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# Measuring suspended sediment characteristics to identify accurate monitoring techniques in stormwater runoff

George Deforest Fowler  
*University of New Hampshire, Durham*

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Measuring Suspended Sediment Characteristics to Identify Accurate  
Monitoring Techniques in Stormwater Runoff

By

George Deforest Fowler  
BA Biology, Stonehill College, 1999

Thesis

Submitted to the University of New Hampshire  
in Partial Fulfillment of  
the Requirements for the Degree of

Master of Science  
In  
Civil Engineering

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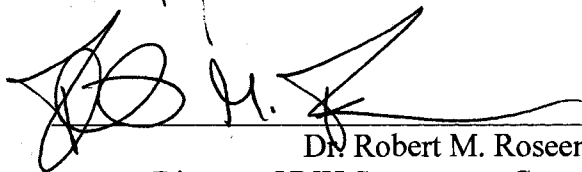
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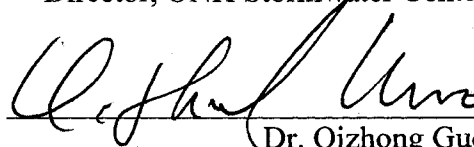
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Thesis Director, Dr. Thomas P. Ballestero,  
Associate Professor, Civil Engineering



Dr. Robert M. Roseen,  
Director, UNH Stormwater Center



Dr. Qizhong Guo  
Associate Professor Civil Engineering

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## List of Abbreviations

AS	Field Method using Automatic Samplers
ASCE	American Society of Engineers
BMP	Best Management Practice
C	Sample measured using Tri-Laser Diffraction
EMC	Event Mean Concentration
EPA	Environmental Protection Agency
FISP	Federal Interstate Sedimentation Project
FTU	Formazin Turbidity Units
KS	Komolgorov-Smirnoff Test
NPDES	National Pollution Detection Elimination System
NTU	Nephelometric Turbidity Units
NTU-S	Paired data for turbidity and results from Suspended Sediment Concentration method
NTU-T	Paired data for turbidity and results from Total Suspended Solids method
PSD	Particle Size Distribution
SSC	Suspended Sediment Concentration
TARP:	Technology Acceptance Reciprocity Partnership
TC	Total Capture
TC Dec	Total Capture Sample Including Decanted Sediments
TSS	Total Suspended Solids
UNHSC	University of New Hampshire Stormwater Research Center
USGS	United States Geological Survey
WS	Sample Measured using Wash Sieve and Hydrometer
WERF	Water Environmental Research Foundation

## **Abstract**

### **Measuring Suspended Sediment Characteristics to Identify Accurate Monitoring Techniques in Stormwater Runoff**

by

George Deforest Fowler

University of New Hampshire, December, 2008

This research examined several methods for monitoring suspended sediment concentration and particle size in stormwater runoff.

Suspended sediment concentration was monitored using the following methods: automatic sampling reported as Suspended Sediment Concentration (SSC), automatic sampling reported as Total Suspended Solids (TSS), turbidity reported as SSC and turbidity reported as TSS. Particle size distribution (PSD) was measured in samples from automatic samplers using tri-laser diffraction. An entire volume of the discharge passing by the automatic samplers and turbidity meter was captured and presumably contained the actual values to which all other methodologies were compared.

Automatic sampling with SSC proved to be the most accurate in representing the actual suspended sediment concentration. The TSS method's accuracy suffered during events with high discharge rates. Turbidity was not found to be an accurate measure to represent suspended sediment concentration. Automatic samplers collected samples containing sand size sediments but did not have a representative PSD.

December 2008

## **Chapter 1**

### ***I Introduction***

#### **1.1 Background**

Stormwater has been identified as the number one source of pollution to surface water (US Environmental Protection Agency 2005). Stormwater runoff from impervious areas degrades receiving waters by increasing the quantity of polluted water in river systems in a short period of time. Common pollutants found in stormwater are heavy metals, petroleum products, bacteria, and suspended sediments (US EPA 2007). These pollutants degrade the quality of surface water and impair fish/macro invertebrate habitat.

For this reason, the regulation of stormwater runoff in large municipalities (populations greater than 250,000) is an important part of the non-point detection and elimination system (NPDES) overseen by the EPA. This program expanded to include all urban areas in the United States (US EPA 2007). There are over 450 of these urban areas and they contain approximately 65% of the population of the United States (US Census Bureau 2002). These areas are required to obtain a permit to discharge stormwater into the waters of the United States. Part of the permit application is the monitoring of stormwater runoff.

A common standard of stormwater monitoring practice was created by federal and state regulatory organizations due to the enormous application of stormwater regulation and the necessity to have reciprocity for all stormwater monitoring. The EPA and a handful of regulated states led the push for this standardization (Pennsylvania Department of Environmental Protection 2007). These guidelines explain how, when, and where samples should be taken from stormwater infrastructure in order to monitor for pollutants. However, when suspended sediments are the pollutant of interest, prior research has shown that some of these guidelines could contribute bias in sampling, analytical and reporting methods (Bent G. et al. 2001; Kayhanian M. et al. 2005)

## **1.2 Research Objective**

The purpose of this study was to evaluate several methods of monitoring suspended sediments in stormwater runoff. These monitoring methods included: grab and composite sampling techniques taken manually or by automatic sampler, total suspended solids (TSS) and suspended sediment concentration (SSC) analytical analysis, turbidity and tri-laser diffraction (light obstruction). Suspended sediment characteristics were reported as: sediment event mean concentrations (EMC), total sediment load, particle size distribution (PSD), and specific gravity. The results of this research should provide guidance in choosing which method is most reliable for monitoring and reporting of suspended sediments in stormwater runoff.

## **1.3 Description of Research**

Two suspended sediment characteristics were selected in order to evaluate the utility of the different methodologies used to measure these variables in stormwater



runoff. The two characteristics were suspended sediments concentration and particle size distribution of suspended sediments. Five monitoring methods utilized a combination of sampling and analytical techniques to measure these two characteristics. The monitoring methods for estimating the suspended sediment EMC were: automatic sampler using the SSC analytical method, automatic sampler using the TSS analytical method, Turbidity measurements transformed into SSC, Turbidity measurements transformed into TSS, and manual sampling followed by a wash sieve analysis. The monitoring methods for PSD were: automatic sampler with Tri-Laser Diffraction and manual sampling with wash sieve and hydrometer analyses.

The manual sampling method captured all of the stormwater runoff that flowed by the automatic samplers and the turbidity meter. This manual sample was a large volume 11,340 L (3,000 gallon) grab sample. This sample contained what was presumed to be the true suspended sediment concentration and particle size distribution to which all other monitoring methods were compared.

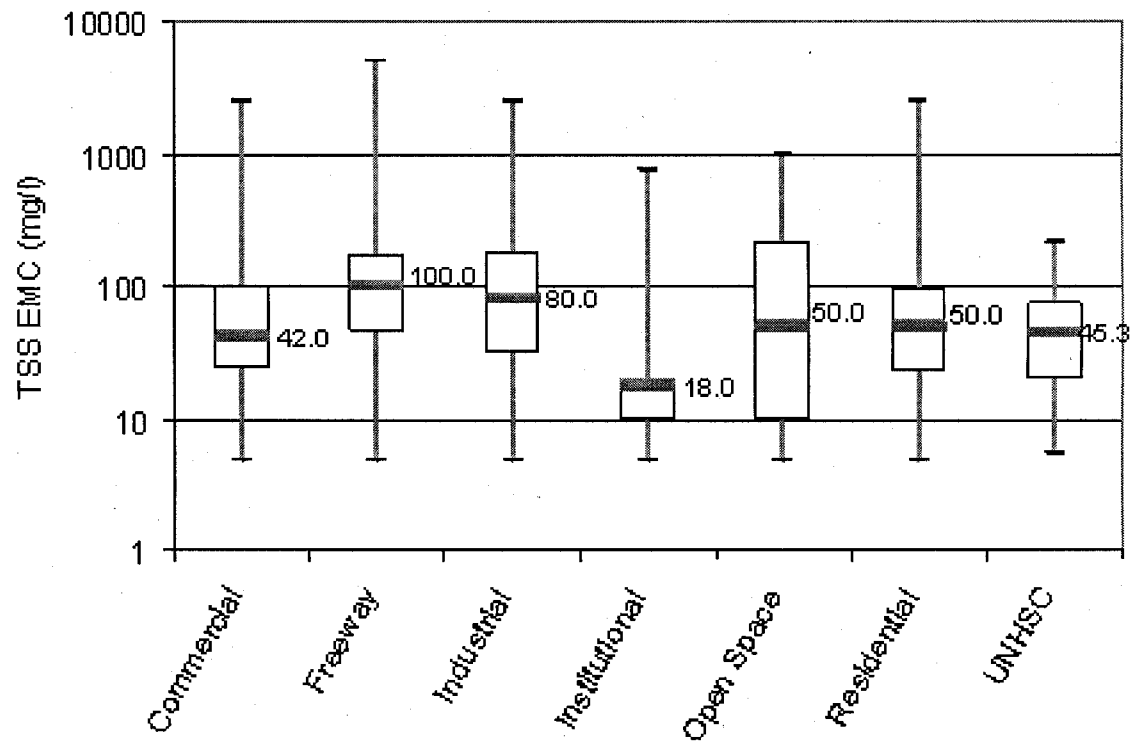
All field monitoring methods in this investigation followed federal and state guidelines as well as previous research recommendations whenever applicable. The EMCs from the four suspended sediment concentration monitoring methods were compared to the presumed known value obtained from the large volume manual sample identify which field method was most accurate. The PSD of the suspended sediments captured by automatic sampling was compared to the presumed actual PSD of the suspended sediments captured in the manual grab sample to determine if the field method had the capacity to capture a representative PSD.

#### **1.4 Site Location:**

This investigation took place at the University of New Hampshire Stormwater Center in Durham, NH. The climatology of the area is characterized as a coastal, cool temperate forest. Average annual precipitation is 122 cm uniformly distributed throughout the year, with average monthly precipitation of 10.2 cm +/-1.3. The mean annual temperature is 9°C, with the average low in January at -9°C, and the average high in July at 28°C.

The dates of performance of this study were between June 2006 and April 2008. The facility is located on the perimeter of a 3.6 hectare commuter parking lot at the University of New Hampshire in Durham. The parking lot, installed in 1996, is standard dense mix asphalt, completely curbed and guttered, and is near capacity throughout the academic year. Activity is a combination of passenger vehicles and routine bus traffic. The runoff time of concentration for the lot is 22 minutes, with surface slopes ranging from 1.5-2.5%. The area is subject to frequent plowing, salting, and sanding during the winter months. When assessing the site runoff water quality, literature reviews indicate that suspended sediment concentrations are above or equal to national norms for parking lot runoff (Roseen R. et al. 2006) as seen in Figure 1.

Figure 1: Comparison of Sediment Concentrations to Site Location (UNHSC)



## **Chapter 2:**

### ***II Literature Review***

#### **2.1 Necessity of Suspended Sediment Monitoring in Stormwater**

##### **2.1.1 Chronology of Stormwater Regulation**

The US Environmental Protection Agency, under the jurisdiction of the Clean Water Act, began to regulate the quality of stormwater runoff in 1990 (US EPA 2007) as part of the National Pollution Detection and Elimination System (NPDES) program. These regulations hold municipalities, industries, and construction sites accountable for the quality of runoff leaving their control. Table 1 describes the chronological evolution of the EPA's regulatory statute concerning stormwater runoff (US EPA 1996). Initially, municipalities (MS4s) fell under the NPDES program based on a population threshold. However, due to the economic sensitivity of coastal areas, the Coastal Zone Reauthorization Act (CZAR) was established to serve as a bridge for smaller Ms4s and urban areas near coastal waters which did not meet this threshold. When Phase II of the NPDES stormwater program began and included urban areas (50,000 populace or 10,000 people per square mile) CZAR became void (US EPA 1993).

Table 1: Chronological History of Stormwater Regulations

Year	Regulatory Phase	Responsible Party	Population	Population Density
1990	NPDES Phase I	Large Ms4s	100,000	
1992	303(D) Listing of Impaired Waters & TDML Program	States	--	--
1993	CZAR	Coastal Urban Areas	50,000	10,000/mi <sup>2</sup>
1999	NPDES Phase II	All Urban Areas	50,000	10,000/mi <sup>2</sup>

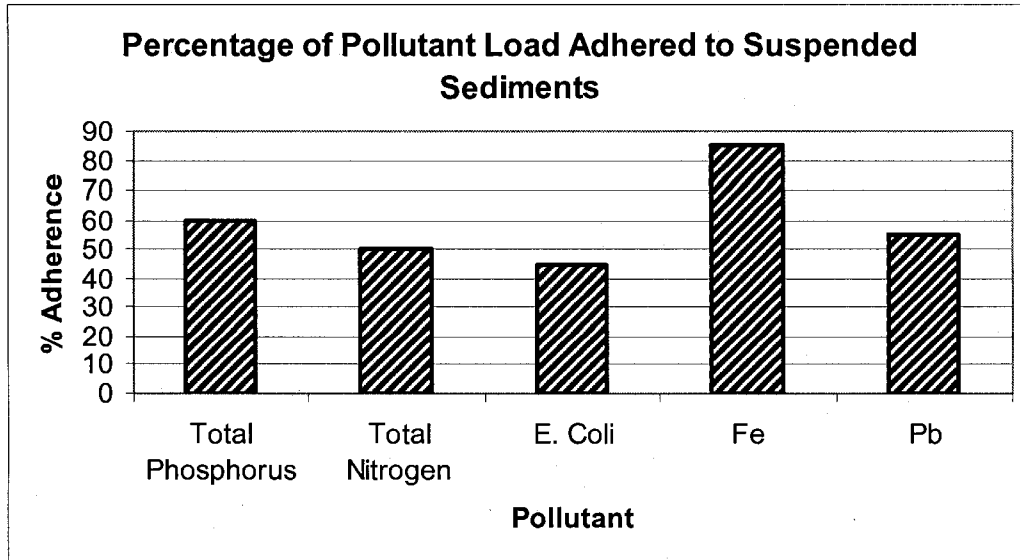
The next step in stormwater regulation was the implementation of the Total Maximum Daily Load (TMDL) program as part of the Clean Water Act. This program began in 1992 under section 303 (d) and states: "...states are required to develop lists of impaired waters. These are waters for which technology-based regulations and other required controls are not stringent enough to meet the water quality standards set by states. The law requires that states establish priority rankings for waters on the lists and develop TMDLs for these waters. A TMDL is a calculation of the maximum amount of a pollutant that a water body can receive and still safely meet water quality standards (US EPA 2008)." These pollutant limits include among others: phosphorus, metals, and suspended sediments. Pollutants in stormwater runoff are considered both point and non point source contributors and fall underneath the TDML regulations.

### 2.1.2 Suspended Sediment Regulation in Stormwater:

Suspended sediments have been identified as a surrogate for other pollutants in stormwater (US EPA 2007) as a measure of the overall quality of stormwater runoff. Many pollutants associate (adhere) with suspended sediments when they are carried off in stormwater runoff. The percentages of adherence for some commonly found constituents in stormwater are listed in Figure 2. These constituents include: Iron (Fe), Lead (Pb)

(Sansalone J. et al. 1997a), Phosphorus, Nitrogen (Vaze et al. 2004) and bacteria (Characklis G. et al. 2005).

Figure 2: Percentage of Pollutants Adhering to Suspended Sediments



Suspended sediments have been selected as a surrogate for trace level pollutants to determine the overall quality of stormwater runoff (US Environmental Protection Agency 1993; James R. 2003; Technology Acceptance Reciprocity Partnership 2003). The EPA and many states have established limits on the suspended sediment concentration levels which can be discharged into receiving waters and have published guidelines on how to monitor for suspended sediments (US EPA 1992; US EPA 1993; Technology Acceptance Reciprocity Partnership 2003).

Federal regulation of suspended sediments in stormwater did not begin until the introduction of CZAR. This act established as 80% reduction in suspended sediment concentration after the completion of new development projects (US EPA 1993). With the expiration of the CZAR act and the beginning of NPDES Phase II, the suspended sediment limit disappeared from the federal limits but was continued by some states

(Technology Acceptance Reciprocity Partnership 2003) still using the 80% reduction of suspended sediment concentration as the target to improve stormwater runoff.

Suspended sediment TMDLs are being established by states as part of their TMDL program for some of their 303(d) impaired waters. Federal guidance offers advice on how these TMDLs can be established for suspended sediments (US EPA 1999). Federal guidance also suggests that the monitoring of sediments is an effective way to gauge if municipalities are improving the quality of their stormwater discharge (US EPA 2005).

### 2.1.3 Suspended Sediment Monitoring Guidelines

With the majority of large urban areas being held responsible for the quality of their stormwater discharge, federal and state guidelines have been established to standardize stormwater monitoring protocols to assist these municipalities in fulfilling their permit obligations (US EPA 2002; Technology Acceptance Reciprocity Partnership 2003; Washington Department of Ecology 2008). This guidance shapes the frequency of event monitoring and which methods are used to monitor for suspended sediments.

Another driver to standardize suspended sediment testing protocol is the advancement of the technologies and interventions used to reduce suspended sediments in stormwater runoff. These are commonly referred to as Best Management Practices (BMPs). The implementation of the NPDES and TMDL programs have driven commercial development of stormwater treatment devices and have improved upon as well as increased the number of technologies used to remove suspended sediments. To compare the pollutant removal efficiency of these best management practices, a national database, hosted by the EPA, was created to exchange removal efficiency information. The EPA established protocols dictating how a BMP should be monitored in order to

develop removal efficiency rates that meet these national database standards (US EPA 2002). A group of five states banded together to form the Technology Acceptance and Reciprocity Partnership (TARP) which developed its own standards which meet or exceed federal standards for BMP testing (Technology Acceptance Reciprocity Partnership 2003).

## **2.2 Monitoring Methods for Suspended Sediments in Stormwater**

To establish the necessary protocol for a monitoring program for suspended sediments, the measurable characteristic(s) of interest should be selected to determine which field and laboratory tests are required (US EPA 1992). This will help shape the overall monitoring methodology such as: sample type, number of samples and analytical method for each sample. The following sections will outline how some suspended sediment characteristics are measured in the field and lab and the potential sources of bias.

### **2.2.1 Suspended Sediment Characteristics**

Various characteristics are used to describe suspended sediments in stormwater such as: suspended sediment concentration, particle size distribution (PSD), suspended sediment load, specific gravity, and optical properties (turbidity). Sediment concentration is the time honored method of measure for suspended sediments in stormwater for regulatory and removal efficiency purposes (US Environmental Protection Agency 1992; US Environmental Protection Agency 1993; US Environmental Protection Agency 2005; TARP 2003). Sediment load, or total sediment mass is a required reporting measure as part of the EPA's TMDL program (US EPA 1999). Particle size distribution is a variable that characterizes the size fractions of suspended sediments (Furumai H. et



al. 2002; Li Y. et al. 2005), which is important because certain pollutants adhere to specific particle sizes (Sansalone J. et al. 1997a). Specific gravity is measured in part to determine the sediment settling characteristics which are an important attribute for BMP design (Li Y. et al. 2006a). Turbidity is an indirect way to measure suspended sediment in surface waters once a relationship between suspended sediment concentration and turbidity has been established (Gartner J. et al. 2004).

### 2.2.2 Definition of Suspended Sediments

Three states of sediments exist in stormwater and the delineation between each state is determined by particle size. The three states of sediments are: dissolved sediments, suspended sediments and bedload. Sediments in stormwater are composed of organic and inorganic particles. The American Society of Civil Engineers (ASCE) has used the Water Environment Research Foundation's (WERF) recommendation to establish the distinction between dissolved and suspended sediments (Environmental Water Resources Institute 2007; Roesner L. et al. 2007). This distinction establishes a lower limit for suspended sediments at 2  $\mu\text{m}$ , which is consistent with Standard Methods 2540 (American Public Health Association 1999). The upper limit of the suspended solids size definition is still unclear. The ASCE has suggested a size distinction for gross solids. This limit is suggested to be at 5.0 mm (Environmental Water Resources Institute 2007). WERF (Roesner L. et al. 2007) has suggested a further distinction between fine and coarse solids using the size of 75  $\mu\text{m}$  which would likely transport in a storm sewer as bed load and are not necessarily suspended in the water column. Nevertheless, for this study, suspended sediments are defined as organic and inorganic particles between 2.0  $\mu\text{m}$  and 5000  $\mu\text{m}$ . Particles above this size limit are called gross solids and include

sediments which behave in stormwater like bed load and are not necessarily suspended in the water column.

### 2.2.3 Overview of Sample Collection

Institutions that discharge stormwater into the waters of the United States need to obtain a permit to do so if they fall under the criteria of the NPDES program. In order to comply with permit conditions, applicants need to sample stormwater discharge in order to quantify pollutant concentrations.

To assist applicants, federal guidance has been established to standardize field sampling methodologies to ensure samples collected from stormwater discharge are an accurate representation of annual average pollution concentration of the passing water (US EPA 1992).

Institutions responsible for stormwater quality integrate BMPs into their management plans. In order to quantify the BMPs' pollutant removal efficiency, states have established testing standards that dictate how a BMP is to be tested in order to determine its pollutant removal efficiency (Technology Acceptance Reciprocity Partnership 2003). This type of guidance delineates when and how stormwater samples, including samples taken for suspended sediments, are extracted.

When and Where to Monitor. EPA guidelines state that municipalities must sample at least three storms to develop pollutant characteristics. The hydrology conditions for these rainfall-runoff events must be within 50% of the average depth and duration (US EPA 1992). Storms should exceed 2.4mm (0.1 inches) in depth and have had at least 72 hours of dry weather in between storms (US EPA 1992). Samples should

be taken from the lowest point in the drainage system, the invert and closest to the outlet of the pipe, with no additional discharge entering the pipe behind the sampling location. For the BMP performance evaluation, TARP protocol states that at least 50% of the annual rainfall depth should be monitored (Technology Acceptance Reciprocity Partnership 2003). TARP protocol varies from the EPA guidance by saying that a sampling event can occur with as little as six hours separating storm events.

Sampling Techniques. There are two basic stormwater sampling techniques: samples can be taken manually or captured using automatic samplers. Obtaining manual samples involves sending personnel to the sampling location before the rain event occurs and physically capturing samples as the stormwater effluent leaves the pipe. This process is burdened with resource issues centering on moving personnel to the sampling locations before a rain event and capturing samples in potentially hazardous situations.

The use of automatic samplers provides a solution to the above mentioned complications. These samplers can be triggered remotely or be programmed with a sampling protocol to begin taking samples as soon as the rain event begins (flow trigger or precipitation trigger). The benefit of using automatic samplers is that many samplers can be placed concurrently in different locations to capture a rain event. The location of the sampling intake of the samplers can be secured to the bottom of the invert of a pipe, swale, or other location of interest ensuring the same cross sectional location of pipe is sampled. This is referred to as a point integrated sample (Lane S. et al. 2003).

Automatic samplers may also include data logging capabilities that can record the following real time data: rainfall, pipe discharge, turbidity, pH, Specific Conductivity, dissolved oxygen, and temperature.

