwater is equal to the density of sand. The data collected in this research showed otherwise. Thus, the theoretical particle removal efficiencies for the BMPs, which commonly include the sedimentation process, will be overestimated compared to the actual particle removal efficiencies observed in the field, if the particle density of runoff is assumed to be 2.65 g/cm^3. The designer must take several factors into consideration when implementing a BMP: particles in stormwater runoff are less dense than sand, organic material may be swept into the runoff, and biological growth may occur in the system.

5.2 Recommendations for Future Research

Future work should focus on developing additional information about particle size distributions of stormwater runoff and the effectiveness of on-site treatment processes. Samples should be collected before and after additional on-site treatment processes to establish a data bank of efficiencies for removal of small particles by various types of BMPs. Future studies also could examine the influences of storm size on the SSCs and the resulting average particle density of stormwater runoff. In addition, the pollutants adsorbed to particles in different size ranges could be explored.

APPENDIX A: SUSPENDED SEDIMENT CONCENTRATIONS AND RAINFALL DATA

LIST OF TABLES

Table A-1 Comparison of SSCs for Bridge Approach Highway Samples

Date	Sieve Size	SSC (mg/L)
1/4/2005	None	116
1/4/2005	None	93
1/4/2005	105 μm	87
1/4/2005	75 μm	77
1/4/2005	75 μm	80
3/26/2005	None	2803
3/26/2005	125 μm	141
3/26/2005	105 μm	141
3/26/2005	75 μm	129
5/8/2005	None	1007
5/8/2005	125 μm	129
5/8/2005	105 μm	126
5/8/2005	75 μm	111

Table A-2 Comparison of SSCs for Bridge Deck Samples

Date	Sieve Size	SSC (mg/L)
11/15/2004	None	25
11/15/2004	None	29
11/15/2004	105 μm	18
11/15/2004	105 μm	16
11/15/2004	75 μm	13
11/1/2004	None	26
11/1/2004	None	25
11/1/2004	105 μm	13
11/1/2004	105 μm	10
11/1/2004	75 μm	12
11/1/2004	75 μm	10

Table A-3 SSCs for Bridge Deck and Bridge Approach Highway Samples Collected from Storm Event on January 27, 2005

Location	Sieve Size	SSC (mg/L)
Bridge Approach Highway:		
Coulter Counter Sample	None	764
Bridge Approach Highway	None	702
Bridge Approach Highway	105 μm	268
Bridge Approach Highway	75μm	249
Sand Filter Discharge	None	3
Bridge Deck:		
Coulter Counter Sample	None	76
Bridge Deck	None	76
Bridge Deck	105 μm	32
Bridge Deck	75 μm	30
Bridge Deck	75 μm	29

Table A-4 SSCs of the Grab Samples from Anderson Mill Basin

Date	Sieve Size	SSC (mg/L)	VSS (mg/L)
5/9/2005	None	7	1
5/9/2005	125 μm	6	0
5/9/2005	75 μm	4	1
5/9/2005	75 μm	5	2
5/28/2005	None	19	8
5/28/2005	125 μm	8	3
5/28/2005	75 μm	6	3
5/28/2005	75 μm	5	2
5/29/2005	None	3	0
5/29/2005	125 μm	5	3
5/29/2005	75 μm	2	1
5/29/2005	75 μm	4	2

Table A-5 SSCs and VSS concentrations for the Inflow and Outflow Samples Collected at Anderson Mill Basin

Coupled Storm	Date	Location	Sieve Size	SSC (mg/L)	VSS (mg/L)
	7/27/2005	Inflow	None	114	29
	7/27/2005	Inflow	125 μm	58	10
	7/27/2005	Inflow	75 μm	42	7
	7/28/2005	Outflow	None	6	3
	7/28/2005	Outflow	125 μm	5	2
# 1	7/28/2005	Outflow	75 μm	4	2
	8/5/2005	Inflow	None	605	32
	8/5/2005	Inflow	125 μm	28	8
	8/5/2005	Inflow	75 μm	16	1
	8/5/2005	Outflow	None	2	2
	8/5/2005	Outflow	125 μm	2	2
# 2	8/5/2005	Outflow	75 μm	1	0
	8/8/2005	Inflow	None	60	18
	8/8/2005	Inflow	125 μm	26	5
	8/8/2005	Inflow	75 μm	15	5
	8/8/2005	Outflow	None	5	2
	8/8/2005	Outflow	125 μm	5	2
# 3	8/8/2005	Outflow	75 μm	4	2

Table A-6 Comparison of the Storm Duration and Rainfall Amount at the Anderson Mill Basin

Storm Date	Duration (hr)	Rainfall Amount (in)
7/27/2005	3	1.02
8/5/2005	16.5	0.41
8/8/2005	15	1.41

Table A-7 SSCs for the Samples Collected from the Vegetated Filter Strip at Site 2 from Storm Event on May 28 to 29 of 2005

Location	Sieve Size	SSC (mg/L)	VSS (mg/L)
0m	None	182	48
0m	None	203	-
2m	None	193	-
4m	None	268	-
8m	None	273	50
8m	None	236	-
0m	125 μm	113	-
2m	125 μm	85	-
4m	125 μm	55	-
8m	125 μm	59	-
0m	75 μm	78	-
0m	75 μm	74	15
2m	75 μm	56	-
4m	75 μm	30	-
8m	75 μm	22	-
8m	75 μm	24	8
8m	75 μm	20	8