Sample Types. There are two sample types, grab and composite samples. The volume needed in both types of samples to measure sediments is between 50-1000 mL (US EPA 1992).

Grab samples are samples that are taken without interruption and represent the stormwater at that instant of time. Grab samples can be taken manually or by automatic samplers (US EPA 1992). “Composite samples are samples simply comprised of a series of individual aliquots that when combined, reflect the average pollutant concentration of the storm water discharge during the sampling period (US EPA 1992).” The spacing between when aliquots are taken is paced using either flow or time. The following four types of composite samples can be developed and are illustrated in Figure A-1:

- Constant Time-Constant Volume: A single composite average sample created from a set of samples having equal volumes which were taken at equal increments of time during an event.
- Constant Time-Volume Proportional to Flow Increment: A single or set of composite samples that were created by varying the volume being placed in them proportionally to the amount of flow that passed by during equal lengths of time.

- Constant Time-Volume Proportional to Flow Rate: A single or set of composted samples that were created by varying the volume being placed in them, depending on the flow at the time each sample was collected.
- Constant Volume-Time Proportional to Flow Volume Increment: A single or set of composite samples that were created by sampling a constant volume varying with time depending on flow rate.

Supportive Data Collection. Regardless of the type of sample taken, grab or composite, the following data needs to be recorded in order to comply with federal and state sampling guidelines. This supplemental data is required in order to obtain the reporting values needed to comply with permitting and/or BMP removal efficiency guidelines (US EPA 1992; Technology Acceptance Reciprocity Partnership 2003). Table 2 shows the required supplemental data that needs to be recorded, and how it should be measured.

Table 2: Required Supplemental Data for Monitoring Suspended Sediment Concentration

<b>Data</b>	<b>Method of Monitoring</b>
Rainfall Depth	Rain Gauge (Tipping, Weighing, etc.)
Pipe Discharge	Weir, Flume, Ultrasonic measure
Date/Time	Digital Clock

Potential Bias in Suspended Sediment Sampling Techniques. Samples extracted manually need to be consistently taken from the same cross sectional location of the pipe and this section of the pipe needs to be well mixed. Different size particles will behave dynamically with larger and finer particles tending to be transported along the bottom and

upper parts of the water column, respectively. A bias can occur if samples are taken from a particular location in the pipe's cross section that is not well mixed.

The type of automatic sampler used in stormwater monitoring can also bias results. A review of the protocol for sampling suspended sediments in surface water, suggests isokinetic samplers are necessary to accurately collect sand size particles and correctly calculate suspended sediment concentrations (US Geological Service 1998; Bent G. et al. 2001; Horowitz A. et al. 2008). An isokinetic sampler possesses the ability to adapt its sampling intake velocity to match the velocity of the incoming discharge. In order to obtain an accurate sample of particles with varying specific gravity and momentum characteristics, the samples should be withdrawn at the same velocity as the discharge (Othmer E. et al. 2002).

The majority of automatic samplers used in stormwater monitoring programs are non-isokinetic samplers. A non-isokinetic sampler does not possess the ability to create a velocity within the sampling tube that mimics the incoming velocity of the stormwater. Another potential bias with sediment monitoring is the location of the sampling probe intake itself. The location of the intake could influence the reporting accuracy of suspended sediment concentration (Horowitz A. et al. 2008). If the intake is located on the invert, it might draw in more coarse sediments and overestimate suspended sediment concentrations (ISCO 2001).

Pressure transducers and bubblers are used to monitor flow stage generally behind a weir or in a flume, and measure stage in or near real time. The weir stage to discharge relationships are usually developed in laboratories for the use in river or pipe monitoring applications. Bubblers are generally reliable except when the velocity in the pipe reaches

5 ft/sec. At this level a low pressure zone is induced around the mouth of the bubbler line producing false results (US EPA 1992).

#### 2.2.4 Characterization: Suspended Sediment Concentration

Regulatory guidance for stormwater quality monitoring and BMP removal efficiency typically quantify suspended sediments as a suspended sediment event mean concentration (EMC) (US EPA 1992; Strecker et al. 2001). A suspended sediment EMC is defined as the total weight of suspended sediments during a recorded event divided by the total water volume of said event as shown in Equation 1.

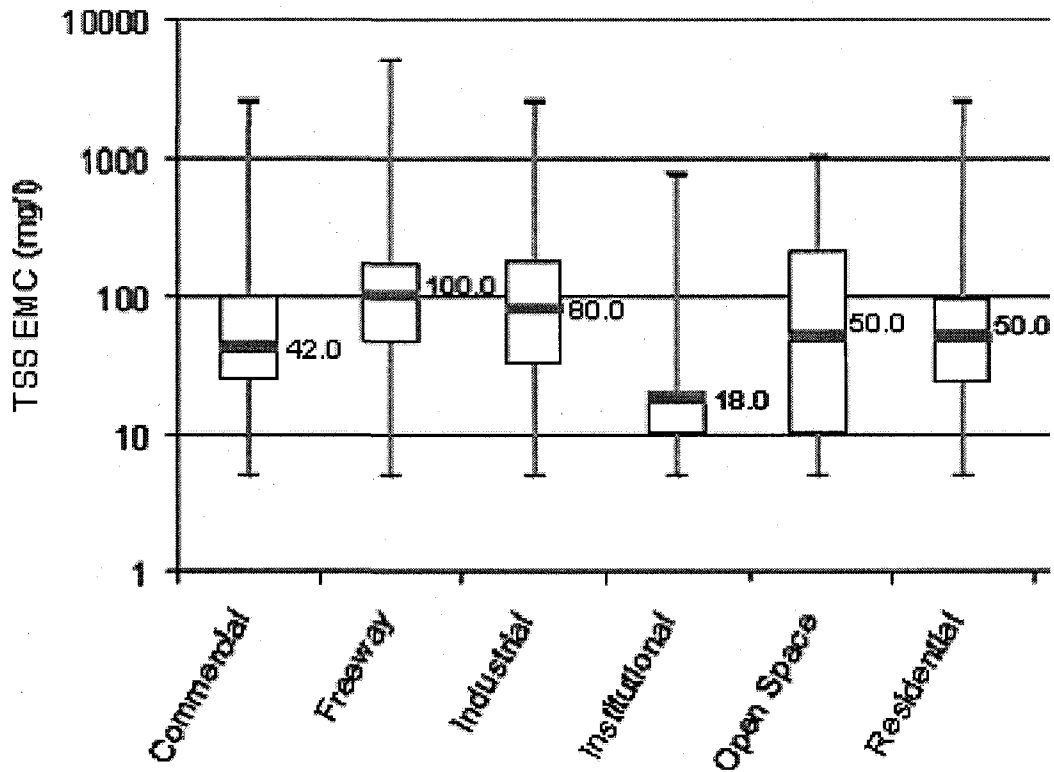
$$EMC = \frac{M}{V} = \frac{\int_0^T c(t)q(t)dt}{\int_0^T q(t)dt} \quad \text{Equation (1)}$$

Where M = the total weight of sediment during the event (kg); V = the total volume of water runoff (L); c(t) = the sediment concentration varying with time (mg/L), q(t) = the time variable flow (L/min); and T = the duration of the event (min).

Suspended sediment EMCs have been studied for several years on the stormwater discharge from the watershed of this investigation. The University of New Hampshire's Stormwater Research Center (UNHSC) has sampled several dozen events for stormwater quality (Roseen R. et al. 2006). The rainwater running off this watershed has been sampled for several contaminants including suspended sediment concentration which is measured as an EMC in units of mg/L. The UNHSC compared the median suspended sediment EMC found in this watershed's stormwater discharge to several other median

EMCs found in stormwater discharge from various land types. Figure 3 shows the range of sediment concentration values found in stormwater runoff from several types of land use (Roseen R. et al. 2006).

Figure 3: Sediment Event Mean Concentrations from Varying Land Uses (Roseen R. et al. 2006)



Analytical Methods. To develop an EMC, stormwater samples are collected, preserved, selected, and sent to the lab for analysis. There are federal and state protocols outlining these processes which are described in section 3.4.1. There are two popular analytical methods used to assess the suspended sediment concentration.

The first is the Total Suspended Solids analytical method (TSS), which has been used to determine suspended sediment concentration in samples since the inception of the Clean Water Act in 1972, and was the originally mandated analytical test for wastewater



effluent standards. Once in the lab, the sample is stirred using a magnetic stirrer and a wide bore pipette is then inserted to extract an aliquot (American Public Health Association 1999). This aliquot is passed through a pre-weighed 2.0  $\mu\text{m}$  filter paper, dried, and reweighed. The resulting weight of sediments is divided by the volume passed through the filter paper to develop the suspended sediment concentration for the entire sample (American Society for Testing and Materials 1998).

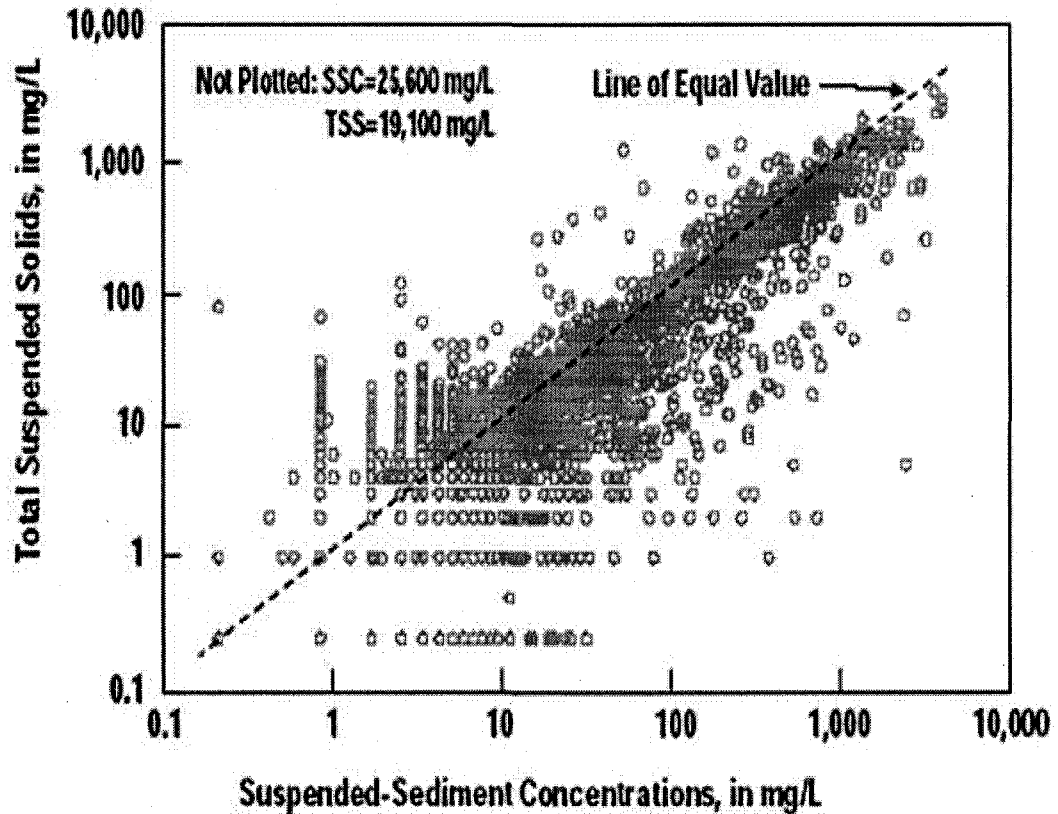
The second analytical method to determine suspended sediment concentration is the Suspended Sediment Concentration analytical method (SSC). This method follows the preliminary protocol as outlined in section 3.4.1. However, this method does not extract a sub sample but rather it utilizes the entire sample and then follows the same procedure as for TSS, using a 2  $\mu\text{m}$  filter paper (American Society for Testing and Materials 2000).

Bias in Suspended Sediment Methods. One source of bias introduced in monitoring for suspended sediment concentration is field sampling error. The potential bias introduced from varying sampling techniques is discussed in section 2.2.3. Failure to capture a representative sample will lead to inaccurate reporting of suspended sediment concentration in stormwater discharge.

The second introduction of bias in suspended sediment concentration is with the analytical methods (laboratory methods). In 2000, the United States Geological Service, (USGS) conducted a study of hundreds of paired water samples obtained from riverine samples. The conclusion of the investigation showed that TSS and SSC results from the paired samples were not the same. A correlation could not be developed of TSS and SSC

results as seen in Figure 4 which displays a plot of over 3,000 of these paired samples (Gray J. et al. 2000).

Figure 4: Correlation of SSC & TSS Results from River Samples (Gray J. et al. 2000)



The cause of this difference was due to the presence of coarse sediments in the samples. The discrepancy was attributed to the generation of the aliquot in the TSS methodology. The location of the pipette and the time lapse between the end of stirring and the extraction of the subsample allowed for coarse particles to settle out of the water column and be missed from the subsample. For this reason, the USGS and Federal Interstate Sedimentation Project (FISP) have suspended the use of the TSS analytical method as a stand alone method to measure suspended sediments in river systems (US Geological Service 2000; Federal Interagency Sedimentation Project 2006).

The influence of particle size distribution on the difference between the two analytical methods was confirmed in follow up research using samples with manufactured sediments of a known PSD (Guo Q. 2007). Figure 5 shows there is little difference between analytical methods in a water sample with a PSD of fine sediments. Figure 6 shows a large discrepancy between analytical methods when there is a coarse PSD.

Figure 5: Fine Particle Size Influence on TSS & SSC (Guo Q. 2007)

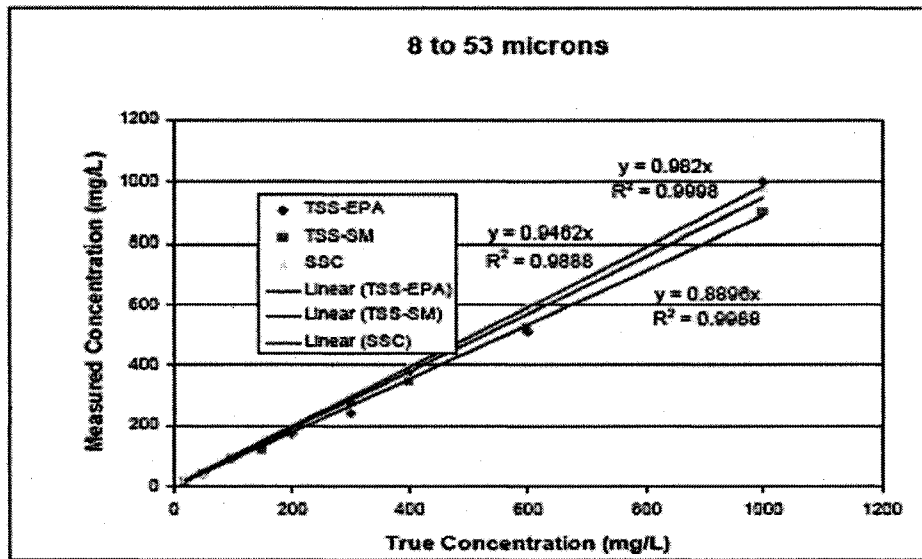
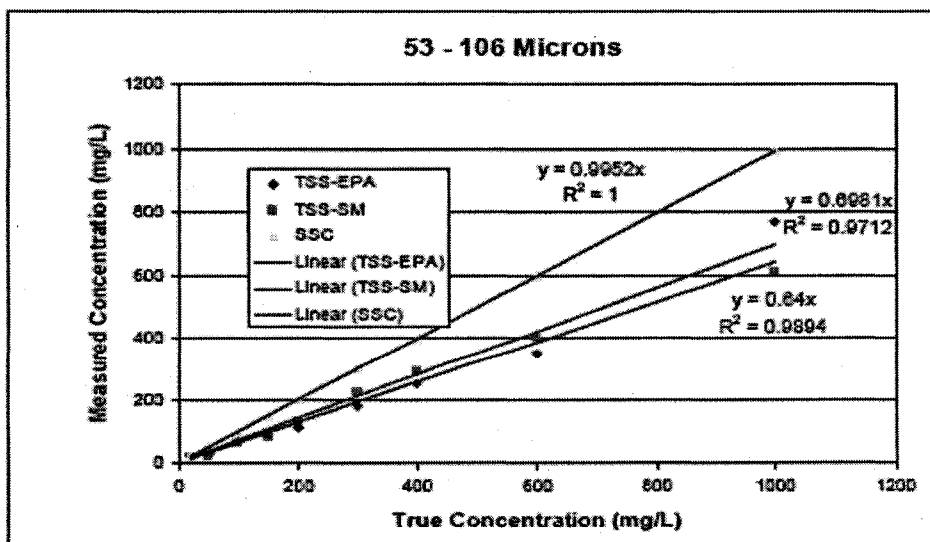


Figure 6: Coarse Particle Size Influence on TSS & SSC (Guo Q. 2007)



Sediments in stormwater typically contain coarse sediments greater in size than 75  $\mu\text{m}$ . Numerous investigations in runoff from transportation surfaces have characterized sediment loads with a PSD ranging in size from 0.5  $\mu\text{m}$  to 10,000  $\mu\text{m}$  (Sansalone J. et al. 1997a; Furumai H. et al. 2002; Li Y. et al. 2005). With this PSD, the TSS analytical method has the potential to inaccurately report suspended sediment concentration.

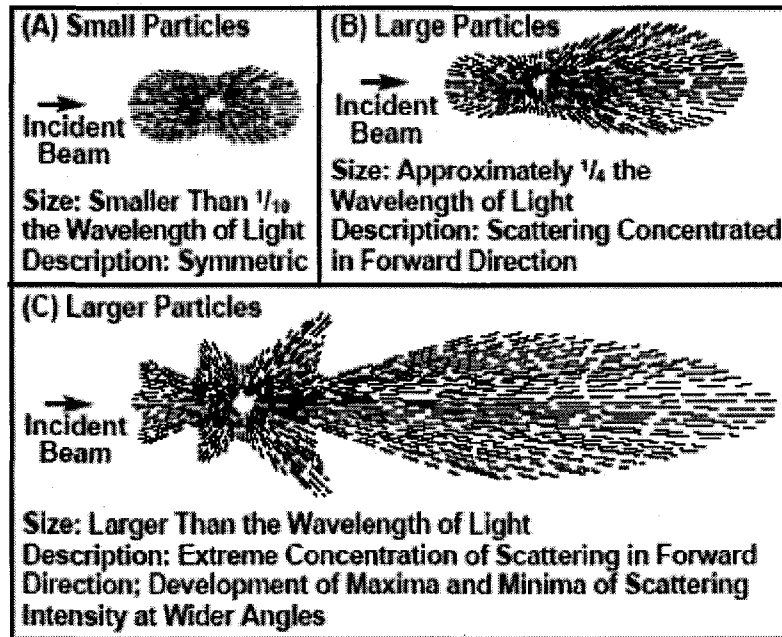
#### 2.2.5 Characterization: Optical Properties

“Turbidity can be defined as a decrease in the transparency of a solution due to the presence of suspended and some dissolved substances, which causes incident light to be scattered, reflected, and attenuated rather than transmitted in straight lines (Ziegler 2002).” Generally speaking, as suspended sediment levels increase, the turbidity also increases in stormwater. Turbidity monitoring of suspended sediment concentration is an attractive method for concentration monitoring in stormwater because it can be a low cost monitoring method (US EPA 2002). Turbidity measurements have been used to measure sediment loads in surface waters with good results (Clifford N. et al. 1995; Gippel C. 2006).

Analytical Methods. Turbidity is measured by instruments which emit a beam of light and then record the amount of light reflected. Figure 7 illustrates the process of how particle size affects the amount and characteristics of reflected light. The light reflected on the same side of the incident light is called backscattering and the light reflected on the opposite side of the light is called front scattering (Brumberger H. et al. 1968).

Turbidity measurements are generally recorded in nephelometric turbidity units (NTU), formazin turbidity unit (FTU), etc. Which turbidity unit is used generally depends on the wave length of light that is emitted from the turbidity meter (Anderson C. 2005).

Figure 7: Illustration of Front and Back Light Scattering (Brumberger H. et al. 1968)



These optical light scattering probes are deployed in surface waters in a manner that allows for an unobstructed viewing area around the light source. The calibration, measurement, and maintenance of these probes is outlined by the USGS (Anderson C. 2005). Concurrent measurements of sediment concentration samples are taken with the real time optical turbidity measurements. These concurrent samples are analyzed using one of the two analytical methods described in section 2.2.4. With these data, a linear relationship is developed.

Strong correlations have been made using this methodology in various river systems. Figure 8 shows a relationship with a strong correlation ( $R^2=.904$ ) of turbidity and sediment concentration measurements in a large (1,000 km<sup>2</sup> watershed area) river

area. Figure 9 shows the same correlation in a river system with urban influences which experience a rapid influx of stormwater after rain events. This correlation is not as strong ( $R^2=0.833$ ).