APPENDIX B: PARTICLE SIZE DISTRIBUTIONS OF THE RUNOFF SAMPLES

LIST OF FIGURES

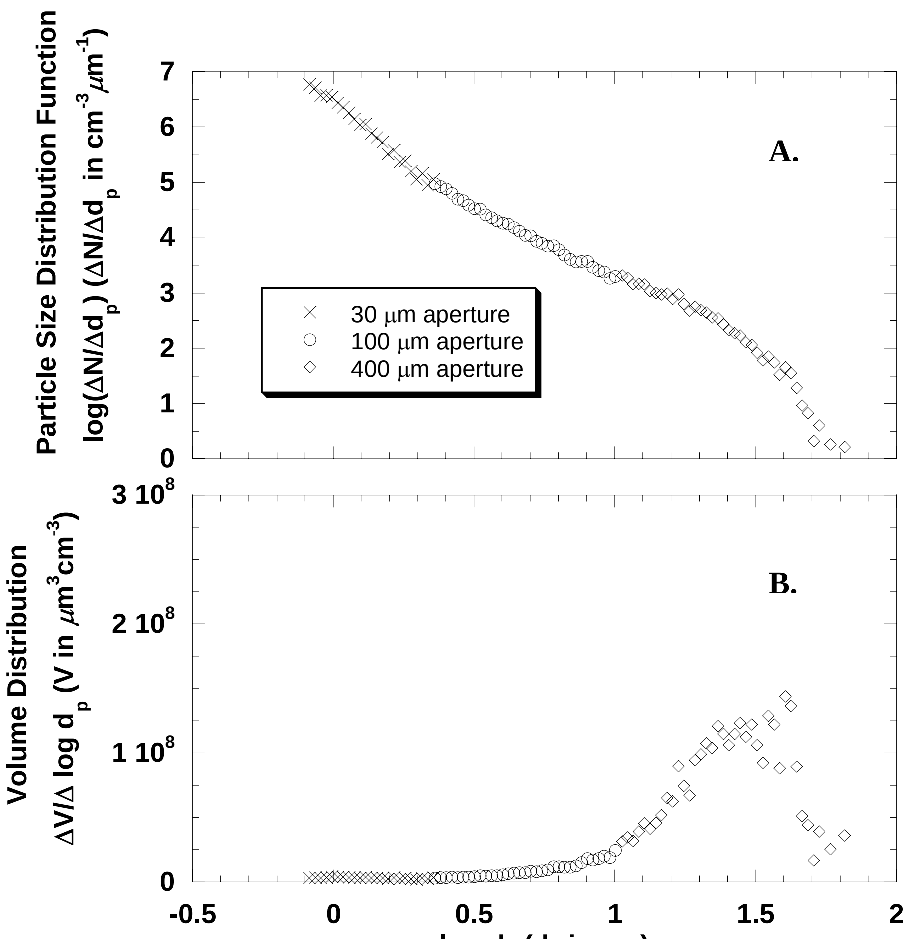

Figure B-1 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution of Bridge Approach Highway Sample Collected on January 4, 2005. Average SSC was 79 mg/L.**

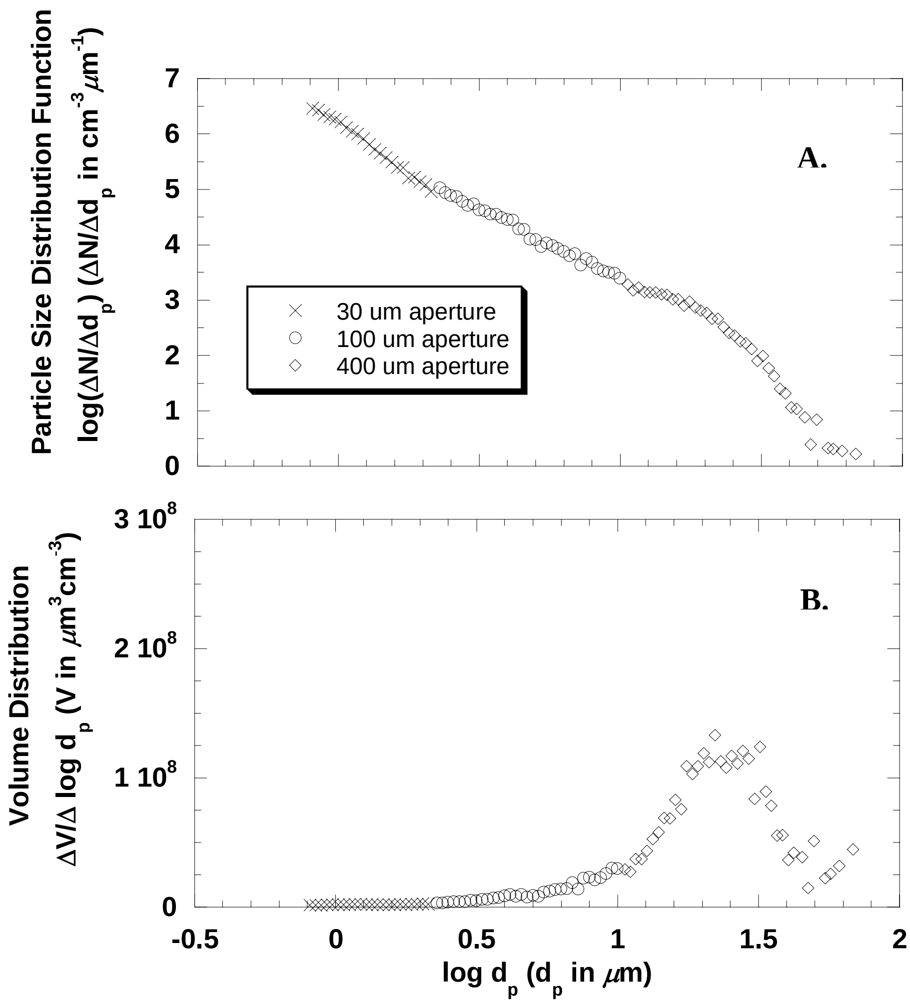

Figure B-2 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of Bridge Approach Highway Sample Collected on March 26, 2005. SSC was 129 mg/L.

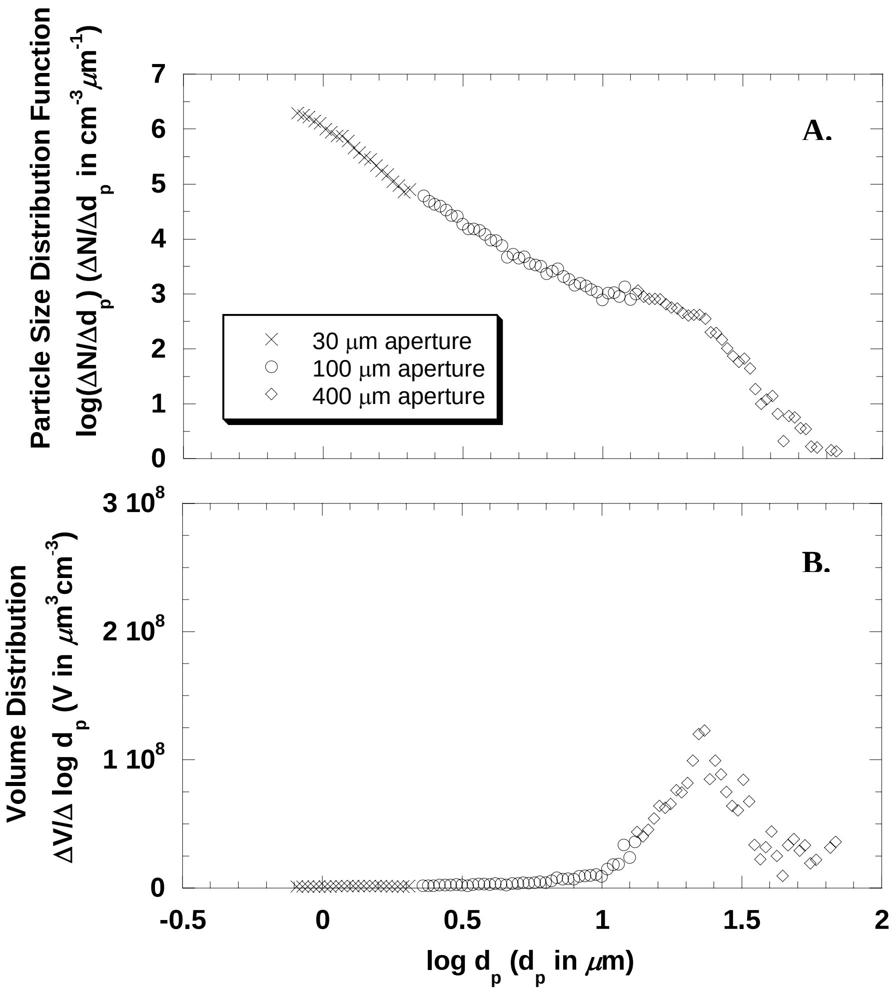

Figure B-3 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of Bridge Approach Highway Sample Collected on May 8, 2005. SSC was 111 mg/L.