Figure 8: Turbidity Regression with Sediment Concentration in Large River Systems (Grayson R. et al. 1996)

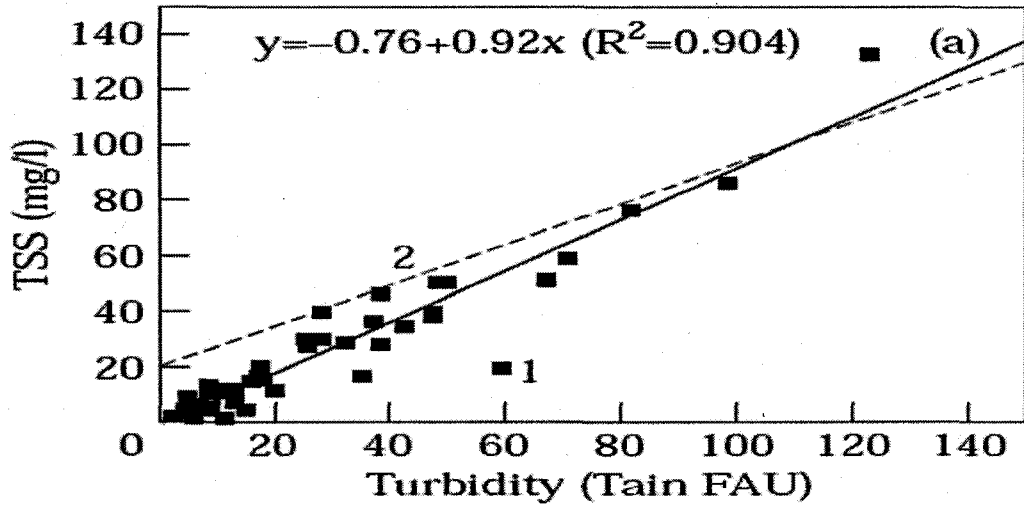
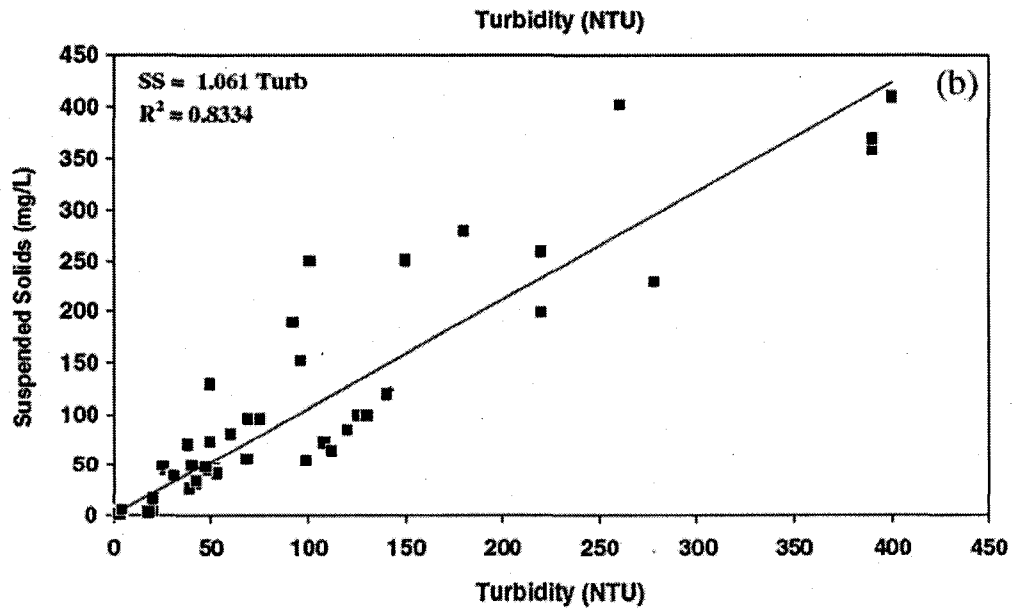


Figure 9: Turbidity Regression with Suspended Sediment Concentration in an Urban River System (Settle S. et al. 2007)



Bias in Optical Methods. Currently several types of instruments are used to measure turbidity and the mechanics of these instrument vary in the way that they measure forward and/or backscattering light. Therefore different instruments measuring the same water will produce different turbidity values (Ziegler 2002). The location of the instrument in the water column is critical for accurate turbidity measurements. A turbidity meter monitors a softball size area of the passing water around its optical viewing area. If this area is not filled completely with water or a reflective barrier such as a wall, or the bottom of a stream is in the optical viewing area, turbidity values will not be accurate. This has ramifications with the deployment of turbidity meters in the small confines of stormwater sewers. Water levels in these pipes fluctuate rapidly and often are shallow, thereby preventing the optical viewing area from being completely filled with water.

Organic staining of the passing water, air bubbles, particle size, shape, and composition all influence measurable nephelometric properties (Downing J. 1996). This makes it very difficult to use an established NTU/suspended sediment relationship from one location at another monitoring location.

#### 2.2.6 Characterization: Sediment Load

Sediment load is another reporting value of suspended sediments in stormwater. Sediment loads are reported in units of weight. Sediment loads can commonly be found as part of the TMDL program which are generally reported in units of weight/time (US EPA 1999).

Analytical Methods. To calculate sediment loads, stormwater samples are collected, selected, preserved, and sent to the lab following federal and state protocols (described in section 3.4.1). The two analytical methods mentioned in 2.2.4 can be used to determine the suspended sediment concentration in the samples. The results of these analyses are then used to calculate sediment load using Equation 2.

$$Sed.Load = \int_0^T c(t)q(t)dt * \sum_0^T q(t) \quad \text{Equation (2)}$$

Where:  $c(t)$  = the sediment concentration varying with time (mg/L),  $q(t)$  = the time variable flow (L/min); and  $T$  = the duration of the event (min).

Bias in Suspended Sediment Load Methods. The same analytical bias exists in calculating suspended sediment loads as described in 2.2.3. Error can occur if field samples are not captured to accurately represent the passing stormwater runoff and suspended sediment size can also influence the accuracy of laboratory tests. Accurate discharge measurements are required to report suspended sediment loads. Loads are more sensitive to inaccurate discharge levels because of their integration into the calculation of suspended sediment load.

#### 2.2.7 Characterization: Particle Size Distribution

Particle size distribution (PSD) is the percentage of mass, volume, or number of particles in a range of particular sizes (Bent G. et al. 2001). The PSD of suspended sediments is an important characteristic to understand because particle size influences: pollution adsorption, particle settling, and the design of stormwater BMPs. Numerous



studies have shown that certain pollutants have a tendency to adhere to certain sediment sizes as seen in Table 3.

Table 3: Pollutant Affinity To Various Particle Sizes

<b>Pollutant</b>	<b>Size Fraction (<math>\mu\text{m}</math>)</b>	<b>Source of Reference</b>
Total Phosphorus	53.0 - 300.0	5
Enterococci	10.0 - 30.0	34
E. Coli	0.45 - 30	34
Heavy Metals	2.0 - 63.0	35

The objective of most BMPs is to remove suspended sediments from stormwater which in turn effectively removes other pollutants of interest. Particle size impacts BMP designs that utilize settling characteristics of particles in order to remove them, since settling characteristics are influenced by particle size.

There are two ways to describe the suspended sediment PSD, effective and absolute PSD. Effective PSD is the actual particle size fractionation of sediments as they leave the stormwater drainage system. The sediments can be isolated or clumped together forming aggregates. Aggregation can occur due to: sediments' electronic charge, biological attachment, or chemical interaction. Absolute PSD is when all aggregates are broken apart and each particle is in isolation. A dispersion agent can accomplish this by breaking the ionic bonds between particles.

Analytical Methods. Several methods exist to report particle size distribution of sediments in stormwater. Particle sizes span four to five orders of magnitude and there is no single instrument or technique that has been proven to characterize the entire range of particle sizes in stormwater runoff. It is recommended that if the long term monitoring

objective is reporting particle size characterization. a consistent method needs to be used (Grant S. et al. 2003). Table 4 lists the several techniques that have been employed in characterizing PSD in stormwater.

Table 4: List of Several Particle Size Measurement Methods

<b>Method of Measure</b>	<b>Source of Reference</b>
Dry Sieving	37
Wash Sieving	22
Light Obscuration	21,38
Coulter Counter	39

Bias in Particle Size Distribution Methods. The first source of bias with this method is error introduced with field sampling (discussed in section 2.2.3). A review of the published studies listed in Table 4 concluded that the authors assumed the samples collected for PSD analysis were a representative sample of the passing stormwater. The methods listed in Table 4 could be accurate for measuring sediments in the sample, but the sample might not be an accurate representation of suspended sediment PSD from the sewer system.

The lapse of time from when the sample is extracted and when it is analyzed and the temperature at which the sample is stored influences PSD (Li Y. et al. 2006b). As time lapses, smaller particle sizes will reduce in number and larger particles sizes will grow in number as seen in Figure 9 (Li Y. et al. 2005). Higher storage temperature will also influence PSD. A possible cause for this is the biological flocculation or the proximity of particles to one another leading to chemical or electrical flocculation.

The second source of bias is the analytical method used to develop the PSD. By drying the sediments for a dry sieve analysis, aggregation occurs and can alter the PSD (Krein A. et al. 2000). Dry sieving increases the size of particles and aggregates by

forming clumps. Wash sieving has reproducibility concerns because there is no standard method or ASTM procedure to describe the protocol for the complete wash sieving process that spans the several orders of magnitude of PSD in stormwater samples (1.0-1000 microns). There are several commercially made instruments available for PSD analysis and their limitations are seen in Table 5.

Figure 10: Change of Particle Size Distribution With Respect to Time and Temperature (Li Y. et al. 2005)

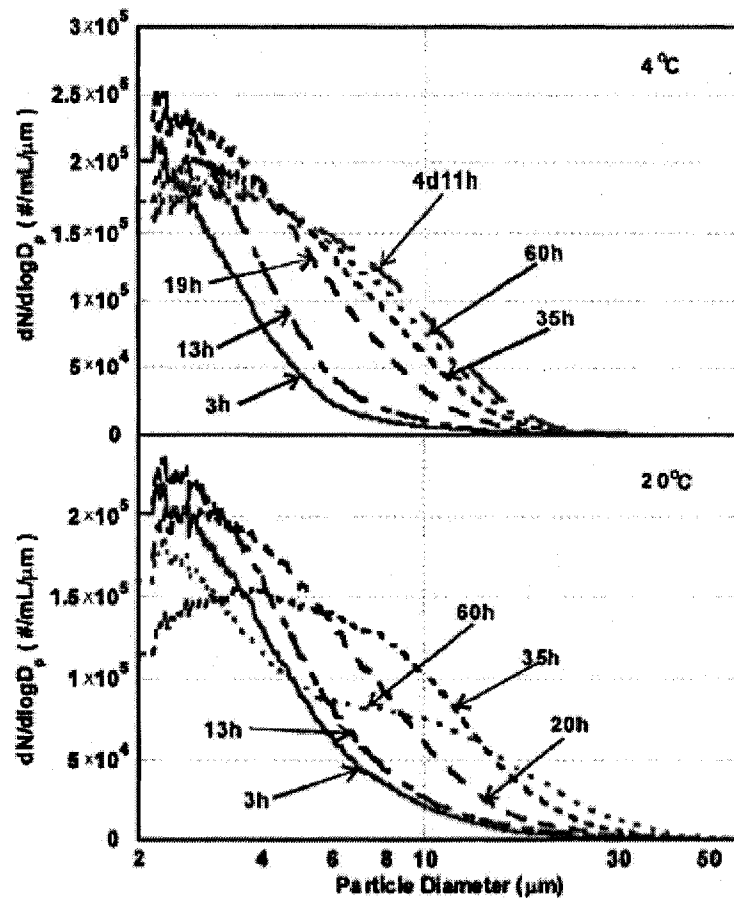


Table 5: Limitations of Several Particle Size Measurement Methods

Method of Analysis	Limitations
Coulter Counter	Coagulation may disrupt fragile flocs
Light Obscuration	May disrupt fragile flocs
Light diffraction	Concentration of solution has great influence on results
Dynamic Light Scattering Property	Needs long time for stability

## Chapter 3

### **III Materials and Methods.**

The objective of the experimental design was to quantify the relative accuracy of different methods which measure suspended sediment concentration and particle size distribution. These methodologies were all compared to a presumed known value, a benchmark. The benchmark value that all method combinations were compared to was achieved by capturing a large volume grab sample of stormwater discharge and analyzing the sediments within that sample – the Total Capture (TC) sample.

The methodologies used in this experimental design are summarized in Table 6 and the methodologies used to develop the presumed known values are listed with a “\*”.

Table 6: Experimental Design

<b>Monitoring Objective</b>	<b>Sampling Technique</b>	<b>Analytical Method</b>	<b>Reporting Value</b>
Suspended Sediment Concentration	Automatic Sampler	SSC	EMC
	Automatic Sampler	TSS	EMC
	Turbidity Meter	SSC	EMC
	Turbidity Meter	TSS	EMC
	Automatic Sampler	SSC	Total Load
	Manual (Total Capture)*	Wash Sieve*	EMC*
Particle Size Distribution	Automatic Sampler	Tri-Laser Diffraction	By Volume
	Manual (Total Capture)*	Wash Sieve*	By Weight*

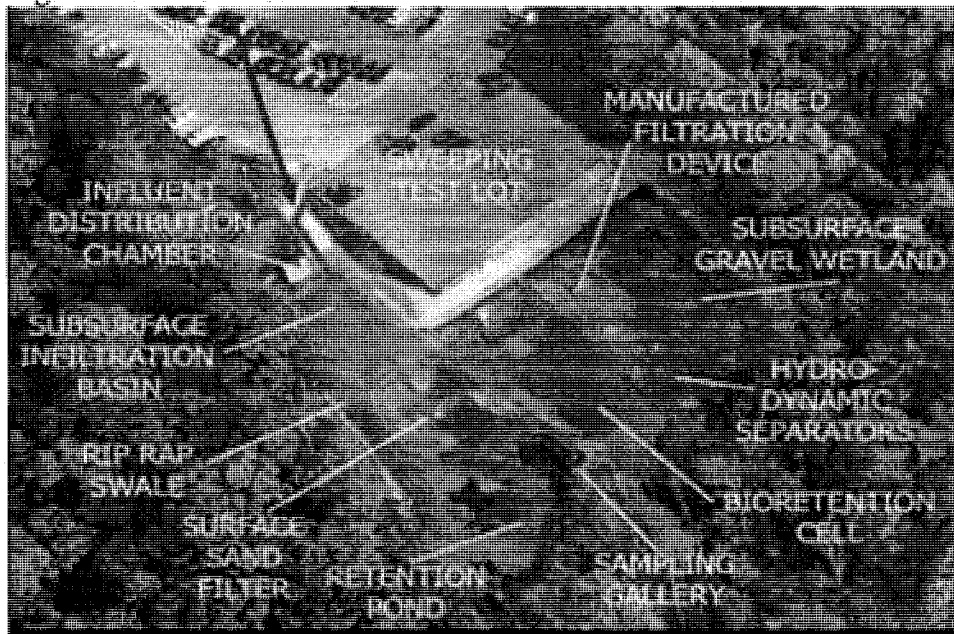
The experimental design was established to isolate sample collection (field) or analytical (laboratory) bias in order to identify which combination of sampling techniques and analytical methods are most accurate compared to the Total Capture (TC). The experiment was performed over the course of two years.

### **3.1 Site and Equipment Description**

#### **3.1.1 Site Description**

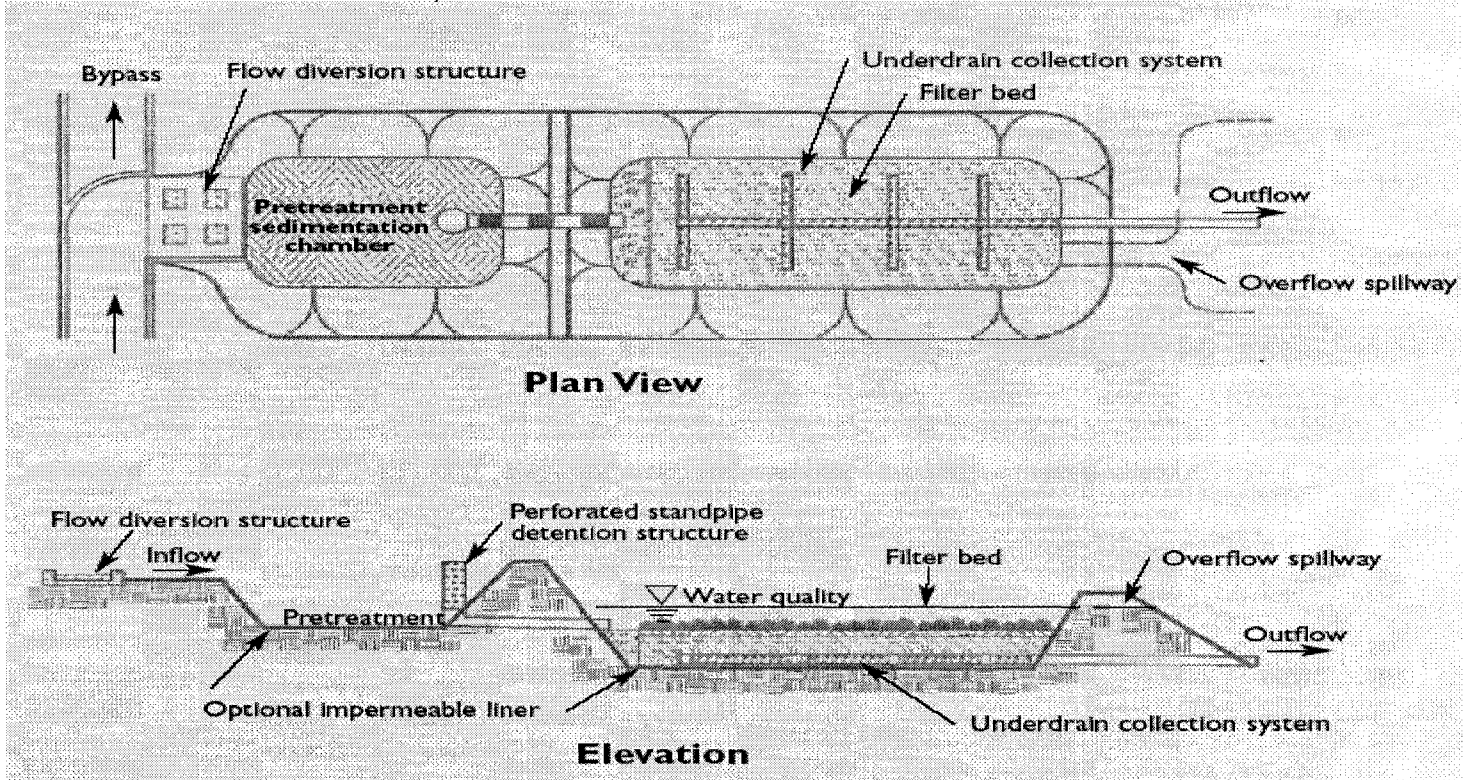
The 3.6 ha parking lot is drained using a typical stormwater sewer system (curb, gutter, catch basin, storm sewer), designed following current design standard of practice at the time of its construction in 1996. This system terminates with a 91.4 cm (36 in) RCP pipe which empties into the University of New Hampshire's Stormwater Research Center main field facility. At the terminal end of this pipe is the influent distribution chamber as seen in Figure 11, with the incoming flow path marked by the red arrow. This distribution box distributes stormwater to a system of ten 30.5 cm (12in) pipes, configured to each receive equal parts of the runoff (Roseen R. et al. 2006). The elevation of the floor of the distribution box was higher than the inverts of the connecting pipes, so designed, to encourage self scouring and minimize back water in the distribution box.

Figure 11: Ariel Photo of UNH Stormwater Research Center



A removable seal was located within the distribution box and was used to prevent the discharge from entering the 30.5 cm (12 in) diameter plastic pipe leading to the surface sand filter, when the seal was in place. The 8.53 (28 ft) long flow path from the distribution box to the sand filter is depicted by the green arrow in Figure 11 and terminated in the sedimentation forebay of the sand filter. A plan and profile view of the sand filter can be seen in Figure 12. The sand filter was taken off line for this investigation.

Figure 12: Plan and Profile View of a Sand Filter BMP (AMEC Earth and Environmental 2001)



At the end of the 30.5 cm (12 in) pipe was a 38.1 cm (15in) expansion joint to which a 0.9 m (3 ft) long 38.1 cm (15 in) pipe was attached. At the outlet of this pipe was a 38.1 cm (15in) ThelMar compound weir. The slope of the pipe outlet was less than 0.02 and was supported by a wooden brace.

### 3.1.2 Sample Monitoring Equipment

Suspended Sediment Concentration & Particle Size Distribution. The sand filter sedimentation basin was lined with two tarps: a 2.5 mm thickness, 30-ft by 20-ft polyethylene tarp, which could be removed and cleaned; and a larger 2.0 mm thick multipurpose polyethylene liner underneath.

Anchored to the invert of the 38.1 cm (15 in) pipe were two low flow sampling intakes. These intakes were located 12cm behind a 38.1 cm (15 in) V-notch compound weir. There were not any additional discharge contributions behind the intakes. It was assumed that the water column was thoroughly mixed at this location.

Each sampling intake was protected from clogging by a strainer and each intake was connected to an ISCO 6700 automatic sampler using 3.35 m (11 ft) of 9.5 mm (3/8 in) vinyl hose. The ISCO 6700 automatic sampler meets EPA, USGS, and TARP specifications for monitoring suspended sediments (US EPA 1992; Lane S. et al. 2003; Technology Acceptance Reciprocity Partnership 2003). The vertical distance between the vinyl hose invert and the sampling pump was 1.8 m (6.0 ft). The maximum suction head for this automatic sampler is 8.5 m (28.0 ft) (ISCO 2001). The 6700 series machines have peristaltic pumps whose typical pump flow rates vary based upon the suction head, as seen in Table 7. The intake sampling velocity reduces with an increase in suction head.

Table 7: Intake Velocity by Different Suction Heads (ISCO 2001)

<b>Suction Head (ft)</b>	<b>Flow Rate (gpm)</b>	<b>Line Transport Velocity (ft/sec)</b>
5	1.03	3.0
10	0.98	2.9
15	0.95	2.7

The samples taken by the automatic samplers were refrigerated, and maintained at constant storage temperature at 4°C, which is the recommended storage temperature for sediment samples (US EPA 1992). These samplers can record the following information every minute: stage, discharge, turbidity, and time when samples were taken. Each sampler could be programmed to take the various types of samples as discussed in section



2.2.3. An ISCO 674 tipping bucket rain gauge was used to record rainfall and was connected to a data logger.

Turbidity. A DTS-12 turbidity probe was attached to the wall of the 38.1 cm (15 in) pipe, 12.0 cm behind the weir using metal clamps. The measurable range of the turbidity probe is from 0-1800 NTU with a 0.01 NTU resolution and can record both front and backscattering light. The probe was angled upstream so that a four inch void was maintained in front of the probe's head with out the interference from the pipe's walls. This instrument and setup followed USGS guidance for monitoring turbidity (Anderson C. 2005). The probe's serial cable was attached to a sampler and a turbidity measurement was taken every minute. A neoprene wiper blade swiped the optical surface once every minute to prevent biological and depositional fouling.

Flow Measurements: Weir. A 38.1 cm (15in) ThelMar compound weir was employed to develop a stage discharge relationship in the pipe. Lower flows occupied the weir's V-notch and higher flows filled the rectangular section. The weir's discharge capacities are listed in Table 8.