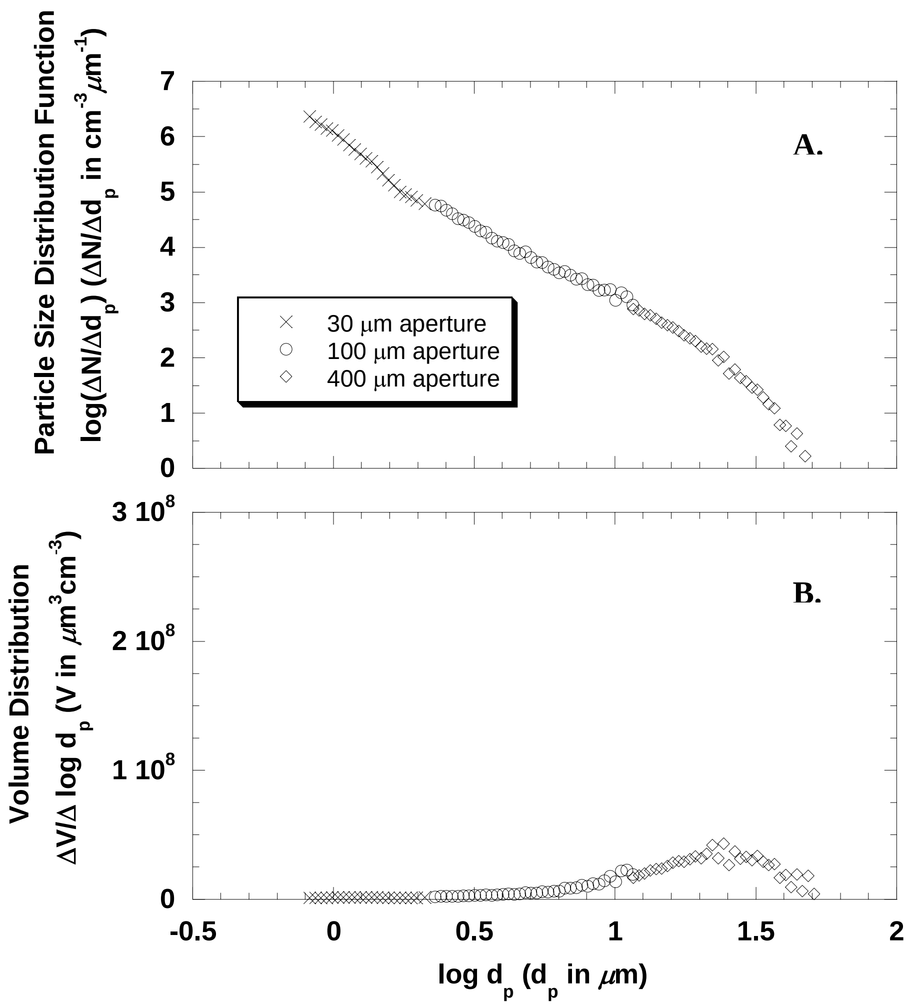

Figure B-4 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution of Bridge Deck Sample Collected on January 27, 2005. SSC was 30 mg/L.**

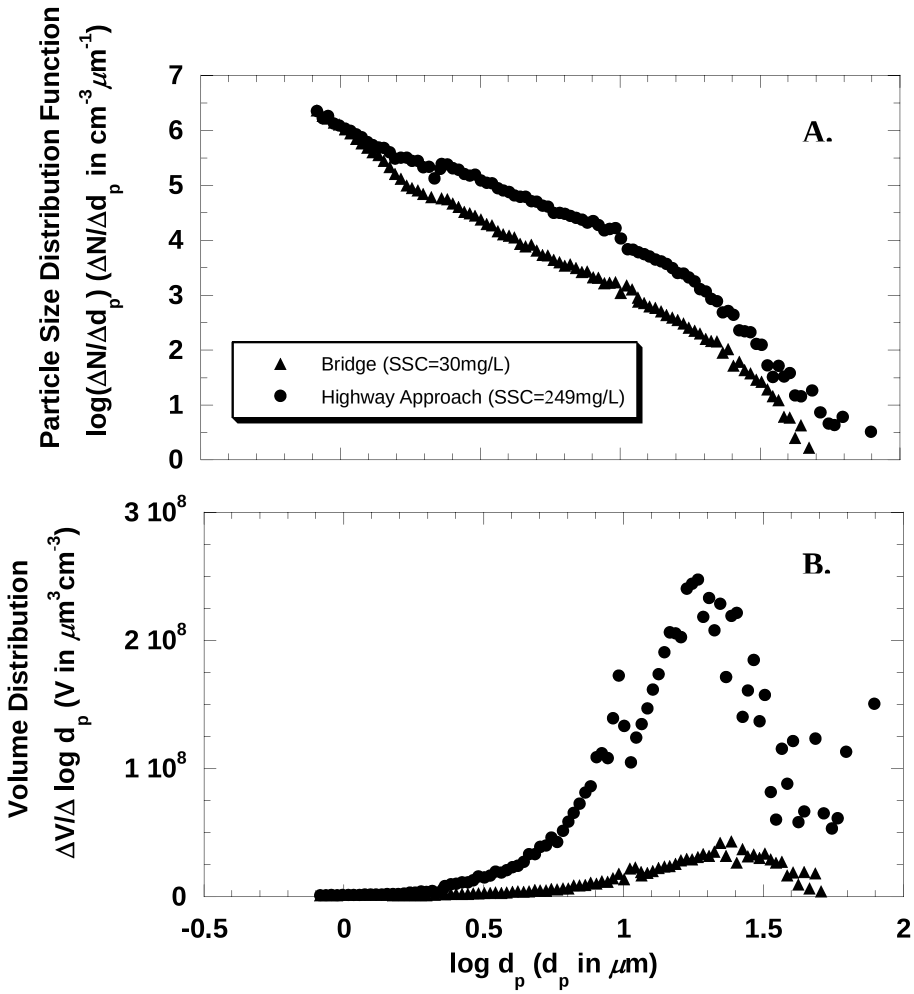

Figure B-5 *(A)* Particle Size Distribution and *(B)* Volume Distribution of Bridge Approach Highway Sample versus Bridge Deck sample that was Collected on January 27, 2005

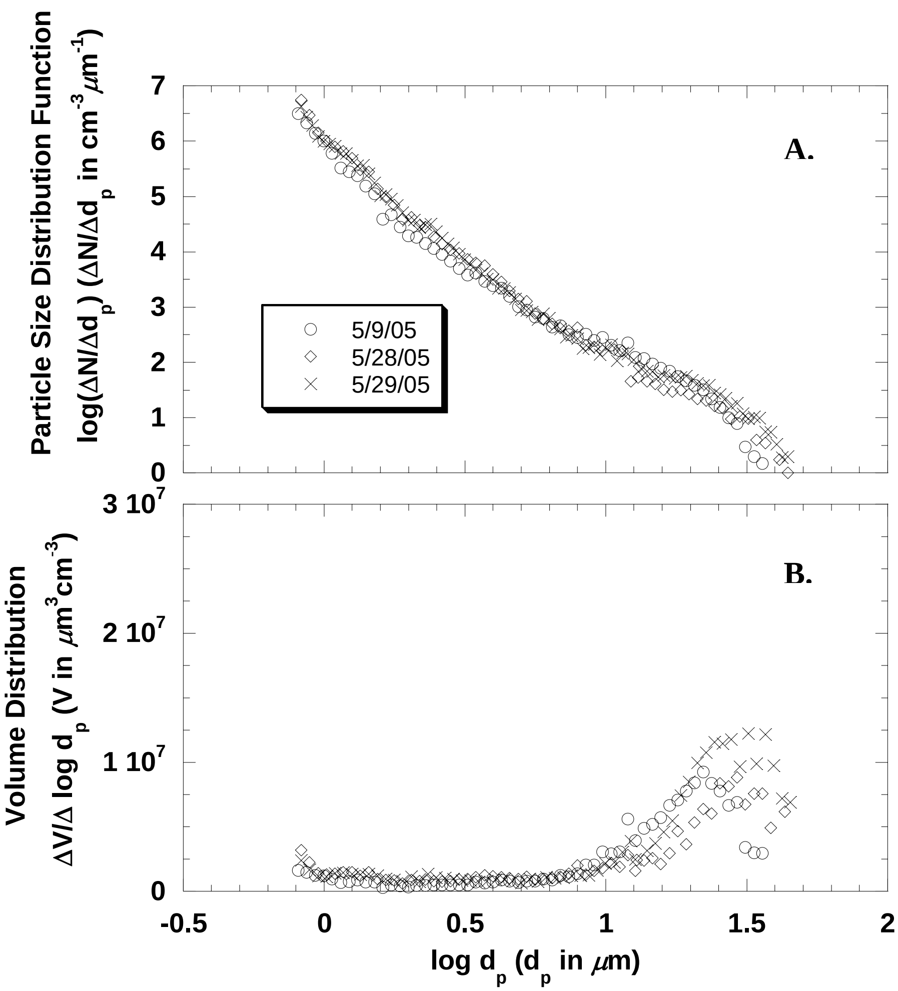

Figure B-6 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution of Grab Samples from Anderson Mill Basin Collected on May 8, 28, & 29 of 2005**

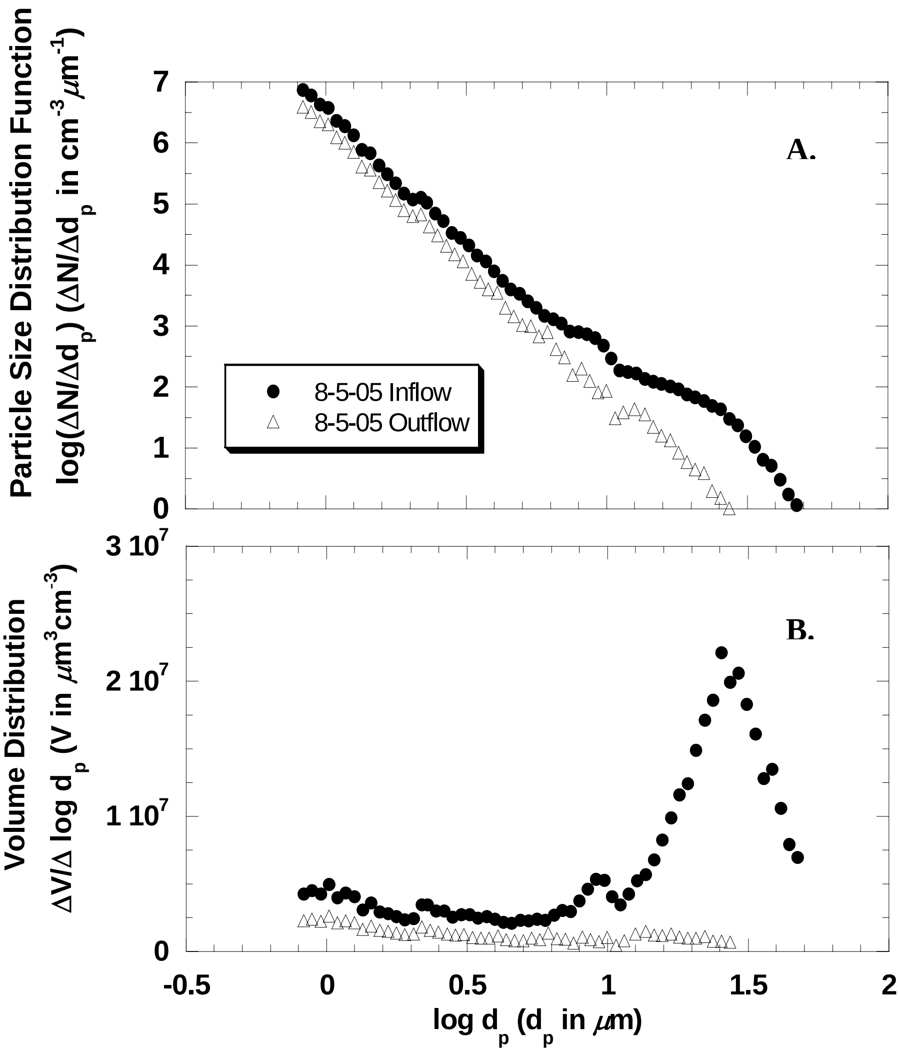

Figure B-7 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of Anderson Mill Basin Inflow and Outflow Samples Collected on August 5, 2005