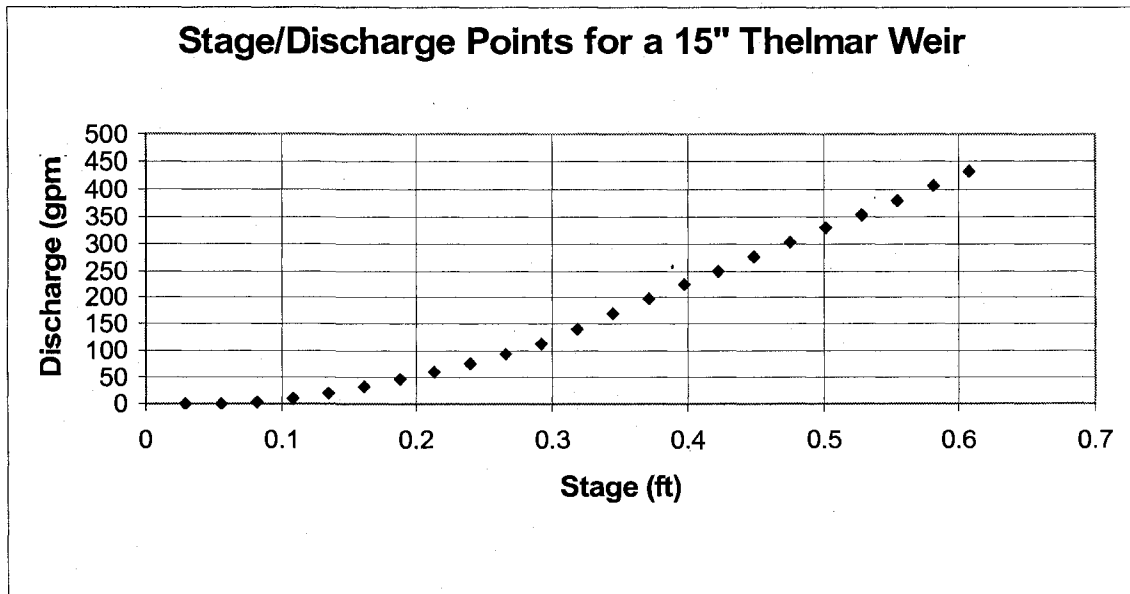
Table 8: Maximum Capacity Measurements for V-Compound Weir

<b>Diameter (inch)</b>	<b>V-Notch Capacity (gpm)</b>	<b>Rectangle capacity (gpm)</b>	<b>Maximum Head (ft)</b>
15	0.04 - 2.57	2.57 - 423.6	0.609

Stage was measured using an ISCO 720 bubbler located 12 cm behind the weir. The line was secured to the invert of the pipe and was connected to the 720 bubbler with

4.0 m (13.0 ft) of 3.2 mm (1/8 in) vinyl tubing. This bubbler model could be calibrated to zero discharge when the water level was at the bottom of the V-notch. The automatic sampler interpolated discharge from a list of stage-discharge points provided by the ThelMar weir manufacturer. These points were measured in a laboratory at Lehigh University by measuring the head directly over the weir using a ruler. These points can be seen in Figure 13. The conveyance system for the stormwater sewer system draining the West Edge parking lot was designed to distribute no more than one cubic foot per second of discharge, equal to 470 gpm to each 30.1 cm (12 in) pipe. This particular weir was able to monitor almost all flow levels (ThelMar Weirs 2007).

Figure 13: Stage Discharge Relationship for 15" ThelMar Weir (ThelMar Weirs 2007)



Ten centimeters behind the bubbler head, was a Global Logger WL400 pressure transducer which also recorded stage behind the weir. The use of a weir and bubbler setup followed EPA guidance to meet NPDES monitoring requirements (US EPA 1992). Another pressure transducer monitored water level upstream of the distribution box to

determine the time of initial rainfall runoff. This device recorded stage once every five minutes.

### 3.1.3 Equipment Calibration

Flow calibration occurred before each event. If a base flow was present, the distribution box seal to the upstream end of the 12-in. pipe was shut preventing any flow from entering the pipe. The remaining water level behind the weir was adjusted by adding or removing water manually until the water surface leveled at the invert of the V-notch of the weir. At this elevation, the bubbler was set to a zero flow mark once the bottom of the meniscus was at the level of the bottom of the V-notch.

The turbidity meter was immersed into a “blank sample” and followed USGS guidance (Anderson C. 2005) and manufactures recommendations’ for blank sample verification . After the first 12 sampling events, the probe was sent to the manufacturer for a complete three point calibration following USGS and ASTM standards.

## **3.2 Targeted Rain Events**

One rain event per month was targeted for sampling. The following conditions were used to determine if a rain event met federal and state criteria.

- 72 hours since last rain event (US EPA 1992; Technology Acceptance Reciprocity Partnership 2003)
- rain event exceeds 2.54 mm (0.10 inch) (US EPA 1992; Technology Acceptance Reciprocity Partnership 2003)

Once a sampling event began, it would continue until the sampling basin was filled. According to TARP protocol (Technology Acceptance Reciprocity Partnership 2003), if a six hour cessation of rain occurs, this signals the delineation between separate rain events. For this investigation, to maximize the stormwater volume monitored for each sampling event, the TARP criteria was not used to separate sampling events if the basin was not filled to capacity after the initial event.

The first flush of a rain event was targeted for sampling. The first flush is colloquially referred to as the initial runoff of a rain event which generally contains the highest pollutant concentration. Previous research has shown that suspended sediments exhibit a first flush behavior by having the highest concentration of sediments in the initial runoff (Li Y. et al. 2006b). By targeting the first flush, there was the high likelihood of having sediments in the discharge.

### **3.3 Sampling Techniques and Analytical Methods**

There is no standard or published guidance to measure suspended sediment concentration in a large volume (3,000 gallons for the Total Capture - TC) stormwater sample. The methodology used to analyze sediment concentration in the TC sample followed ISO standards and ASTM protocol when applicable. The methods used to analyze for suspended sediment concentration in the samples recovered by automatic sampler followed EPA, AWWA and ASTM standards.

There is also no standard or published guidance to measure PSD in stormwater (Li Y. et al. 2005) so the methodology used to develop the PSD for the sediments in the

total capture and automatic samplers followed previous research recommendations and ASTM protocols when applicable which will be discussed in section 3.4.2.

To report suspended sediment concentration and particle size distribution (PSD), several combinations of sampling techniques and analytical methods were developed to achieve the desired reporting values while isolating any bias (field or laboratory).

### 3.3.1 Sampling Technique and Analytical Method: Total Capture

Sampling Technique. Before a rain event began, the seal in the distribution box was removed to allow runoff to enter the 30.1 cm (12 in) pipe leading to the sand filter. Once the runoff began to leave the outlet of this pipe, the automatic sampler programs were turned on and the uppermost liner was adjusted so that this discharge could fall into the tarp. Once the sedimentation forebay was filled, water was diverted away from the tarp, the programs were shut off, and the seal in the distribution box closed. A sketch of the experimental design can be seen in Figure A-2. This sketch also identifies the four field monitoring methods used to measure suspended sediment concentration and the single field method to monitor for particle size distribution. The values determined from these field methods will be compared to the presumed actual values from the total capture sample.

Sample Processing. Stokes Law was used to determine the necessary time required to allow for fine sediments to settle out of the water column. Stokes settling velocity equation is reported in Equation 3.

$$V_s = \frac{2(\rho_p - \rho_f)}{9\mu} g R^2$$

Equation 3

Where:

$V_s$  is the particles settling velocity (m/s)

$g$  is gravitational acceleration ( $m/s^2$ )

$\mu$  is the dynamic viscosity of water ( $N*s/m^2$ )

$\rho_p$  is the density of the particles ( $kg/m^3$ )

$\rho_f$  is the density of water ( $kg/m^3$ )

$R$  is the particle radius (m)

The following assumptions were made to determine the particle settling velocity from Equation 3:

- The smallest particle of interest, i.e. smallest suspended sediment (Environmental Water Resources Institute 2007; Roesner L. et al. 2007) is  $2.0 \mu m$ .
- Water viscosity is constant at value of  $1.51 \times 10^{-3} N*s/m^2 @ 5^\circ C$
- The density of water is  $1,000 kg/m^3$
- The density of the solids was assumed to be  $2650 kg/m^3$ , of a silica sand (Li Y. et al. 2006a)
- The particles are spherical (Li Y. et al. 2006a)
- Reynolds number is  $1.26 \times 10^{-5}$  when  $V_s = 9.5 \times 10^{-6} m/s$ ,  $R = 2.0 \times 10^{-6} m$ ,  $\rho = 1000 kg/m^3$  and  $\mu = 1.51 \times 10^{-3} N*s/m^2$

If these assumptions are not correct, then finer sediments would not settle out of the water column before decanting would begin. For example, if the particles were not spherical but planar, increased drag would reduce settling velocity. Also, if the density of the solid, whose value was used from previous research (Li Y. et al. 2006a), was lighter than the assumed value, its weight force is less which will increase settling time of the particle and particles coarser than 2  $\mu\text{m}$  will be pumped off.

When the basin filled to capacity, the maximum depth a particle would have to settle was 1.54 m (5 ft). Following the assumptions listed previously, all particles, 2.0 micron or coarser should fall out of the water column after 48 hours and rest on the tarp. To begin the recovery of sediments in the total capture sample, a 1/3 hp pump was lowered to about half the depth of the water in the basin. The pump was turned on and the pumped water measured volumetrically using two 180 L (51.6 gal) demarcated barrels. This continued until the pump began to intake air. During the decant of this pumped water, 1 L grab samples were taken generally at the 2<sup>nd</sup>, 9<sup>th</sup>, 19<sup>th</sup> and 24<sup>th</sup> barrels. These samples were stored at 4°C until they were able to be analyzed for suspended sediment concentration.

The remaining sample and all the sediments on the polyethylene tarp were then pumped into a 10,455 L (3,000 gal) tank. The assumptions made from the previous decanting step were applied for the next volumetrically measured decanting step including the maximum distance a particle would settle (1.54m).

After another 48 hour settling period, another volumetric decant of this tank lowered the depth of water until the water surface was 25.4 cm (10 in) from the bottom of the tank. During this process, other grab samples were obtained generally following the

same sampling pattern as when dewatering the forebay. The remaining 25.4 cm were removed by non motorized siphon with two 9.5 mm (3/8in) nylon tubes. A grab sample was also taken during this process.

The sediments on the bottom and sides of the tank were recovered and preserved at refrigerator temperature for no more than 24 hours until the sample could be wash sieved.

Analytical Method: PSD and Suspended Sediment Concentration. There is no standard method or ASTM protocol outlining a wash sieve process using sieves ranging from 2500 to 2 microns that does not involve a drying step. Drying the sediments will increase aggregate size, due to clumping, and therefore does not result in an accurate estimate of the effective particle size distribution (Krein A. et al. 2000). ASTM Standard D2217 does outline the process of wash sieving sediments using only sieves with the size fraction from 2000 to 425 microns without a drying step. Protocol 6.1.2 of this standard was followed for the wash sieving process using sieves from 2500 microns to 75 microns (American Society for Testing and Materials 1998). This process consisted of soaking the sediments in the 2000 micron sieve and stirring the sediments while minimally scraping the sediments on the bottom of the sieve. This process was followed for all sieve sizes to the 75 micron size. Initially, the sample was passed through a 4.5 mm sieve to capture any large particles or organic matter such as leaves before the wash sieving process. The organic material captured on this sieve was not included in the PSD.

After the wet sieving, sediments finer than 75 microns were recovered, dried, and weighed. When feasible, a 50 g sample of these sediments was prepared for a



hydrometer test using a 151H hydrometer. This step included using a dispersing agent, Sodium Hexametaphosphate so the absolute particle size distribution could be measured. ASTM D422 was used for guidance (American Society for Testing and Materials 2002) for the hydrometer test. At the completion of the particle size sieve and hydrometer analyses, all the sediments were recovered (by size fraction), bagged, and stored in the freezer. The weight of sediments recovered for all size fractions were added together and used to calculate the suspended sediment EMC which is explained in section 3.4.1.

### 3.3.2 Sampling Technique and Analytical Method: Automatic Sampler

Sampling Technique. Once runoff entered the 30.1 cm (12 in) pipe leading to the forebay and emptied into the basin, the programs of the automatic samplers were turned on. Two sampling programs were established for the automatic samplers. The program for one sampler took 1.0 L grab samples using short time increments between grab samples. Depending on the rate the basin filled, the sampling time intervals between grab samples were shortened or lengthened to ensure the maximum amount of samples were taken during the filling of the basin. The initial interval length was two minutes and if pacing adjustment was necessary, ranged from 4-18 minutes between the 1.0 L samples. Up to twenty four, 1.0 L samples could be obtained per sampling event.

The second sampler's program took a single composite sample using "equal volume, time proportional to flow volume increment" (US EPA 1992) subsamples. This program would take a 40 mL sample every 261 L (75 gal) that passed by.

Both programs were set to begin sampling once the flow rate exceeded a base flow if such base flow existed. Once the forebay filled, water was diverted away from

tarp, the programs were terminated, and the seal in the distribution box closed so that no more water filled the tarp lined basin.

Sample Processing. Once the sampling programs were turned off the samples were kept at 4°C until they were sent to the lab for analysis. Holding time was minimized to reduce the change of PSD in samples and processing generally followed EPA guidelines (US EPA 1992).

Suspended Sediment Concentration. Eight to nine samples were selected for suspended sediment concentration analysis. This sample selection process is described in Section 3.4.1. Each of the eight to nine samples were analyzed for both TSS and SSC following American Public Health Association and ASTM standards, respectively (American Public Health Association 1999; American Society for Testing and Materials 2000). The following data was downloaded from the automatic samplers using an ISCO 581 Rapid Transfer Device (RTD): discharge, stage, timing of when samples were taken, and rainfall depth.

Particle Size Distribution. The single composite sample was sent to MicroTrac for a PSD analysis using a S3500 Particle Size Analyzer. This analyzer complies with ISO 13320-1 particle size analysis-light diffraction methods and has a range from 0.02 to 2800 microns (MicroTrac 2008). The sample was sent to MicroTrac as soon as possible following an event.

### 3.3.3 Optical Method: Turbidity

All turbidity data was recorded at one minute intervals and stored within the automatic sampler's data recorder. This information was downloaded from the automatic sampler along with the above mentioned data.

### 3.3.4 Specific Gravity

A storm event from each quarter/season was selected for a specific gravity analysis. A subsample of the sediment from each event was recreated using the sample's original PSD to determine how much mass would be taken from each size fraction (from the bagged sieve samples) to create a 10.0 g sample. The specific gravity protocol used the ASTM 854-Standard Test for Specific Gravity of Soil Solids as a reference. Each sample was suspended in deionized water, stirred under vacuum and weighed.

## **3.4 Reporting Values**

### 3.4.1 Sediment Event Mean Concentration

Total Capture. The total capture EMC was developed by summing up the mass of sediments recovered from the sieving and hydrometer processes and dividing this value by the total volume of the sample (Equation 4). The volume of water decanted from the total capture sample also contained water from rain that fell directly onto the forebay during and after sampling. To adjust for this volume, the area of the pond was measured after sampling and was multiplied by the total amount of rainfall during the period between sampling and the initial decanting.

$$EMC = \frac{Mass_{sediments}}{Vol_{runoff} - Vol_{rainfall}} \quad \text{Equation 4}$$

Where:  $Mass_{\text{sediments}}$  = the weight of sediments in the TC sample (kg);  $Vol_{\text{runoff}}$  = the total volume of water in the TC sample (L);  $Vol_{\text{rainfall}}$  = the volume of rainfall which fell on the TC sample while it was in the forebay (L).

The results from the grab samples taken during the decanting process were used to determine the amount of sediments pumped out during the decanting method. This mass was calculated using equation (5).

$$Mass = \int_0^B c(b)v(b)db$$

Equation 5

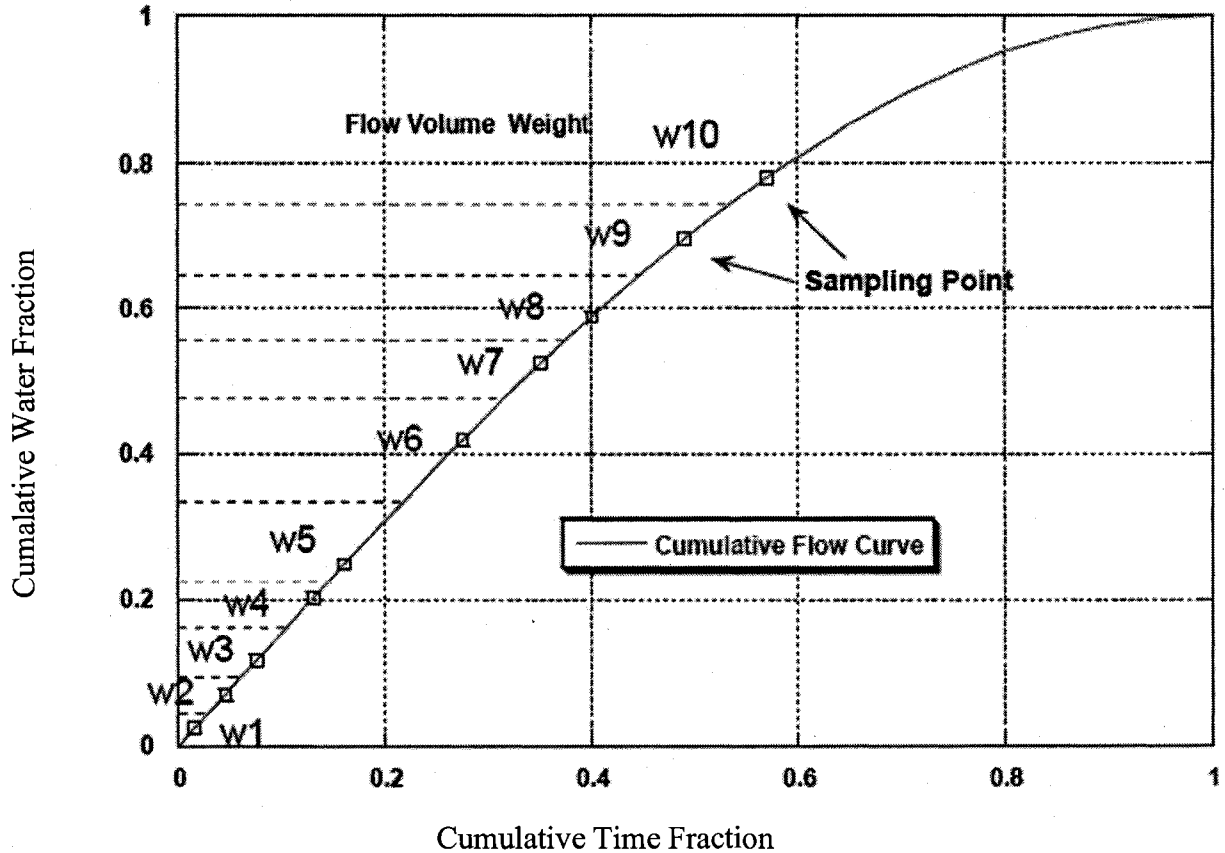
Where:  $M$  = the total weight of the sediment removed during decanting (kg);  $c(b)$  = the sediment concentration of each sample taken at a particular volumetric count (mg/L),  $v(b)$  = the water volume during that volumetric interval (L/min);  $(b)$  = the particular barrel; and  $B$  = cumulative volume (L)

The resulting weight was added to the weight of sediments of equation (4) to generate an event's suspended sediment EMC.

Automatic Sampler. To determine the event suspended sediment EMC using the automatic sampler technique, eight to nine samples were selected from the possible twenty four samples from a storm event. The objective of this selection process was to choose samples at points in time that best represented the cumulative volume and a linear change of sediment concentration. An example of this sample selection approach can be seen in Figure 14 (Stenstrom 2005). Each blue square in the figure represents the point in time and cumulative volume when a sample was selected to ensure there is a complete

representation of the event's cumulative volume and consequently the event's suspended sediment concentration.

Figure 14: Sample Selection to Develop Sediment Event Mean Concentration (Stenstrom 2005)



Both a TSS and SSC analytical test was completed for each selected sample. One suspended sediment EMC was calculated from the 8-9 SSC results and another EMC from the 8-9 results from the TSS tests. These two EMCs will be compared to the presumed actual suspended sediment EMC from the total capture sample.

The EMC calculation used for this study split the mid-point between two consecutive concentration samples to define the interval ((t) in Equation 6. This process is standard practice (Charbeneau R. et al. 1998; Stenstrom 2005) and allows a flow weighted EMC to be derived from the suspended sediment concentration of the 8-9 discrete grab samples using Equation 6.

$$EMC = \frac{M}{V} = \frac{\int_0^T c(t)q(t)dt}{\int_0^T q(t)dt} \quad \text{Equation 6}$$

Where: M = the total weight of sediment during the event (kg); V = the total volume of runoff(L); c(t) = the sediment concentration varying with time (mg/L), q(t) = the flow at time 't' (L/min); and t = the total duration of the event (min)

Turbidity. Each sample's TSS and SSC value was paired with the corresponding turbidity measurement (NTU) taken at the same time that the sample was captured by the automatic sampler. The paired data from all events was used to develop the relationships between turbidity and sediment concentration. One linear relationship was developed using all the NTU-SSC (NTU-S) values and a second linear relationship from all the NTU-TSS (NTU-T) paired values. The resulting linear regression equation was then used to convert turbidity values (NTU) to a sediment concentration value (mg/L). A regression, converting NTU to sediment concentration, has been used in urbanize open channel river systems as seen in Figures 8 and 9 with good results. These studies completely submerged the turbidity meter to monitor the optical properties of the passing

water. This study used a turbidity meter in the confined environment of a 38.1 cm (15 in) pipe. The results from the NTU-mg/L linear regression created two EMCs, NTU-S and NTU-T, both developed with Equation 6.

#### 3.4.2 Suspended Sediment Particulate Size Distribution

Total Capture. The PSD developed for sediments 2500-75 microns in the TC sample was measured by using the mass of each particle size fraction, and described by Equation 7, which follows ASTM D422.

$$\%Finer = \frac{Mass_{size}}{Mass_{Passing}} \quad \text{Equation 7}$$

Where: % Finer = the percentage of total weight that passes through a certain size sieve;  $Mass_{size}$  = the weight of sediments retained on a certain sieve size;  $Mass_{Passing}$  = the remaining weight finer than a certain sieve size.

The PSD for the sediments finer than <75 microns were reported following the ASTM D422 protocol. The two PSDs were then combined to form the representative PSD for the sediments in the total capture sample.

Automatic Sampler. The MicroTrac S3500 Tri-Laser Diffraction Analyzer measures the volume of certain particle sizes in a known sample volume and the concentration of the particle sizes. The result is the mass of that particle size

#### 3.4.3 Specific Gravity

Specific gravity measurements used ASTM standard D854 (American Society for Testing and Materials 2000) as a reference to develop specific gravity values for the

sediments for four events. This method uses a water pycnometer, not a gas pycnometer as outlined in ASTM standard D5550. Previous research used ASTM 5550 to determine specific gravity in stormwater sediments (Sansalone J. et al. 1999; Kayhanian 2008). The experimental design of this research avoided the problems of insufficient finer particle sized materials and the need to preserve sorbed surface constituents (Sansalone J. et al. 1999). Specific gravity was calculated using Equation 8. Ottawa sand, with a known specific gravity of approximately 2.65 was used as a reference for this procedure.

$$G_s = \frac{W_o}{W_o + (W_A - W_B)} \quad \text{Equation 8}$$

Where:  $W_o$  = the weight of the oven dried soil sample;  $W_A$  = the weight of the pycnometer filled with water;  $W_B$  = the weight of the pycnometer filled with water and soil;  $G_s$  = specific gravity

### **3.5 QA/QC**

#### **3.5.1 Sediment Concentration**

Field blanks were sent to the lab using deionized water to test for sample contamination due to reagents and laboratory analysis. Duplicate field samples were collected throughout this investigation and sent to the lab for replication assessment. A duplicate was made by splitting a 1L sample (collected during a sampling event) using a USGS approved Teflon cone splitter into two 500 mL sample bags and sending them both to the lab for analysis.

Testing accuracy was done by sending sediments with a known concentration to the lab to verify testing accuracy. A sediment sample with a representative PSD for all



events was created from stormwater sediments captured during this investigation. The target PSD for this sample was obtained by using the median values of all the events' major particle size fractions. After processing each sampling event, the sediments are stored in bags based on particle size and sediments were removed and weighed from several events using the target PSD to determine the weight of sediments required from each size fraction. Figure 15 shows the target PSD used to create the representative PSD used to create the sediment sample for this QA/QC test. Table 9 lists the concentrations that were created and sent to the lab for testing. The samples sent to the lab with a concentration for 150 mg/L were made using the cone splitter.