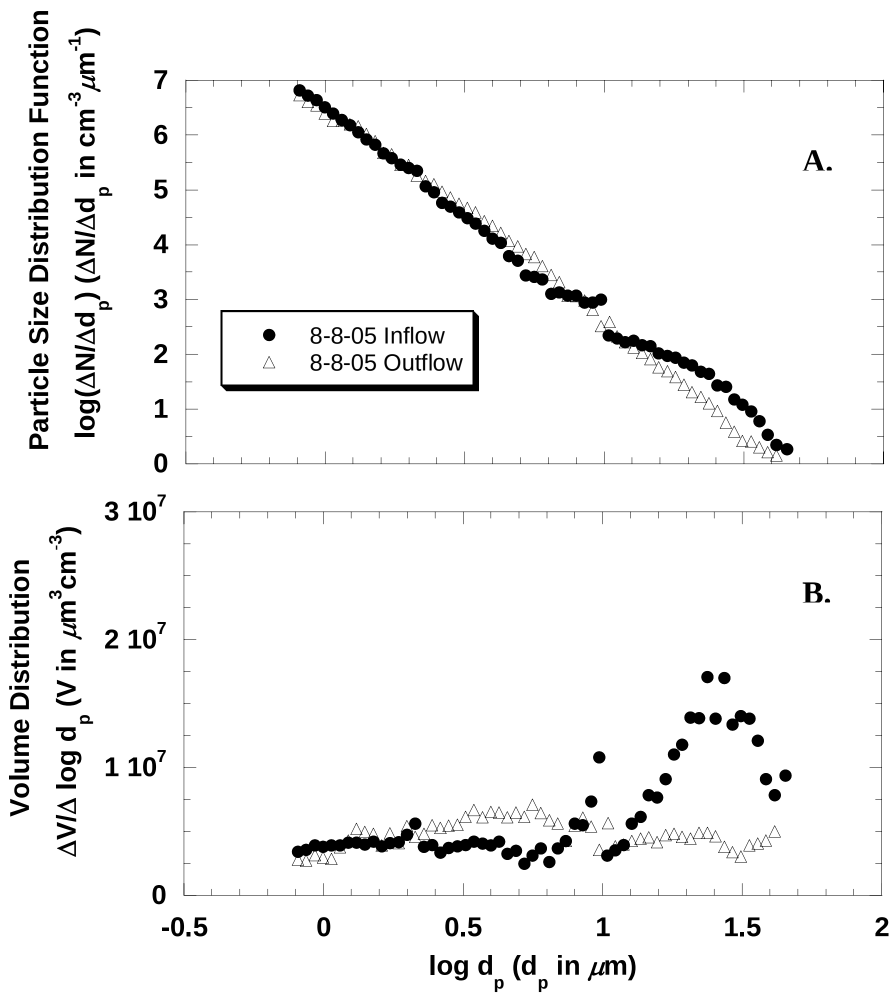

Figure B-8 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of Anderson Mill Basin Inflow and Outflow Samples Collected on August 8, 2005