Figure 15: PSD Using Medians of All Sampling Events' Major Particle Size Fractions

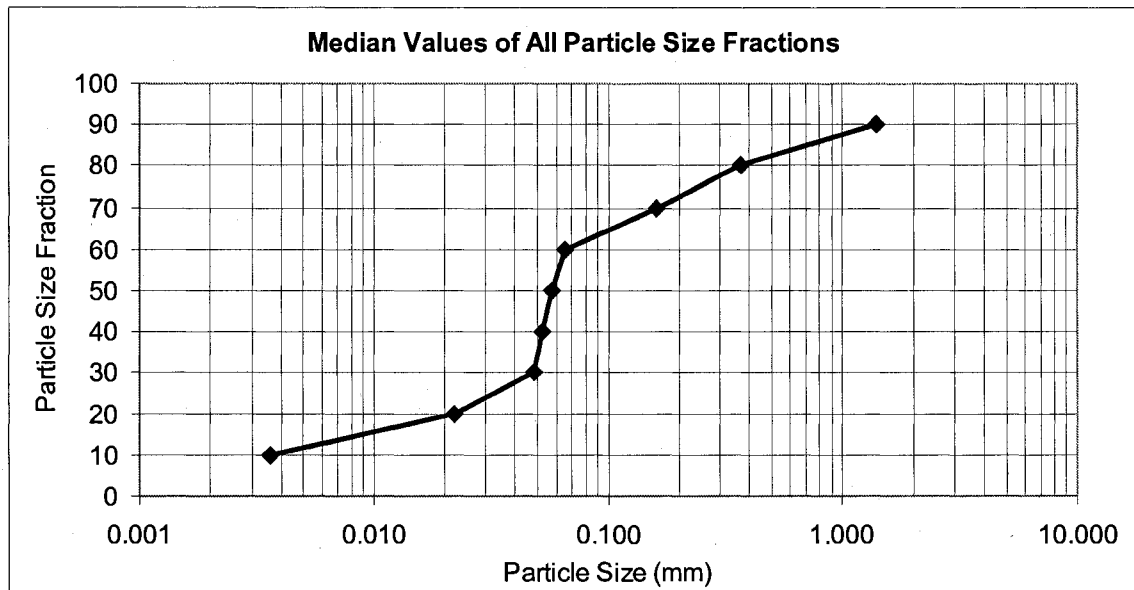


Table 9: Known Suspended Sediment Concentration for Sample Verification

Concentration (mg/L)	# of Samples	Note
80	5	--
300	5	--
150	5	Samples created with cone splitter

### 3.5.2 Particle Size Distribution

The PSD of the sediments in the AS and TC methods were obtained using different methodologies. To be able to compare these PSD, the influence of these different methodologies on PSD was investigated. The sediment size fractions from three storm events were resuspended using sodium hexametaphosphate (a dispersing agent) and RO water. These sediments sat for 16 hours (recommended time from ASTM D422, Hydrometer test). Additional RO was added to the sample and the entire sample was passed through a cone splitter. Three one liter and one seven liter sample was obtained for each resuspended sample. The three one liter samples were sent to MicroTrac for analysis and the seven liter sample was wash sieved immediately.

### 3.5.3 Evaluation of Weir Rating Curve

A rating curve was provided by the ThelMar weir manufacturer that related stage at the weir (ft) with discharge (gpm). This rating curve was developed in a lab, measuring the head over the weir, at the weir location. To examine the influence of sampling probes and bubbler location in field conditions, a series of empirical rating curves were developed under various scenarios. An empirical rating curve was developed for each of the following three scenarios:

- Known Discharge with Current Setup
- Known Discharge with Bubbler Behind Weir
- Known Discharge with Bubbler Behind Weir, No Probes

For each known discharge, approximately seven minutes of stage data was recorded to ensure a stable stage measurement was reached. Once this stable stage measurement was

reached, the stage values were averaged and this value was used with its corresponding discharge value to develop an empirical curve.

## Chapter 4

### ***IV Results and Discussion***

The following section describes the evaluation of the combinations of sampling methods and their ability to accurately characterize suspended sediments in stormwater discharge. Environmental factors that could influence the methodologies' reporting values are also evaluated. Examples of these factors include: the presence of an iso-kinetic condition, antecedent dry period, maximum and median flow during the TC, and sampling duration.

#### **4.1 Sampling Event Characteristics**

The dates, parking lot occupancy, sampling duration, time of initial rainfall runoff, and sampling starting time are listed in Table 10. The West Edge parking lot parking occupancy was estimated by the degree (percentage) of cars present. Highest occupancy rates occurred during the school year, less so on school year weekends and generally the watershed would be less than 10% capacity during school breaks. If a sampling event monitored the initial discharge from a rain event, (criteria defined in section 4.1.1) then a "Y" in column 6 of Table 10.

Table 10: Sampling Event Duration and Characteristics

	1	2	3	4	5	6	7	8
Date:	Sampling Duration (min)	Parking Lot Rate (%)	Sampling Start Time	Time of measured Discharge	Antecedent Dry days (Days)	Initial Sampling	Max. Rainfall Intensity (mm/hr)	Max. Discharge (Lpm)
6/20/06	62	<10	9:17	8:58	10	N	15.2	87
6/23/06	24	<10	9:24	9:20	3	Y	25.4	496
7/21/06	35	<10	5:08	5:07	8	Y	66.0	863
7/28/06	15	<10	5:48	5:50	7	Y	35.6	583
8/15/06	31	<10	6:34	5:38	11	N	20.3	170
12/1/06	22	80	3:39	3:42	8	Y	20.3	261
1/6/07	113	<10	1:19	12:19	5	N	10.2	155
3/2/07	126	80	1:21	1:14	51	Y	20.3	68
4/12/07	79	80	11:52	11:14	6	N	5.1	132
4/28/07	114	50	5:09	5:12	8	Y	10.2	87
5/11/07	22	80	7:45	7:50	10	Y	25.4	473
9/11/07	60	80	11:44/1:04*	6:15/12:05*	24	N	30.5	168
9/27/07	8	50	10:39	10:46	11	Y	66.0	981
10/19/07	58	50	7:38	7:40	7	Y	15.2	168
11/03/07	170	50	12:13	12:17	6	Y	5.1	194
1/11/08	108	<10	12:00/6:47*	11:56/6:49*	10	Y	30.5	235
3/4/08	128	80	5:14	4:55	5	N	10.2	102
4/28/08	186	80	10:59	10:57	14	Y	10.2	161

\*Multiple start times occurred for sampling events in which the forebay was not filled to capacity after the first event.

The range of antecedent dry days was 5-51 days. The longest loading period (dry, no surface runoff period) during this investigation occurred during the winter months.

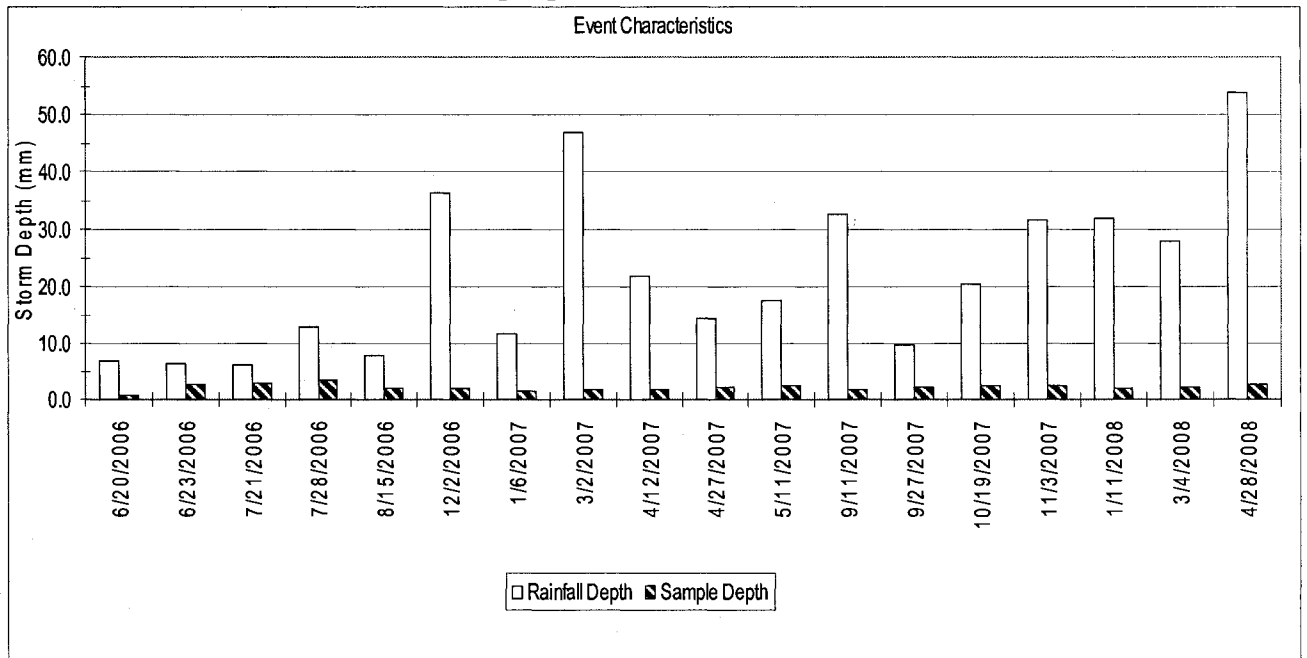
Snow fall events were not counted as rain events even if snowmelt generated runoff.

EPA guidance did not provide insight if snowmelt constituted a rainfall event (US EPA 1992). If a snowfall event included liquid rainfall then the snowfall event was treated as a rain event. Rainfall intensity was measured by the tipping rain bucket and discharge measured by the ISCO bubbler. The volume of discharge captured in the total capture sample is listed in Table D-1.

#### 4.1.1 Event Hydrology

Eighteen events were monitored over the course of two years. The rainfall depth for each event and the amount of rainfall depth captured, assuming the watershed sampling area is approximately one acre, is shown in Figure 15 and calculated using Equation 9. The duration of each sampling and rain event can be seen as Figure B-4.

Figure 15: Rainfall & Sampling Depth per Event



$$Depth = Vol * \frac{1ft^3}{7.485gal} * \frac{1acre}{43,560ft^2} * \frac{1ft}{12inch} \quad \text{Equation (9)}$$

Where: Vol = the volume of the Total Capture Sample (L<sup>3</sup>)

First Flush. The definition of the first flush for a rainfall event is the period of time experiencing a discharge with a higher concentration in the early part of the storm relative to the later part of the storm (Stenstrom M. et al. 2005). The first flush was

targeted for sampling because it contained the highest sediment concentration and the focus of this research was suspended sediment.

Discharge entering the UNHSC research facility was recorded by a pressure transducer just upstream of the D-box and recorded stage levels every 5 minutes. The time of the first increase in stage which also signifies the initial runoff from the parking lot, is listed in column 4 of Table 10. If the sampling start time (column 3 in Table 10) and the recorded time of the initial rainfall runoff were close (<7 minutes) it was assumed that sampling occurred during the first flush. The time of concentration for this watershed is 22 minutes (Roseen R. et al. 2006) which means that if the sampling criteria was met, then part of the volume collected was the first flush from some parts of the watershed.

In some instances, the sampling start time was before the time of the first increase in stage. Initial rain runoff entering the research facility could have occurred up to 5 minutes before the first measured increase in stage due to the 5 minute time gap between stage recordings, hence why some sampling start times (column 3) were before the time listed in column 4 of Table 10. If an event met these initial sampling time criteria, a “Yes” was recorded in column 6 in Table 10. If an event did not meet these criteria, the hyetographs in B-1 were used to evaluate if a significant amount of rain fell before the sampling start time or not.

The first flush begins with the first runoff from a rain fall event but there are several theories concerning when the first flush ends (Bertrand-Krajewski J. et al. 1998). A common definition for a first flush is that 80% of the mass is contained within the first 20% of the cumulative runoff volume (Stahre P. et al. 2001). However, a previous study

on watershed used in this investigation determined that none of the events studied met this definition (Roseen R. et al. 2006). For this study, a different definition for the end of a first flush was used. This theory given by Gupta and Saul, is illustrated in Figure 17 (Gupta K. et al. 1996). These authors concluded that the first flush ends when the maximum difference occurs between the cumulative percentage of sediment mass and the cumulative percentage of water volume plotted against the cumulative percentage of time. This maximum difference is show in Figure 16 and occurred at 0.52 of the cumulative water volume/total water volume (Gupta K. et al. 1996) .

Figure 16: Illustration of First Flush Concept (Gupta K. et al. 1996)

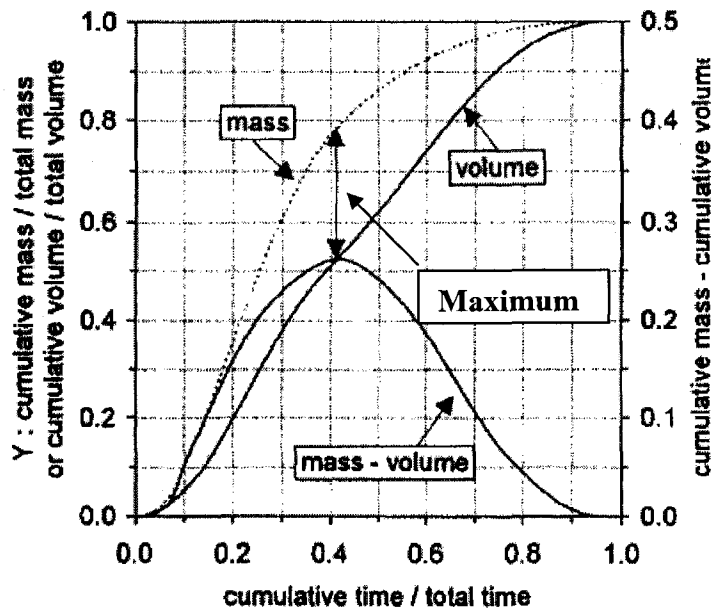


Table 10 shows five events in which the initial sampling criteria were not met (“N” in column 6). Sampling did not occur at the beginning of an event usually due to the lack of human resources present during the initial rain runoff. To evaluate if sampling occurred during the first flush, using the initial runoff criteria and the ending runoff criteria of Gupta and Saul, cumulative rainfall depth plots were made. Cumulative



rainfall depth plots for four out of the five events are in Figures B-2a-d. The 9/11/07 event does not have a cumulative rainfall depth for reasons which will be explained later. The plots in Figure B-2a-d show where sampling began and ended, outlined by the dashed lines.

The entire depth of a rainfall event was not captured because of the water volume capacity of the forebay hence the cumulative rainfall lines on the plots not reaching 1.0. From these plots, only the 4/12/07 (Figure B-2d) event met both the initial and ending criteria for sampling during the first flush. Sampling occurred outside of the ending criteria of the first flush for the other events. Sampling for the 9/11/07 event occurred over three days (9/9-9/11) and between the times of sampling, roughly forty percent of the total rainfall depth was missed meaning that sampling did not occur continuously during the first flush. The three events in which sampling occurred outside of the first flush and the 9/11/07 event are considered events in which the first flush was not sampled

Further evaluation of the Figures in B-1 show that the event on 3/2/07 (Figure B-1h) had unusual characteristics because approximately 0.50 inches of rain fell before any discharge occurred. This was due to the presence of approximately 8-10 inches of snow on the watershed which absorbed the rain before it entered the sewer.

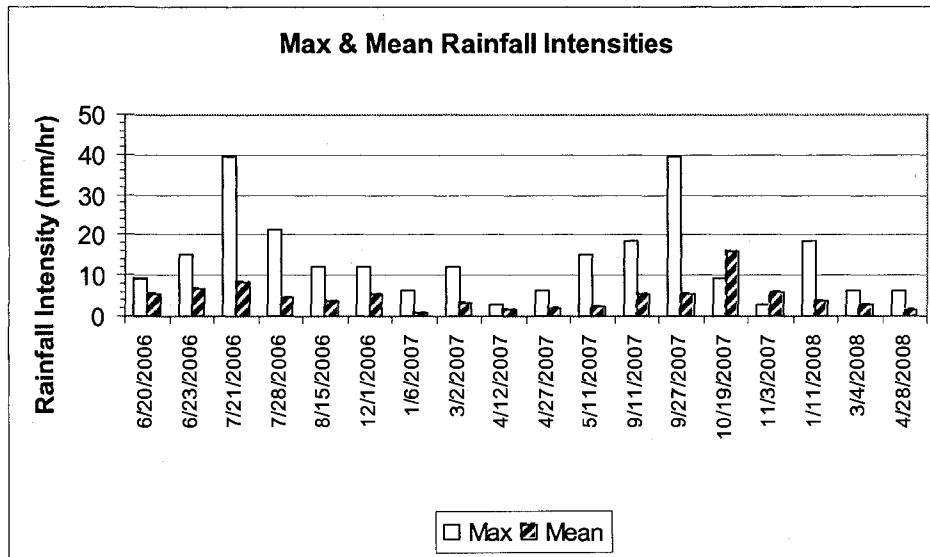
Table 11: Events In Which First Flush was Sampled

<b>Date</b>	<b>First Flush Sampled</b>
6/20/06	No
6/23/06	Yes
7/21/06	Yes
7/28/06	Yes
8/15/06	No
12/01/06	Yes
1/06/07	No
3/02/07	Yes
4/12/07	Yes
4/27/07	Yes
5/11/07	Yes
9/11/07	No
9/27/07	Yes
10/19/07	Yes
11/03/07	Yes
1/11/08	Yes
3/04/08	Yes
4/28/08	Yes

By sampling during the first flush, this allowed for the antecedent dry period to be examined as an environmental influence on: PSD, EMCs, and any potential differences between the actual and monitored EMCs.

Rainfall Intensity. Rainfall intensity data was recorded on site by the ISCO tipping rain gauge in five minute intervals. Maximum rainfall intensities which fell during a sampling event can be seen in Figure 17.

Figure 17: Maximum & Mean Rainfall Intensities



Since the units of measurable rainfall were recorded on site as units of depth/5minutes, the mean rainfall intensity was determined by dividing the total rain depth by the number of five minute intervals during the rain event.

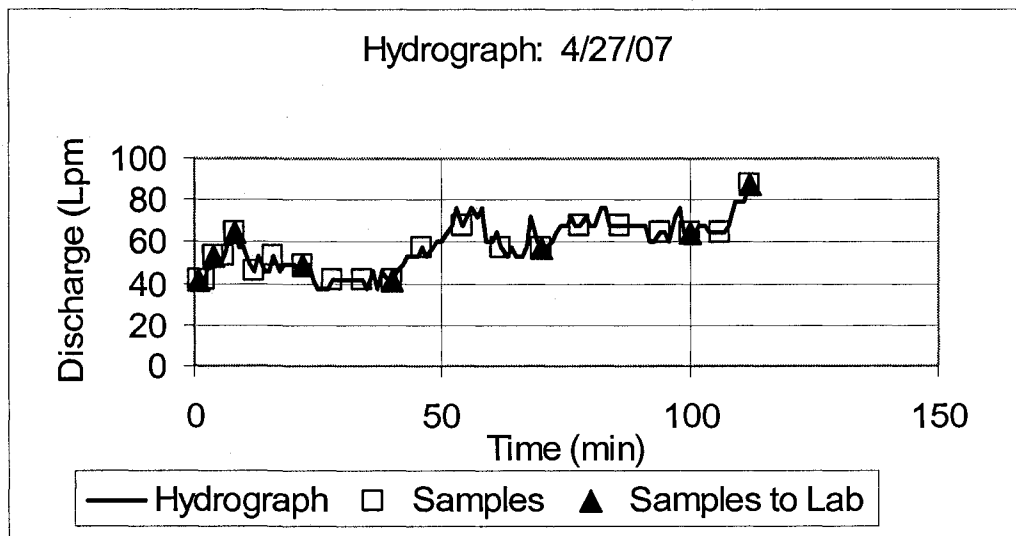
The most intense rain storms were experienced during summer thunderstorms. Five out of six storms with the highest intensities occurred between the months of May through September. This rainfall distribution is typical for southern New England which experiences lower intense storms during late fall through early spring.

A review of the rainfall data from Figures B-1 show the amount of rainfall intensity required to induce runoff is not consistent, but a maximum threshold does exist. Events on 6/23/06, 1/6/07, 4/27/07, 11/3/07 and 3/4/08 (Figures B-1b,g,j,o and q respectively) manifest that if 0.51mm (0.02 in) of rain fell over a ten minute span, then surface runoff occurred. If 0.25mm (0.01) in. of rain fell over a 5 minute time interval, runoff did not necessarily occur, as demonstrated by events on 7/21/06, 8/15/06, 9/27/07 and 10/19/07 (Figures B-1 c,e,m and n respectively). Watershed and previous weather

conditions such as snow can influence the rainfall intensity threshold that determines the onset of surface runoff.

Stormwater Discharge. The hydrographs of each event can be seen in Figures B-3a-r and an example of a hydrograph can be seen in Figure 18. Stage was converted to discharge during each event by the automatic samplers. Time “0” began when the sampling programs were turned on and the stormwater runoff flowed onto the polyethylene liner covering the sand filter forebay. The hydrograph ended when the samplers were shut off and the water was diverted away from the forebay.

Figure 18: Hydrograph of 4/27/07 with Sampling Times

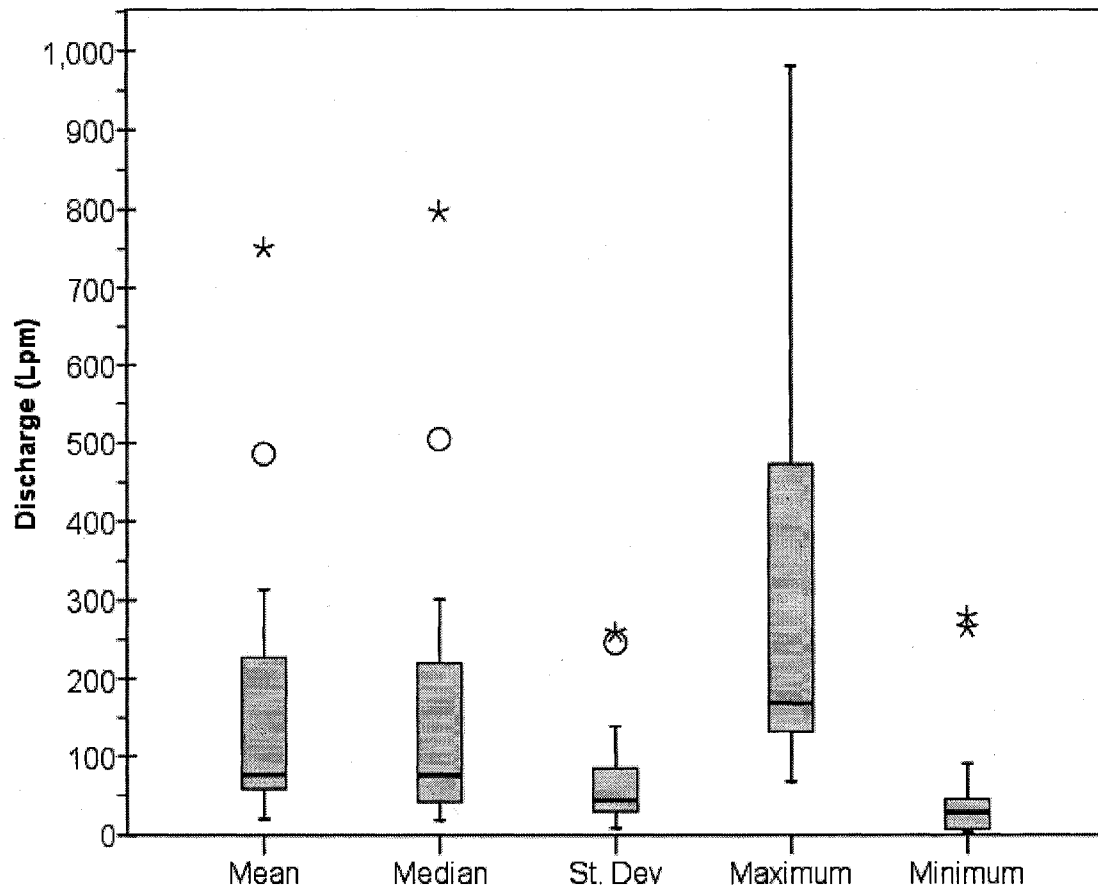


The automatic samplers took samples throughout the entire event, the squares on Figures B-3 and Figure 18. From these samples, eight to nine samples (triangles) were selected for suspended sediment concentration lab analysis which is consistent with previous research (Stenstrom 2005). Descriptive statistics (n=18) for each event's

discharge: mean, median, standard deviation, maximum, and minimum flows are described in Table B-1. A box plot for each event's values of median, maximum, and minimum flows can be seen in Figure 19. In this figure, there is the presence of an outlier (°) and an extreme outlier (\*) for all statistics except for the maximum flow. The length of the box plot is the interquartile range (IQR). If a value is greater than three IQRs from the end of the box plot, the value is an extreme outlier (Statistical Package for the Social Sciences 2008). A value between 1.5-3 times the IQR is labeled as an outlier. The outlier and extreme outlier are from the 7/28/06 and 9/27/07 events, respectively.

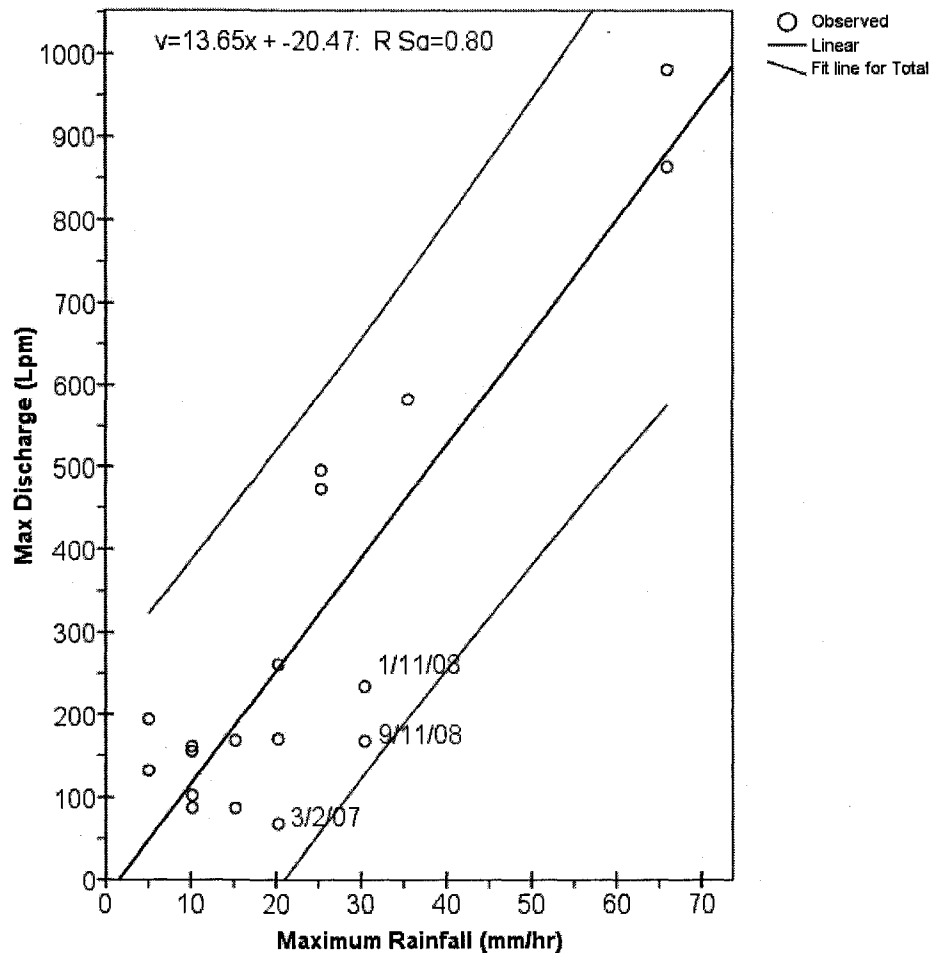
The distribution of median and mean discharge values, 45 and 43 gpm respectively, are almost identical and are positively skewed. Flow levels never exceeded the weir's capacity to monitor flow because the maximum discharge recorded was under the 470 gpm (stage of 0.607 ft) design threshold.

Figure 19: Box and Whisker Plot for Flow Statistics



The watershed is between 90-95% impervious so there should be a strong correlation between max discharge and rainfall intensity. Figure 20, (n=18) shows the correlation ( $R^2=.809$ ,  $y = 1896.8x + 1.8433$ ) between max rainfall intensities and max discharge during sampling events.

Figure 20: Regression for Maximum Rainfall and Maximum Discharge



There are three visual outliers close to the 95% confidence interval that are noted in Figure 20. Event 3/2/07 and 1/11/08 experienced rainfall while there was snow on the watershed. The snow absorbed rainfall and reduced the rate of discharge into the storm sewer. The event on 9/11/07 experienced a heavy rainfall intensity during the tail end of sampling as seen in this event's hyetograph in Figure B-1n. The full volume from this burst of rain might have not reached the sampling location before the seal was placed onto the pipe leading to the basin. If these three events were excluded from Figure 20, then the  $R^2$  value improves to 0.918.

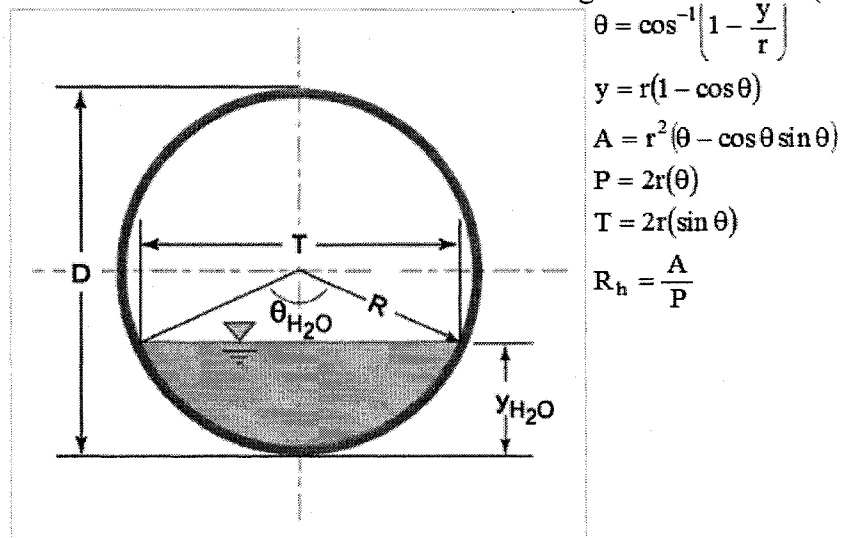
Velocity. The stage and discharge data was used to calculate the velocity in the 38.1 cm (15in) pipe using continuity. The continuity equation is:

$$Q = VA \quad \text{Equation 10}$$

Where:  $Q$  = discharge (ft<sup>3</sup>/sec),  $V$  = velocity (ft/s) and  $A$  = area (ft<sup>2</sup>)

The cross sectional area of pipe flow was determined using the stage data. Stage depth (ft) was converted to area using the following equation in Figure 21.

Figure 21: Calculation of Cross Sectional Area From Stage Measurements (ORST 2008)



Velocity was then calculated for all events and descriptive statistics such as mean, median, etc. are presented in Table B-2 (n=18). Events were broken into groups based on median velocity flows as seen in Table 12, the values (median velocities) used to split events into different groups, or storm profiles, were arbitrary and used to summarize the variety of velocities in the pipe during a sampling event to evaluate if the velocity conditions in light of isokinetic sampling conditions



Table 12: Grouping of Events Based on Median Pipe Velocities

Storm Profile	# of Storms	Range of Median (ft/s)	Max (ft/s)	Min (ft/s)
I	6	0.01-0.50	0.47	0.09
II	9	0.51-1.00	0.81	0.51
III	3	>1.01	3.52	1.3

The velocity in the intake sampling tube is determined by the total suction head the automatic sampler has to overcome in order to extract a sample. The velocity head for this sampling setup is 3.0 ft/sec. The intake velocity was faster than the majority of velocities in the pipe during sampling events. A non-isokinetic environment existed so the potential for field sampling bias exists due to the automatic sampler's intake velocity. Only one event, 9/27/07, experienced a median velocity value (3.38 ft/sec) that approximately matched the intake velocity.

## **4.2 Sample and Data Collection**

### **4.2.1 Sample Collection**

Six to 24 samples were collected by automatic sampler during each event as listed in Table 13. For eleven of these events, 20 or more samples were collected. Of these samples, 6-19 samples were sent to the lab for sediment concentration analysis. Towards the end of this research, more samples were sent to the lab for analysis to increase the robustness of data used to develop the turbidity-suspended sediment concentration regression which will be explained further in the following section.

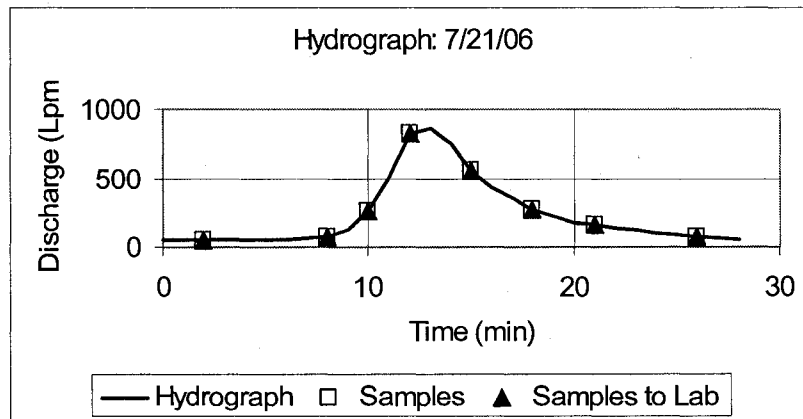
The Figures B-3a-r, show the hydrograph for each event and when grab samples were taken and an example of a hydrograph can be seen in Figure 22. The dots represent

the points during the event when 1L grab samples were taken and the triangles are the samples that were selected for suspended sediment concentration analysis.

Table 13: Number of Samples Taken During Sampling Events and Analyzed

Date	Samples Taken	Samples To Lab
6/20/06	24	8
6/23/06	24	8
7/21/06	24	8
7/28/06	15	7
8/15/06	21	8
12/01/06	22	9
1/06/07	23	11
3/02/07	17	8
4/12/07	18	9
4/27/07	21	8
5/11/07	12	8
9/11/07	22	9
9/27/07	6	6
10/19/07	13	7
11/03/07	22	8
1/11/08	20	19
3/04/08	16	8
4/28/08	24	16

Figure 22: Hydrograph form 7/21/06 Event with Sampling Times



Samples were selected throughout the entire hydrograph to be consistent with previous research (Stenstrom 2005) as stated in section 3.4.1. If the hydrograph was

discretized into volume intervals, it would show that the selected samples would best represent these intervals.

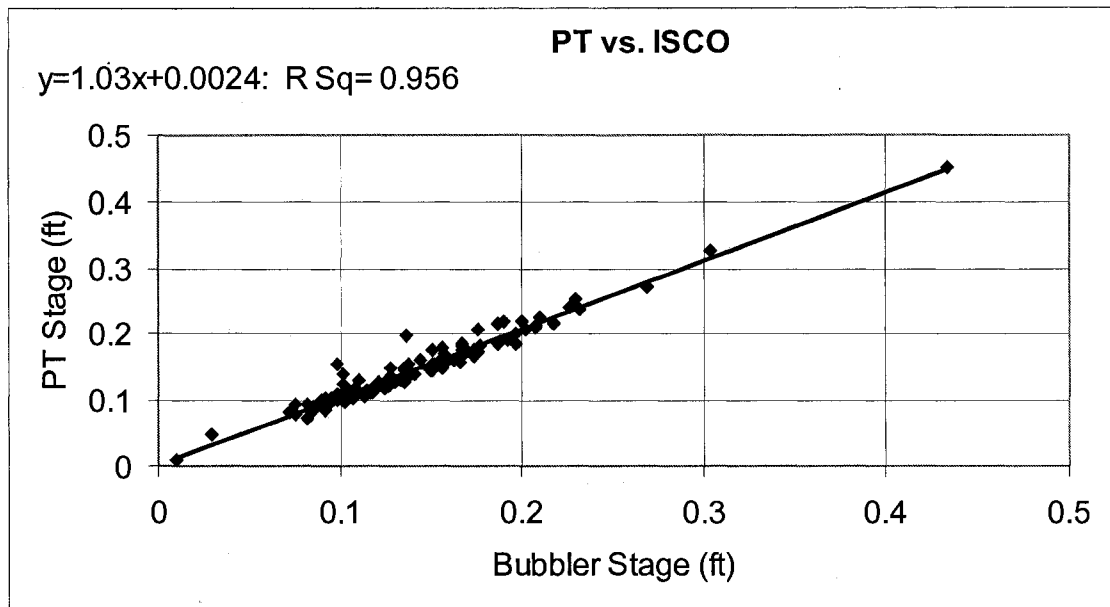
The pollutographs for each event are seen in the Figures B-5a-r. Thirteen events showed a large spike in concentration during the beginning of the sampling event with the concentration tailing off toward the end of the sampling event. All of these events occurred during the first flush and met the beginning and ending criteria of a first flush as discussed in section 4.1.1. The events that did not experience this tailing off characteristic were events in which the first flush was not captured as identified in Table 13 or the event on 1/11/08: an event that sampling occurred over two days.

Using the suspended sediment concentration results, a probability plot in Figure B-6 illustrates the probability of suspended sediment concentration of all the samples. This figure shows there is a 0.48 probability that samples captured by the automatic sampler are 50 mg/L (expected sediment concentration from this land type shown by the dashed line) or less.

#### 4.2.2 Stage Measurement Equipment

The pressure transducer and ISCO bubbler monitored stage behind the ThelMar weir. To ensure that the instruments were measuring the same stage, a regression analysis was performed between the bubbler data and the pressure transducer data, and can be seen in Figure 23.

Figure 23: Regression of Stage Measurements



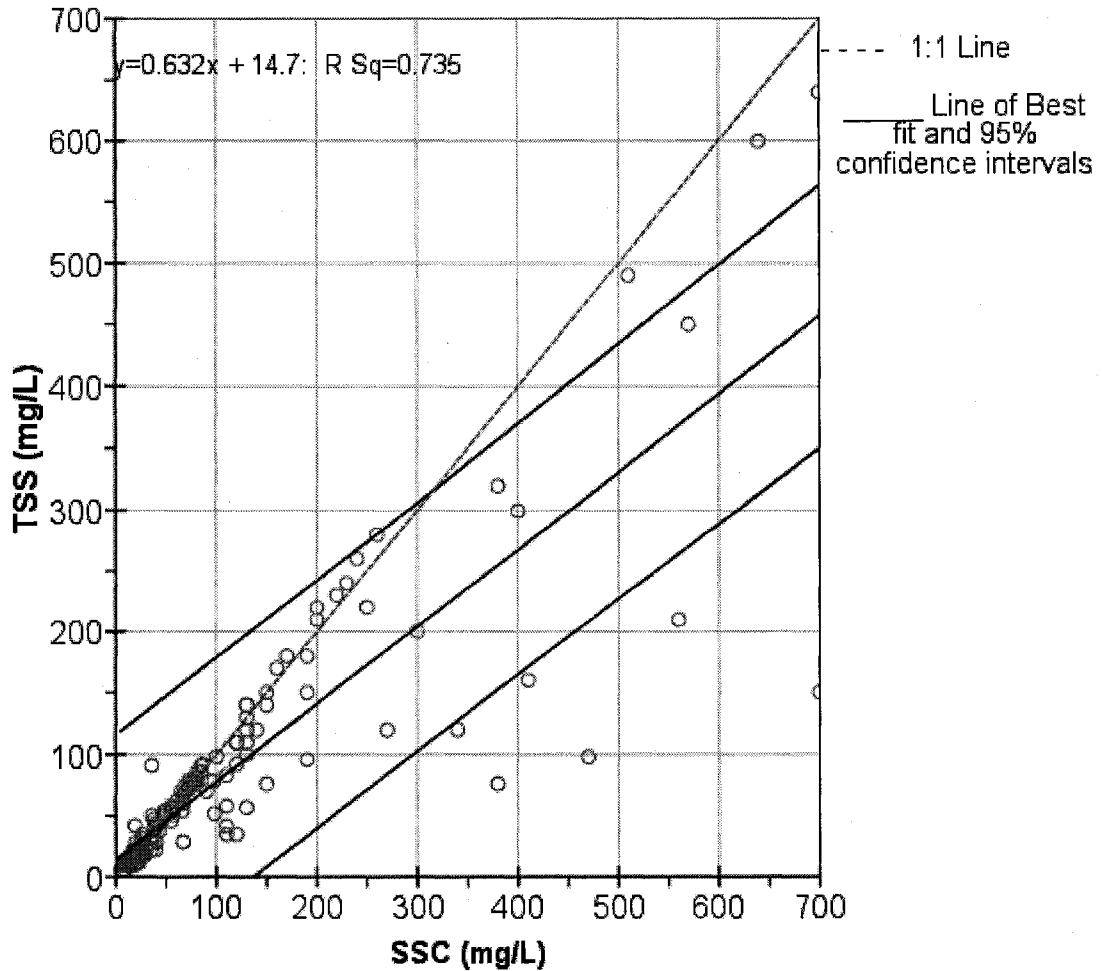
The values seemed to be 1 to 1 (slope 1.027 and  $R^2=0.956$ ). When there is a difference, the pressure transducer seemed to read a higher stage. Stage was converted to discharge by the automatic samplers. To verify if the stage - discharge rating curve was accurate, the total measured volume, as recorded by the automatic sampler was compared to the volume from the Total Capture sample, the presumed actual volume. This will be addressed in section 4.7.3.

#### 4.2.3 Sample Suspended Sediment Concentration Results

The lab suspended sediment concentration results were plotted to compare SSC and TSS values. These results can be seen in Figure 23,  $n=167$ . There is not a strong correlation between the synoptic TSS and SSC values ( $R^2=0.7351$ ). It appears that the TSS measurements are generally lower than the SSC values (slope of line 0.632). The discrepancy between the two values seems to increase as the value of SSC increases, as indicated by the increasing differences from the line of best fit in Figure 24.

The samples were then categorized by level of discharge during the time they were captured by the automatic sampler.

Figure 24: Comparison of TSS & SSC Sample Results



Prior research has tried to improve the correlation between SSC and TSS in hopes of using TSS results to predict SSC results. The correlation between SSC and TSS could not be improved to a satisfactory level where TSS could be reliable predictor for SSC (Gray J. et al. 2000).

All the discharges measured at the time a grab sample was taken by the automatic sampler were used in the non-exceedance probability ( $P_n$ ) plot in Figure 25. Table 14

explains Figures 26a-d, which shows the linear relationships between TSS and SSC values at different  $P_n$  values.