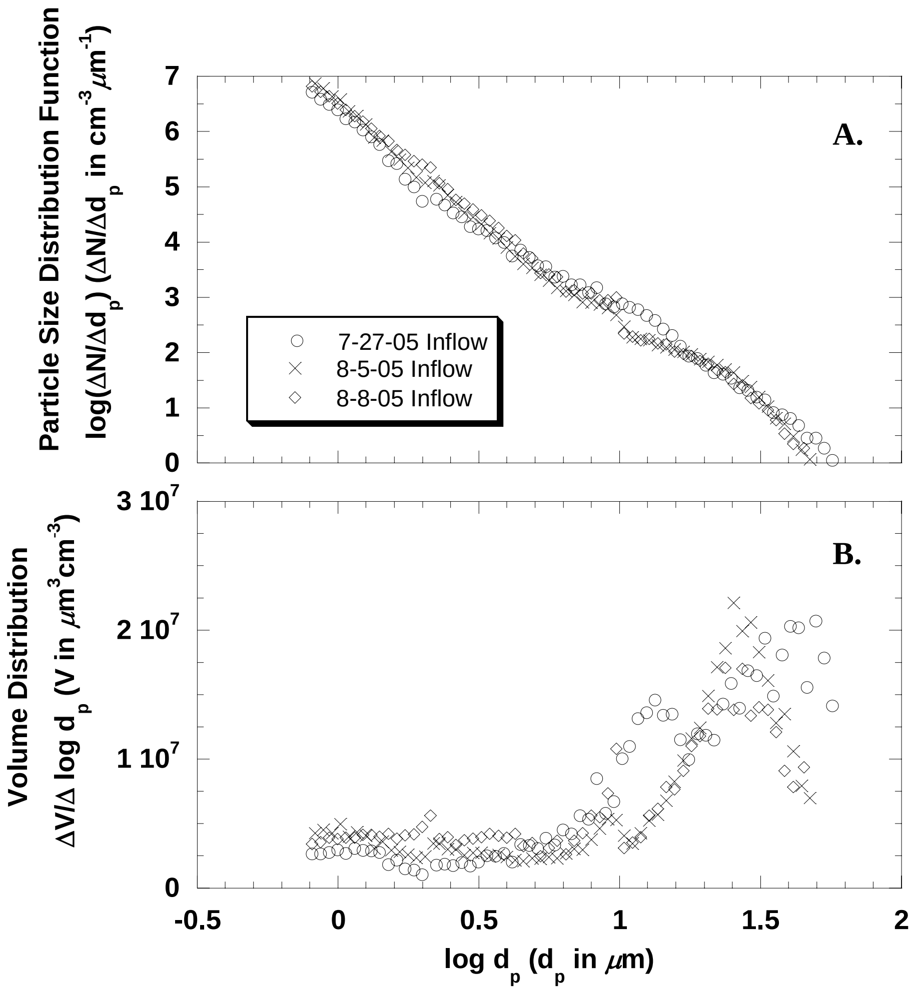

Figure B-9 *(A)* Particle Size Distribution Function and *(B)* Volume Distribution of Inflow Samples at Anderson Mill Basin Collected on 7-27-05, 8-5-05, & 8-8-05

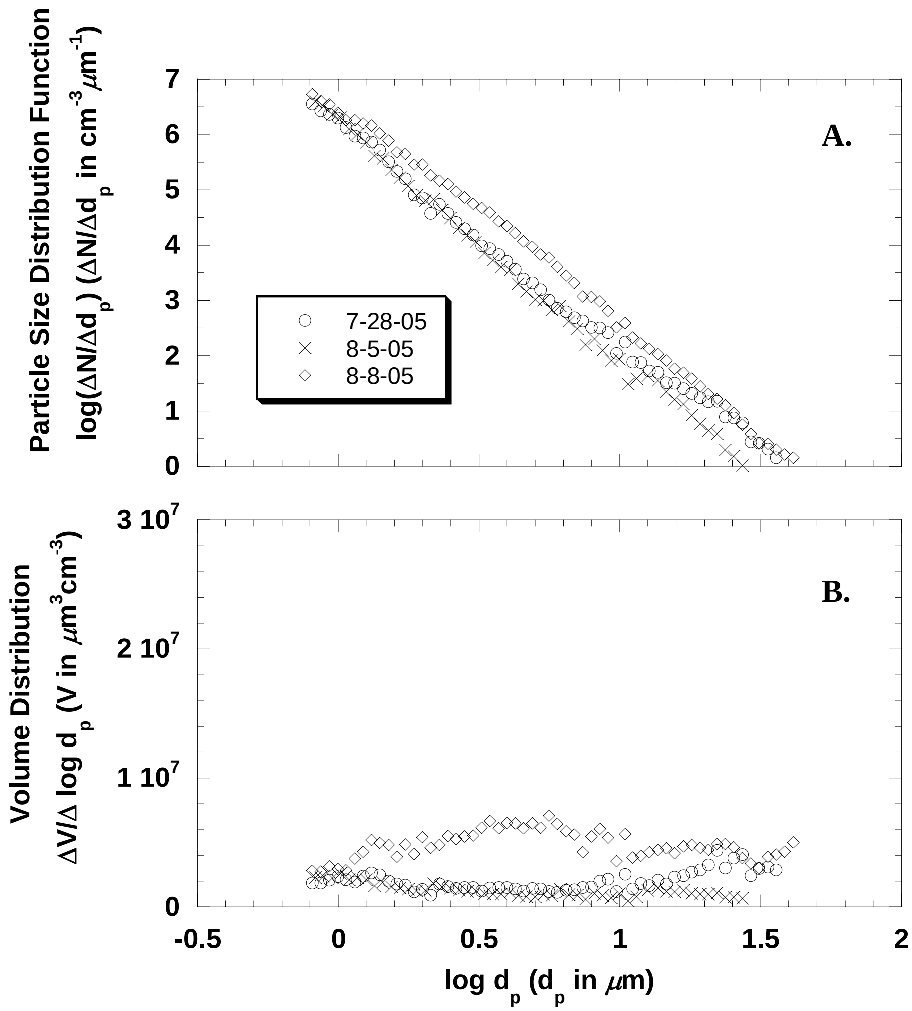

Figure B-10 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution of Outflow Samples at Anderson Mill Basin Collected on 7-27-05, 8-5-05, & 8-8-05**