Figure 25: Non-Exceedance Probability Plot of Discharges at Time of Sampling

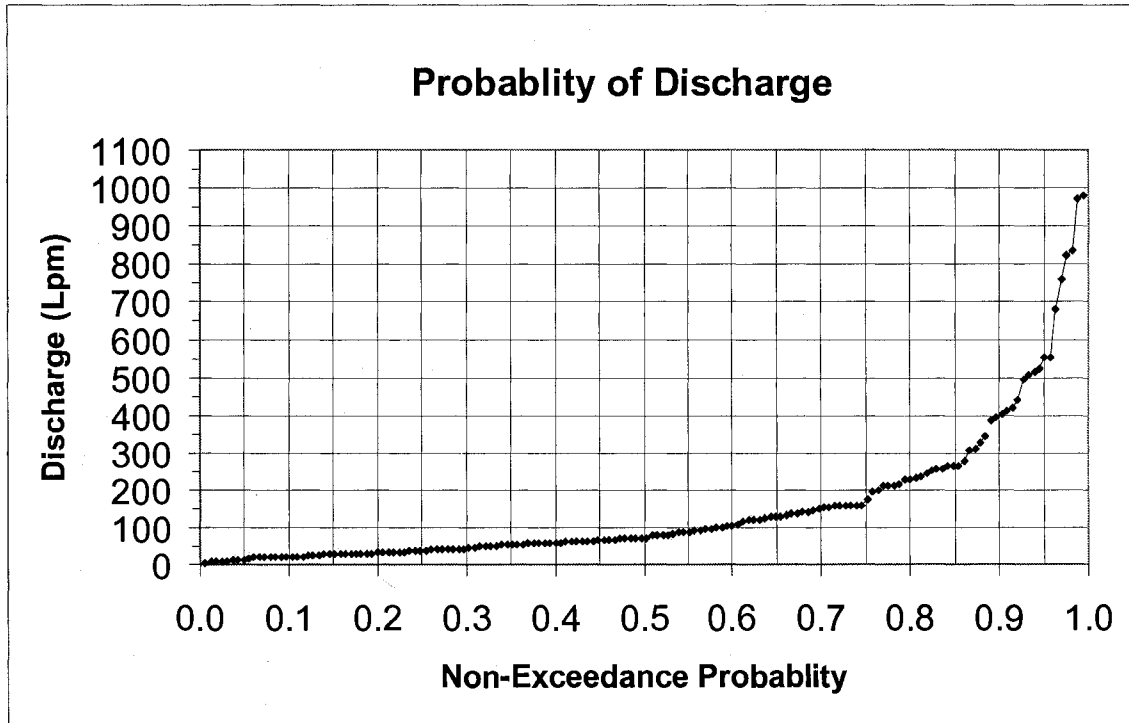


Table 14: Description of Figures 25a-25d

Figure	Discharge (Lpm)	$P_n$
26a	3.78-37.8	0.01-0.25
26b	40.1-72.0	0.26-0.50
26c	77.5-174.7	0.51-0.75
26d	197.0-979.4	0.76-0.99

Figure 26a: TSS & SSC values at Pn:0.01-0.25

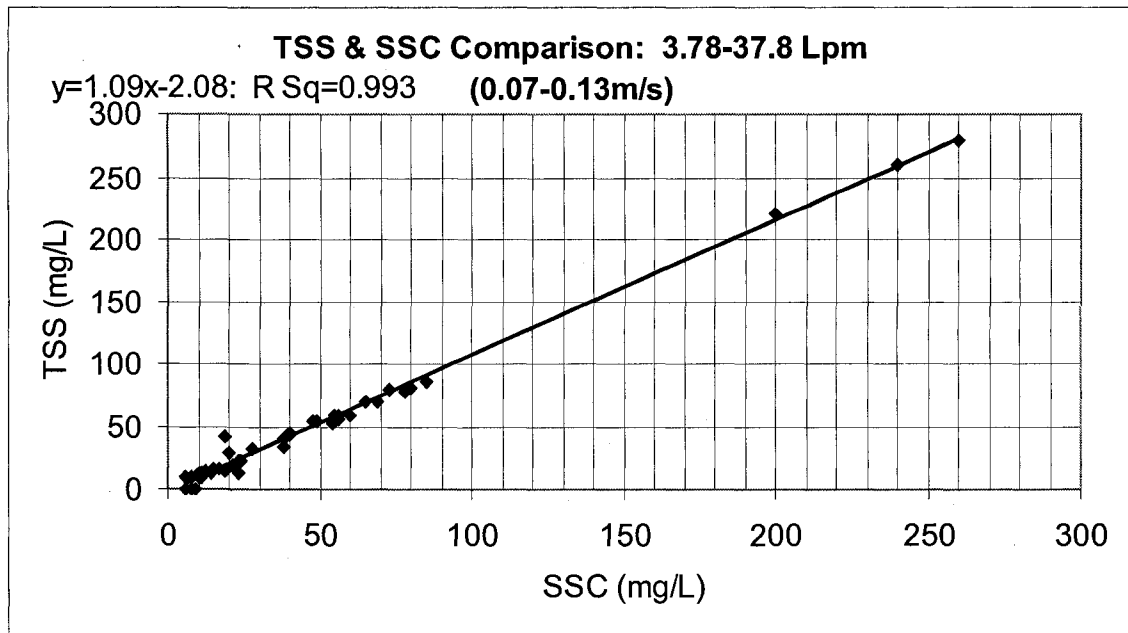


Figure 26b: TSS & SSC values at Pn:0.26-0.50

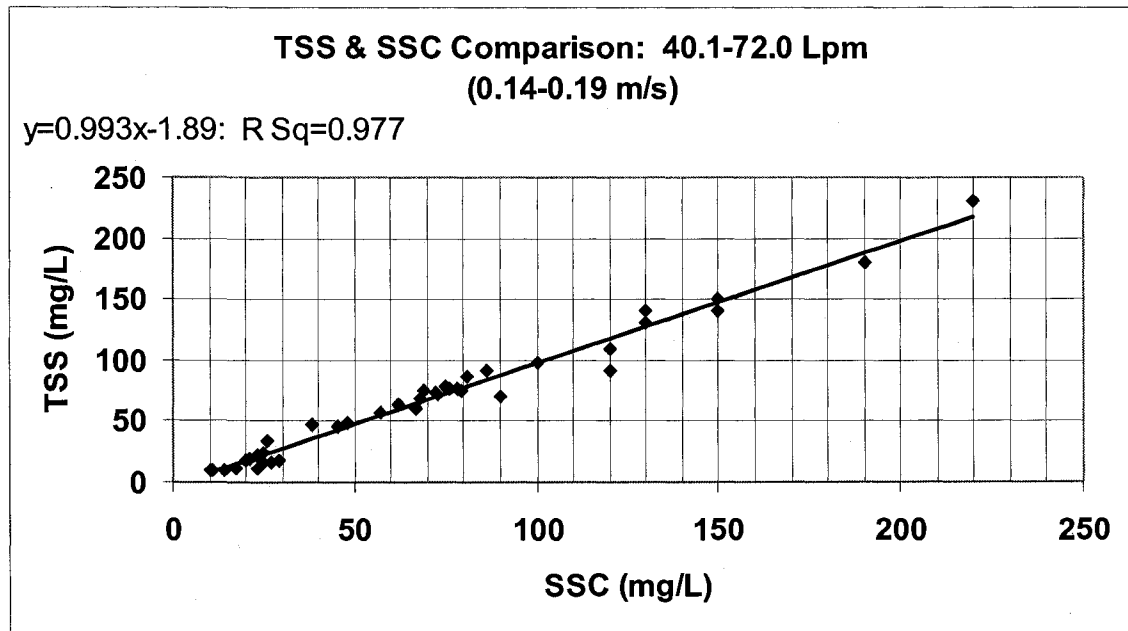


Figure 26c: TSS & SSC values at Pn: 0.51-75

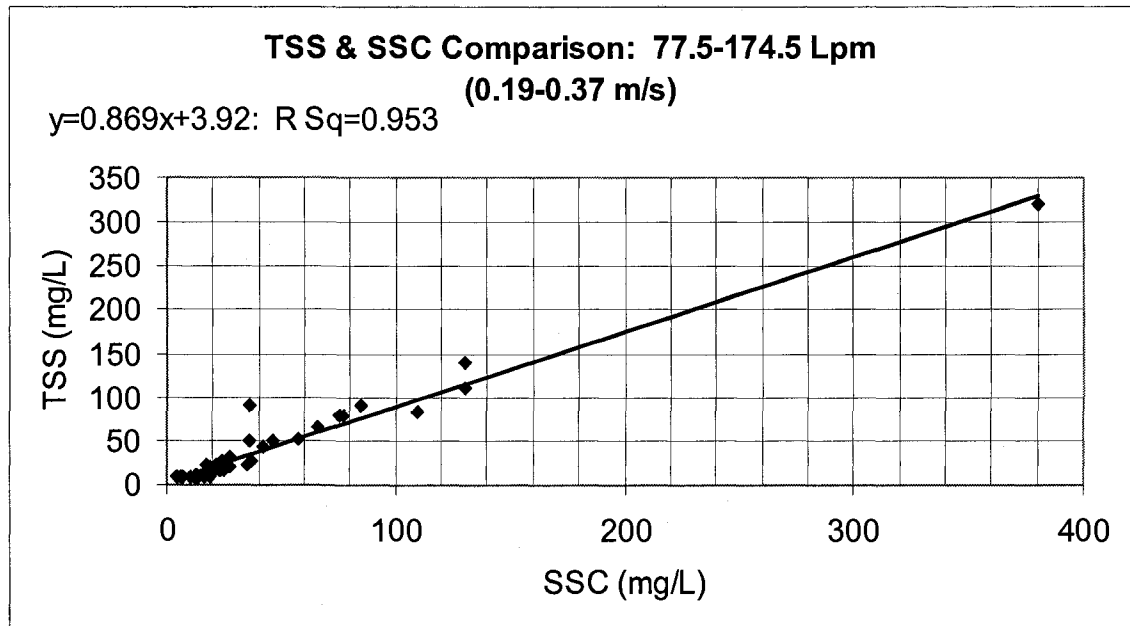
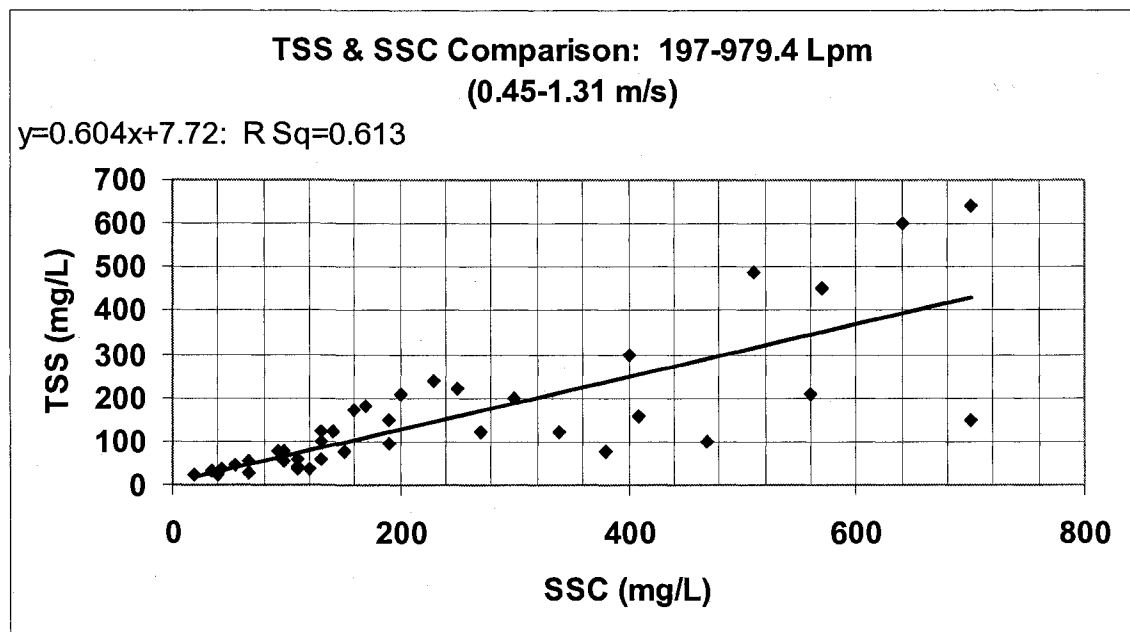


Figure 26d: TSS & SSC values at Pn: 0.76-0.99



A TSS and SSC test was completed for every 1L grab sample. During times of lower discharge, TSS and SSC measurements are very similar. As the discharge increased, TSS values were lower than the SSC value and the values became less alike.



Table 15 shows the  $R^2$  and n values for the Figures 26a-d. Evaluating Figure 26d, it appears that the TSS value is under reporting the SSC value for this range of discharge (slope of line 0.603).

Table 15:  $R^2$  and n values of TSS & SSC relationships at different flows

Figure	Discharge (Lpm)	$R^2$	N
26a	3.78-37.8	0.993	42
26b	40.1-72.0	0.977	41
26c	77.6-174.6	0.953	41
26d	197-979.4	0.613	40

#### 4.2.4 Optical Results: Turbidity

Turbidity measurements (in NTU) were taken every minute during sampling events. An NTU value was then paired with both the sample's TSS and SSC sediment concentration (mg/L) values. A greater number of samples were sent to the lab for analysis from the last few events to increase the number of samples used for these two turbidity regressions. The regression for turbidity-suspended sediment concentration and SSC (NTU-S) and turbidity-TSS (NTU-T) are seen in Figures 27 and 28, respectively.

Figure 27: Turbidity Regression using SSC Results

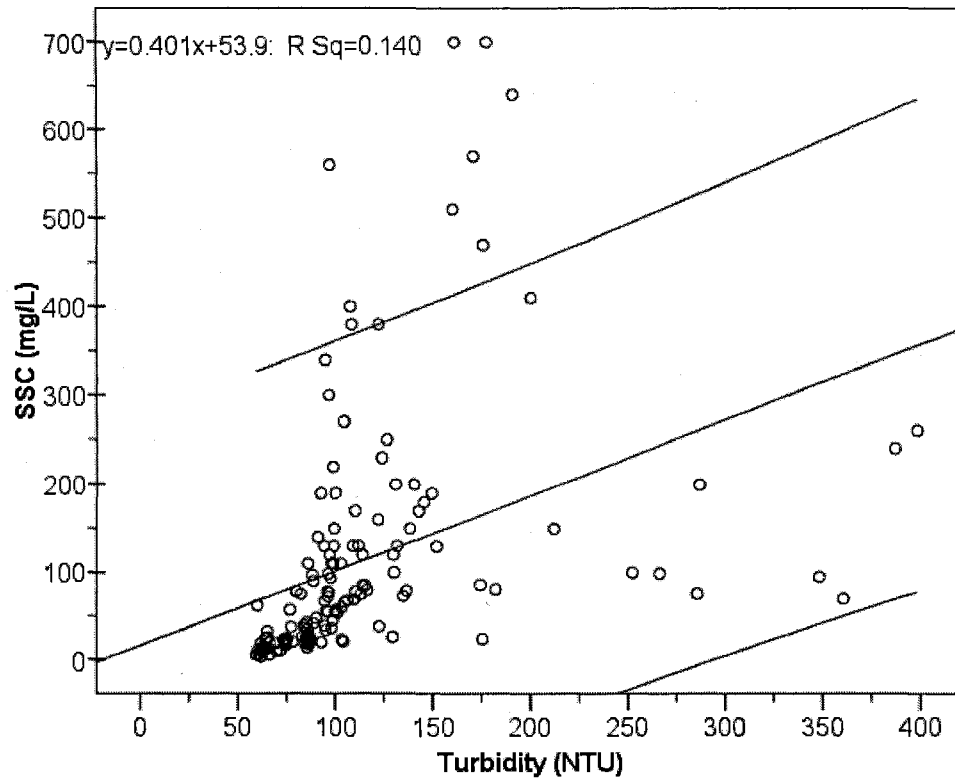
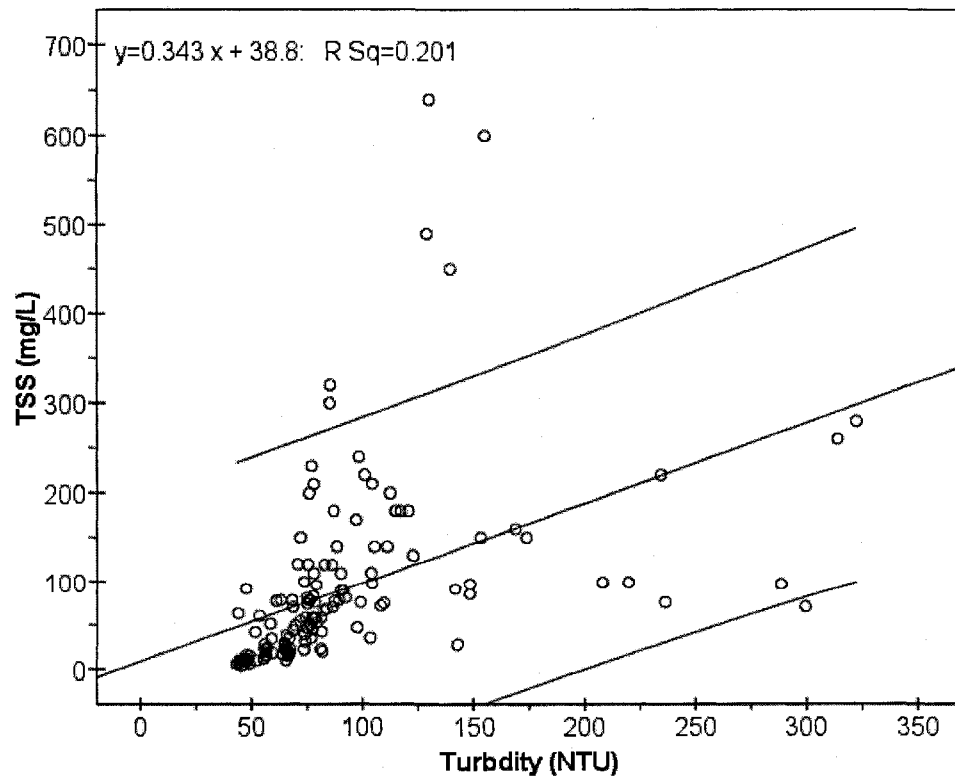


Figure 28: Turbidity Regression using TSS Results



Both regressions show a poor relationship between NTU-S and NTU-T,  $R^2=0.175$  and 0.233, respectively. These relationships are not as good as the NTU-sediment mg/L correlations seen in Figures 8 and 9. The relationships in Figures 8 and 9 were developed from measuring the optical properties of urbanized streams in which there was not a concern of a constricted space or a water surface elevation that might drop into the optical viewing area of the turbidity meter. A concern with the relationships in Figures 27 and 28 is the y-intercept of the line of best fit. When the turbidity meter is reading “0” NTUs, there should be a corresponding “0 mg/L” suspended sediment concentration. For the regression relationships, the y-intercept for “0” NTUs is 54 and 39 mg/L for NTU-S and NTU-T respectively. This raises concern if the turbidity meter could measure “0” suspended sediment concentration.

To determine whether the turbidity meter was reading correctly in a sediment-free sample, the blank sample verification data was reviewed. The turbidity meter was submersed in a bucket containing reverse osmosis (RO) water which was assumed to be sediment free. The results are in Table 14.

Table 14: Turbidity Blank Sample Verification

<b>Date</b>	<b>1<sup>st</sup> Trial</b>	<b>2<sup>nd</sup> Trial</b>	<b>3<sup>rd</sup> Trial</b>
1/12/2007	0*	0*	0*
5/26/2007	1.44	1.58	1.47
4/28/2008	1.14	1.09	1.12

In January 2007 (data labeled with a “\*”), the turbidity probe and meter were sent to Forest Technologies, its manufacturer, for lab calibration which followed USGS and ASTM protocols (American Society for Testing and Materials 2003; Anderson C. 2005).

At that time, the instrument was recalibrated and measured 0 NTU for a sample with 0 mg/L of suspended sediment concentration.

The other two times the blank sample verification was performed (Table 14) at the UNH Stormwater Center. This verification occurred in a container with dimensions much larger than the interior of the pipe ensuring the optical viewing area surrounding the turbidity probe was not compromised. After the results from Table 14 were obtained, the manufacturer stated these results were within the margin of error for field sample verification. It appears the turbidity meter was monitoring “0 NTU-0 mg/L (suspended sediment concentration)” correctly which does not explain why the y-intercept was high for NTU-S and NTU-T. Possible explanations could be the configuration of the turbidity meter in the pipe did not provide enough room for the optical viewing area. If this space was inadequate and the pipe’s wall was within the optical viewing area, this could skew results. Also, the turbidity meter was placed near the 15” expansion joint. This change in flow pattern could have introduced turbulence resulting in air bubbles in the water column. Air bubbles are known to introduce error into turbidity readings under turbulent flow conditions. An attempt to “clean” the data in order to develop a suspended sediment EMC was made and will be discussed in section 4.3.3.

The natural log of all values was calculated and plotted because of the wide range of turbidity and suspended sediment concentration values of Figures 25 and 26. By taking the natural log, measured values are in a narrower range as seen in Figures 29 and 30 which have the 95% confidence interval.

Figure 29: Regression using Natural Logs of NTU and SSC Results

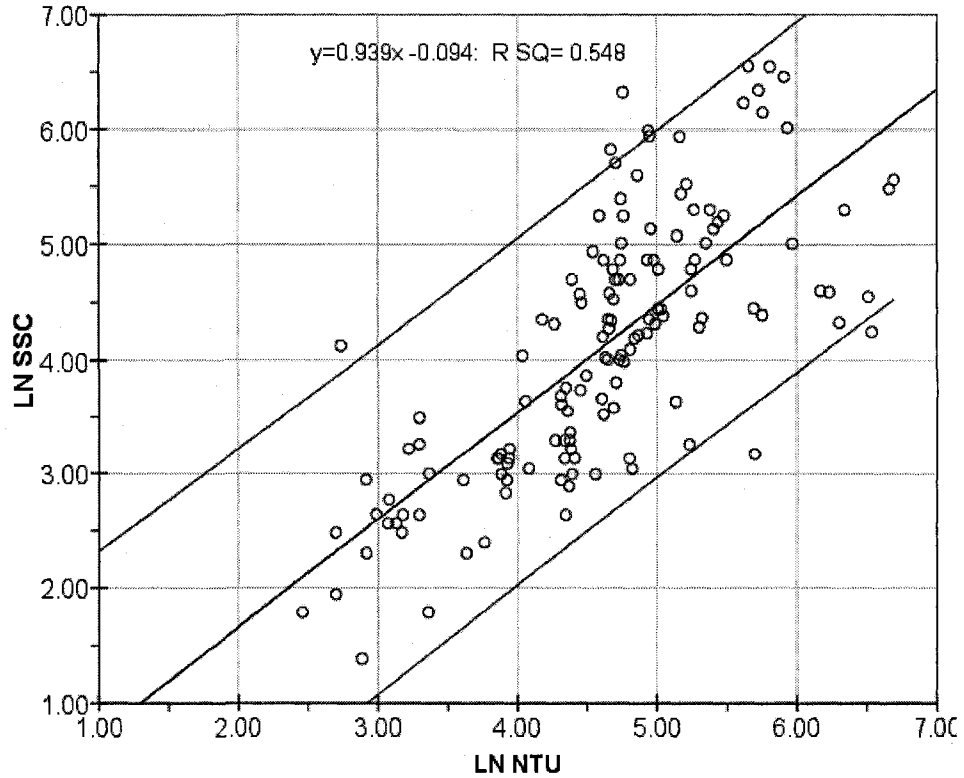
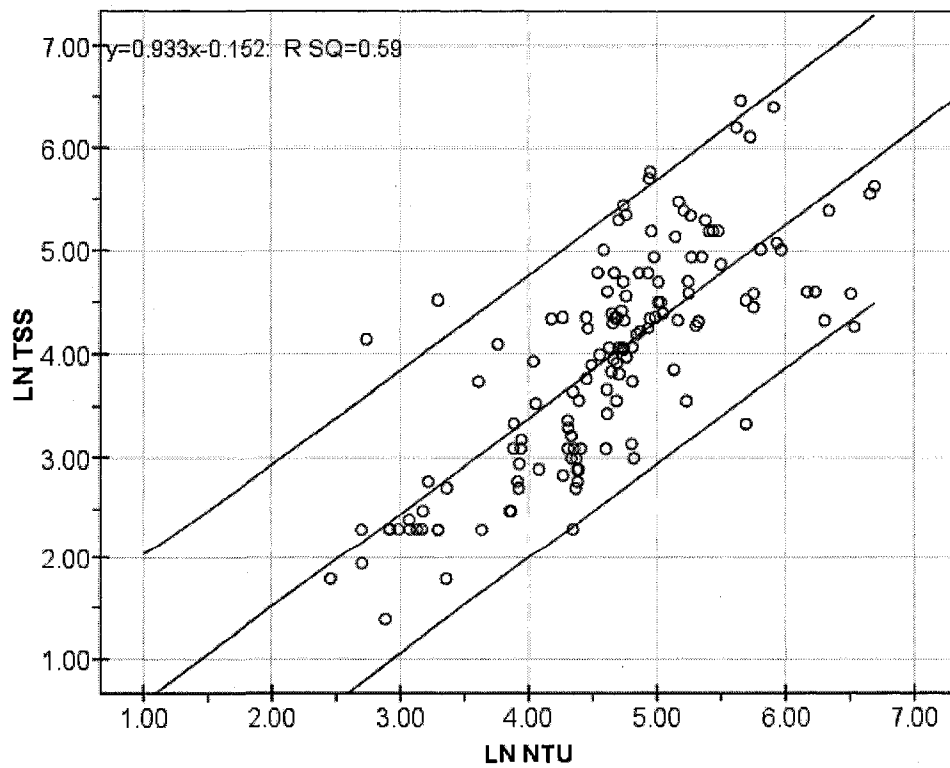


Figure 30: Regression using Natural Logs of NTU and TSS Results



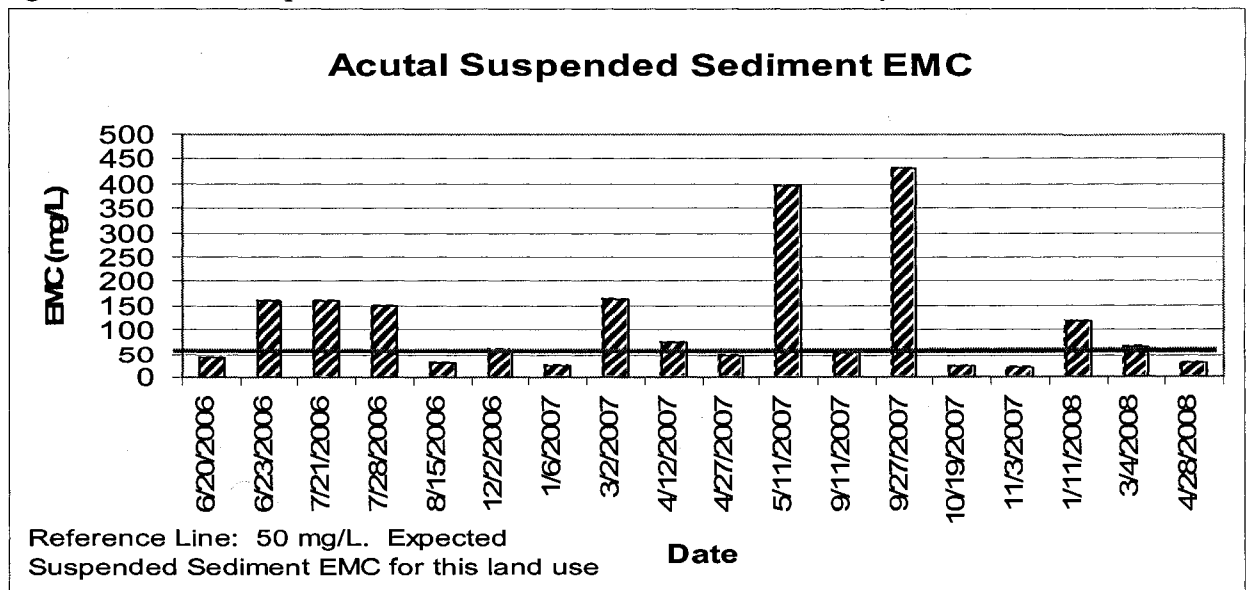
### 4.3 Suspended Sediment Event Mean Concentration

#### 4.3.1 Total Capture Sample:

The suspended sediment EMCs from the Total Capture (TC) samples can be seen in Figure 31. A reference line was added at 50 mg/L to represent the average suspended sediment concentration EMC expected from this type of land use (Roseen R. et al. 2006). The TC EMCs are the presumed actual values of the suspended sediment concentration for each event's EMC. The suspended sediments recovered in this process were between 2 $\mu$ m and 4.5 mm, in size, in accordance with the ASCE definition of suspended sediments discussed in section 2.2.2.