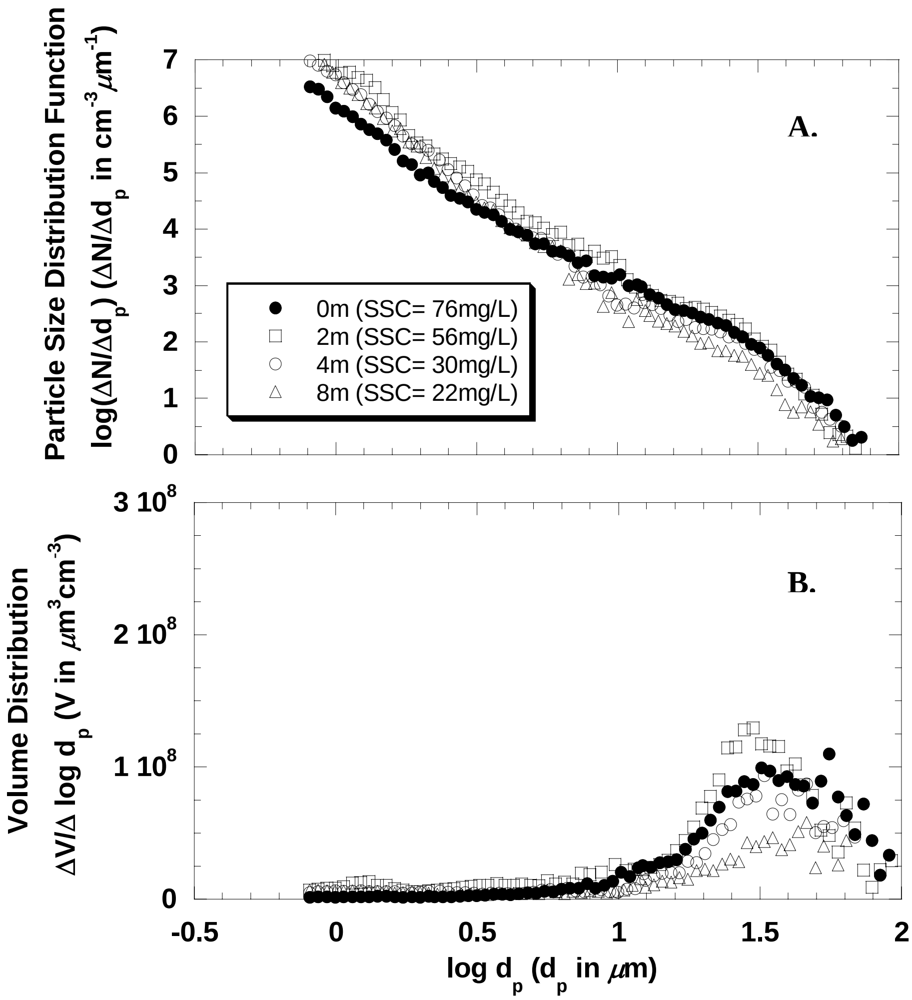

Figure B-11 (A*)* Particle Size Distribution Function and *(B)* Volume Distribution of the Samples Collected on May 28 and 29 at the Second Vegetated Filter Strip Site

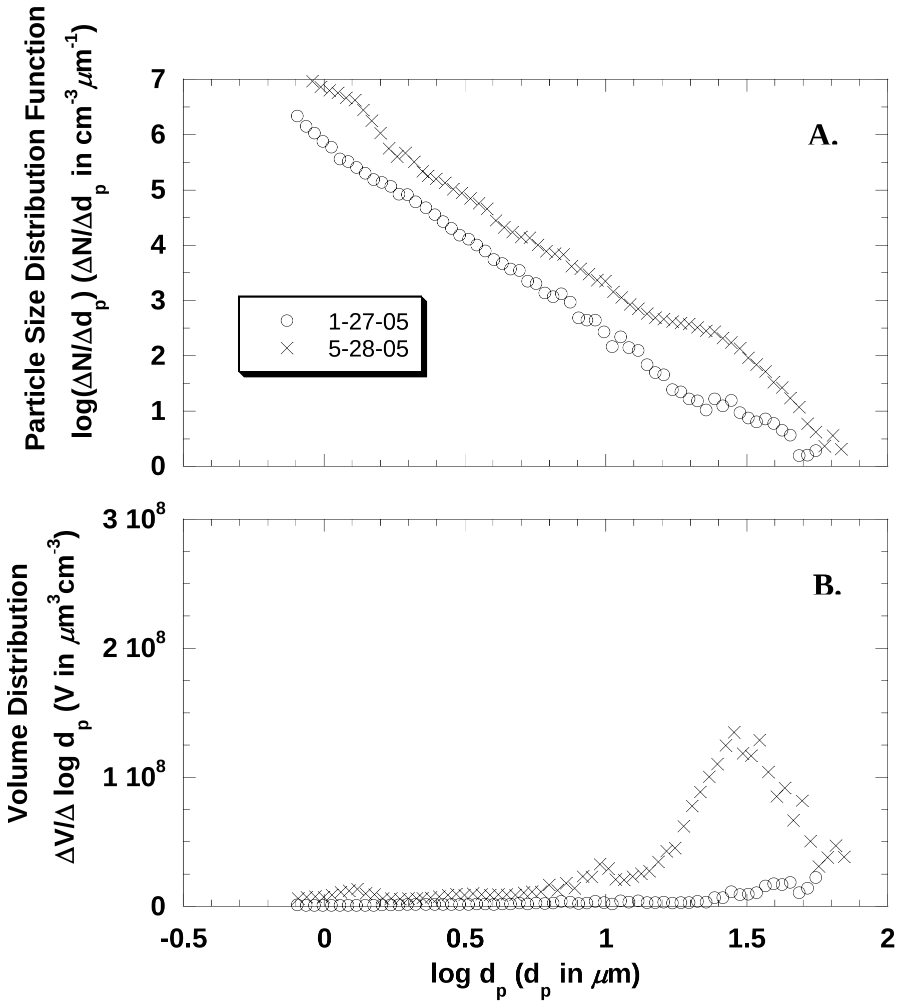

Figure B-12 ***(A)*** **Particle Size Distribution Function and** ***(B)*** **Volume Distribution of Vegetated Filter Strip Samples at 2 m from Sites: 1 (Collected on 1-27-05) and 2 (Collected on 5-28-05)**

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