Ten of the eighteen events exceeded the 50mg/L level. Descriptive statistics for these EMCs can be seen in Table 15. The maximum EMC was measured during the 9/27/07 event and the lowest on 11/3/07. Five out of seven events' EMCs which exceeded 100 mg/L occurred during summer months (May through September), perhaps due to the high discharge levels during thunderstorms flushing the sewer system.

Figure 31: Actual Suspended Sediment Event Mean Concentration by Event



The event on 3/2/07 had the largest antecedent dry period of any event during the sampling period which allowed for an unusually large sediment load to build up on the lot.

Table 15: Descriptive Statistics of TC Suspended Sediment EMC (all values in mg/L)

<b>Method</b>	<b>Mean</b>	<b>Median</b>	<b>Max</b>	<b>Min</b>	<b>St. Dev.</b>
TC	122.2	68.6	432.9	20.9	120.7

The median value of the suspended sediment EMCs are 68.6 mg/L. This value is slightly more than what is expected for this land use (50 mg/L (Roseen R. et al. 2006)), but well within the natural range of variability. The mean EMC is much higher, 122.2 mg/L, and is inflated because of the very large EMCs for the 5/11/07 and 9/27/07 events.

Figures C-1a-c show the regressions used to identify which environmental factors might influence the TC EMC. The “n” for maximum discharge and rainfall intensity is 18 but 14 for the antecedent dry period regression because the first flush was missed for four events: 6/20/06, 8/15/06, 1/06/07 and 9/11/07 as described in section 4.1.1.

The maximum discharge, rainfall intensity and antecedent dry day regressions did not exhibit strong correlations with the TC EMC ( $R^2=0.547, 0.433$  and  $0.073$ , respectively) which is consistent with previous research (Han Y. 2006). The regressions for maximum discharge and rainfall intensity do show a positive correlation: as the discharge and rainfall intensity increase so does the TC EMC. During times of intense rainfall, the velocity of the sheet flow across the parking lot surface is greater and can sweep coarser sediments into the sewer. Higher discharges in a pipe cross section will increase the shear stress which improves the capacity of the runoff to move more coarse

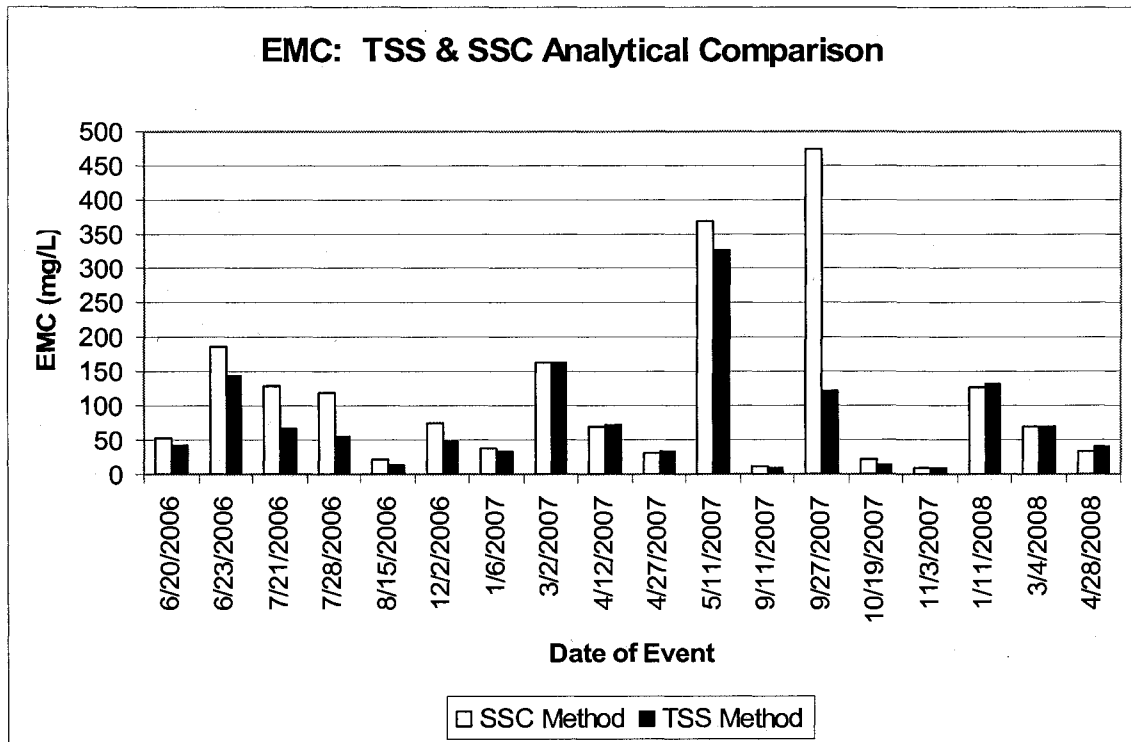
sediments towards the outlet. Coarser sediments generally create higher suspended sediment concentrations (Furumai H. et al. 2002).

#### 4.3.2 Automatic Sampling Samples

The automatic sampler suspended sediment EMC values using the two analytical methods (TSS and SSC) are shown in Figure 32.

Five events with the largest discrepancy between TSS and SSC occurred during the months of May-September, the time of year which experiences thunderstorms.

Figure 32: TSS & SSC analytical comparison



Descriptive statistics of the two analytical method EMCs are shown in Table 16. There is a large difference between the mean and median EMC values of TSS and SSC. The mean EMCs values should not be used as a comparison tool because a few events



(5/11/07 & 9/27/07), with large results, can skew the arithmetic mean. Its also important to note, the highest TSS EMC did not occur during the same event as the highest SSC EMC (9/27/07). The highest TSS EMC event occurred during the 5/11/07 event.

Table 16: Descriptive Statistics of Analytical (SSC, TSS) EMCs (all values in mg/L)

<b>Method</b>	<b>Mean</b>	<b>Median</b>	<b>Max</b>	<b>Min</b>
SSC	110.8	70.1	472.9	8.5
TSS	77.4	51.3	326	10.1
TC	122.2	68.6	432.9	20.9

A Wilcoxon signed rank test was performed on the data to see if a statistically significant difference existed between the SSC and TSS EMC results. This test was chosen because the data is paired and the difference between the SSC and TSS is non-normally distributed which can be seen in Figure B-7. If the differences were normally distributed the observed cumulative probability would be approximately the same as the expected cumulative probability (a one-one slope). However, Figure B-7 shows, this relationship does not exist, so the Wilcoxon signed rank test is more appropriate than the student paired t-test which assumes normal distribution. The results from the Wilcoxon signed rank test are found in Table 17. The Wilcoxon signed rank test is used to determine if the median value of the differences between paired EMCs equals zero. This means there is an equal amount of positive differences to negative differences and if this criterion is satisfied there is no statistical difference between the pairs. A statistically significant difference exists if using a 95% confidence level, the significant level (p-level) is less than 0.05. The results in Table 17 indicate that there is a statistically significant difference between the TSS and SSC EMC results.

Table 17: Statistical Test Results for TSS & SSC EMC Comparison

Test Statistic	
Confidence Level	0.95
$\alpha$	0.05
Z	-2.286
p-level	0.022
St. Difference	YES

To examine what might contribute to the difference between TSS and SSC EMCs several regressions were developed. Four environmental variables were chosen for regression analysis to assess their influence on the difference between EMCs: maximum (Max) discharge, antecedent dry period, duration of sampling event and  $D_{70}$  particle size of the total capture. Antecedent dry period was used in these regressions because they were investigated in previous research for their influence on EMCs (Kayhanian 2003). Max discharge was also used because in Figures 26a-d, samples which were collected at higher discharge levels had a greater disparity between SSC and TSS suspended sediment concentration results than samples that were collected at lower discharge levels. Particle size influence on the difference between SSC and TSS EMC will be addressed in section 4.4.4.

Figures 33 through 35 show the linear regressions for each of the four above mentioned environmental variables. The linear line of best fit is the middle line in the plots. The two outer lines are the bands of the 95 % confidence interval.

Figure 33: Regression Model Using Max Discharge

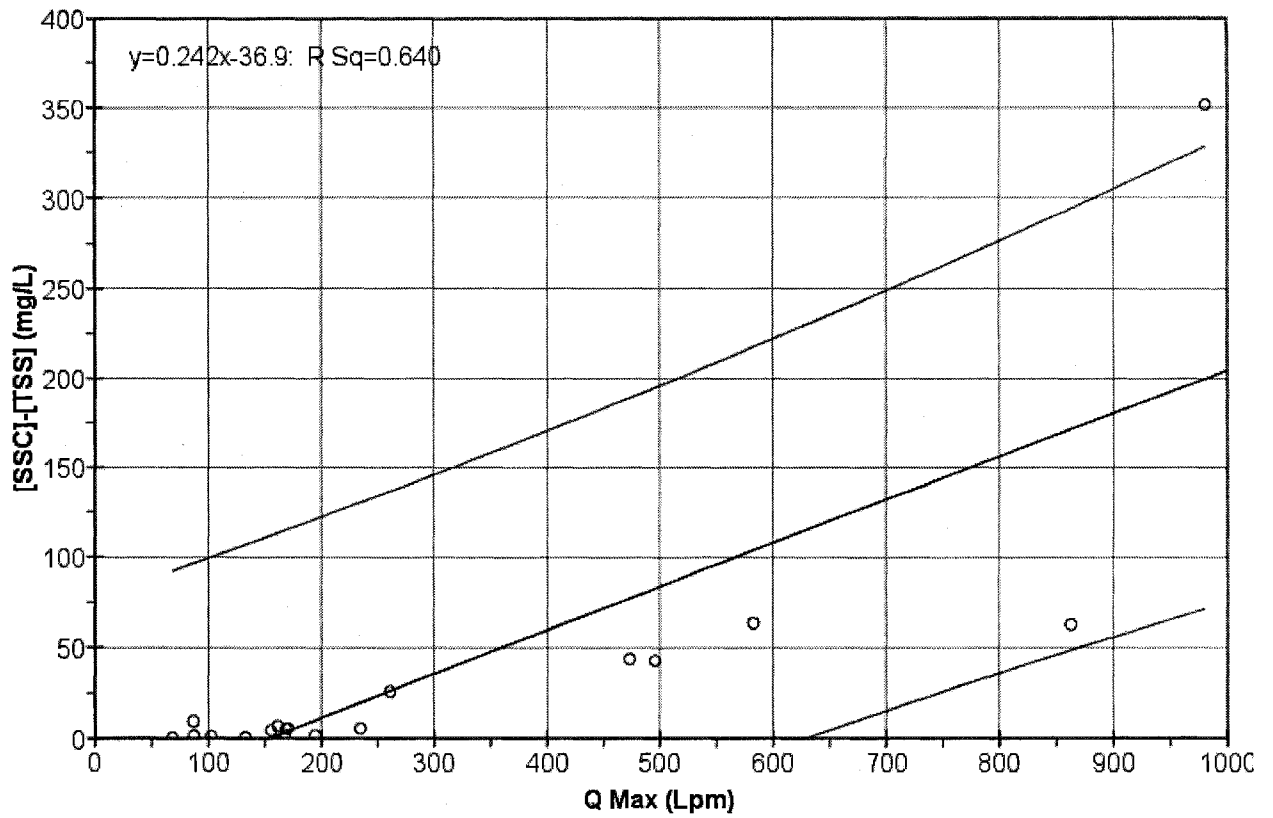


Figure 34: Regression Model Using Duration of Sampling Event

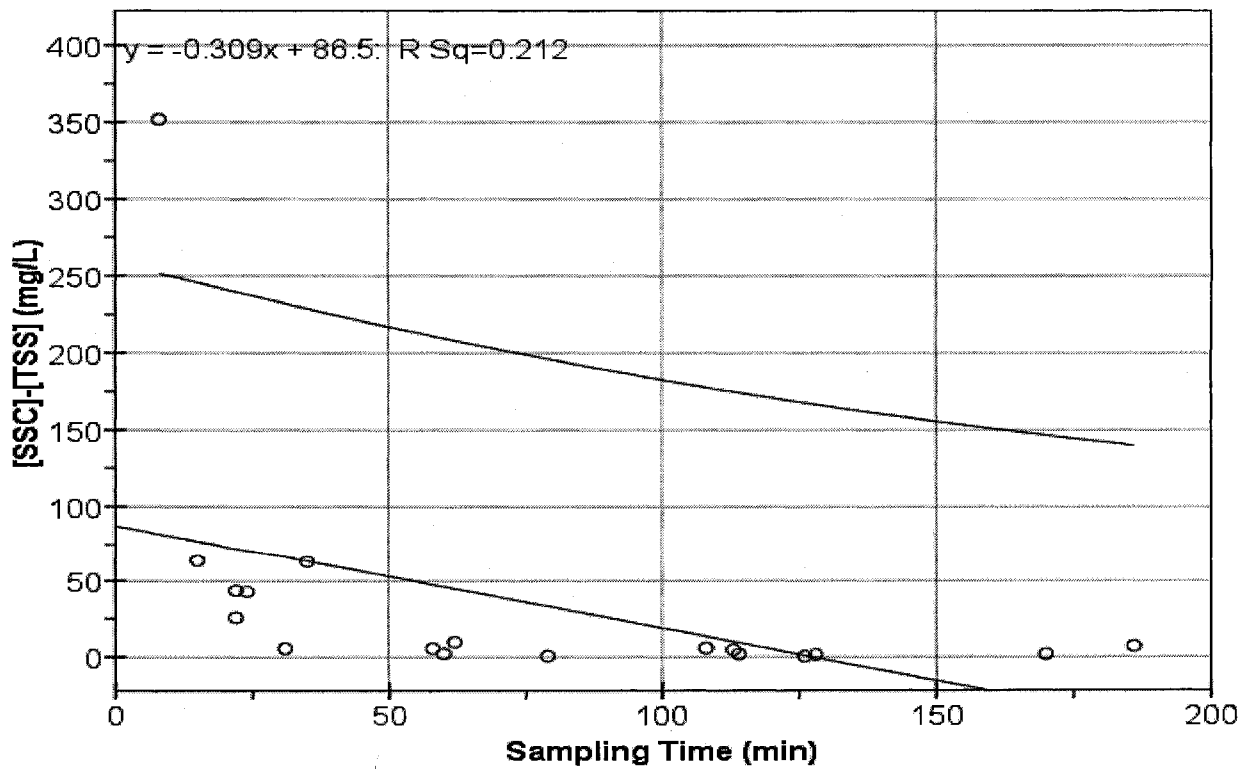


Figure 35: Regression Model Using Antecedent Dry Period

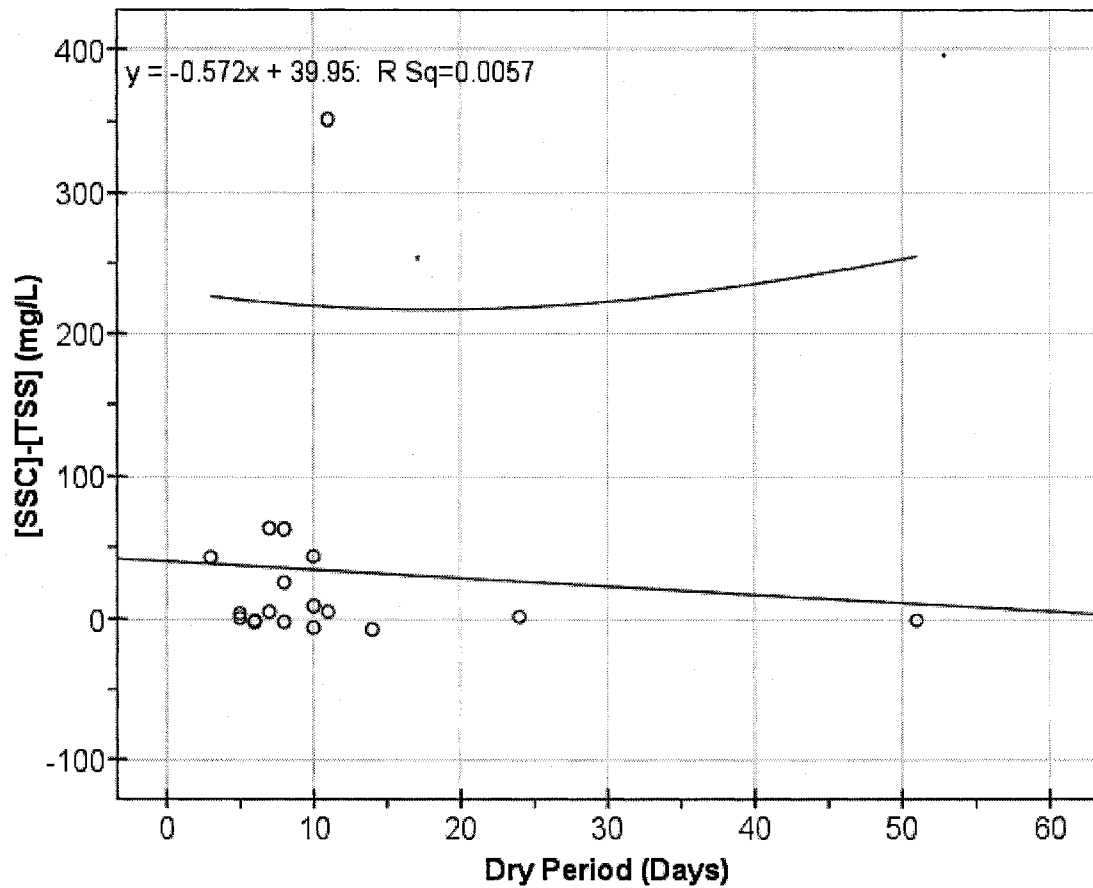


Table 18 shows the  $R^2$  values of the regression estimate and the ANOVA p-levels. The  $\alpha$  value used at 0.95 confidence is 0.05. The “n” value for the three regressions is 18 except for the comparison using the  $D_{70}$  values. The PSD of the first six events were completed using a drying step in the sieving process which was not included in the rest of the events. This drying step caused aggregation among the particles and for this reason the PSD results for the first size events could not be compared to the PSD results of the wash sieving.

The regression between the EMC difference and the maximum discharge had the highest  $R^2$  value and lowest p-level (level of significance), meaning that the null

hypothesis should be rejected. In this case, the null hypothesis means there is not a linear relationship between the independent variable (max discharge) and the dependent variable (difference between SSC and TSS EMCs). The regressions with sampling duration and  $D_{70}$  had a lower  $R^2$  value but still had a p-level below the  $\alpha$  value. This could be explained by the presence of the outlier which will be discussed in the next paragraphs. The antecedent dry period did not have a strong correlation or a low p-level meaning it did not appear to influence the difference between the EMCs.

In each of the previous figures, there is a consistent outlier, 9/27/07. The difference between the SSC and TSS EMCs is consistently outside the uppermost bound of the 95 percent confidence interval. This outlier was removed from the data and the regression models were run again. The results of the new analysis are found in Table 18. The removal of the outlier improved the  $R^2$  value greatly and reduced the p-level for the regression models excluding the antecedent regression. The max discharge model still showed the highest correlation.

Table 18: Regression Values for Environmental Variables Influence on ([SSC]-[TSS])

Regression	n	Before removal of outlier		After removal of outlier	
		$R^2$	p-level: ANOVA	$R^2$	p-level: ANOVA
$\Delta$ -Qmax	18	0.643	0.000	0.848	0.000
$\Delta$ -duration	18	0.237	0.041	0.524	0.001
$\Delta$ - $D_{70}$	12	0.256	0.032	0.566	0.005
$\Delta$ -Antecedent	18	0.006	0.766	0.06	0.322

#### 4.3.3 Turbidity

The data for turbidity did not correlate well with sediment concentration as seen in Figures 25 and 26. The data was reviewed and a 95% confidence interval was used to identify outliers. A number of the outliers were found to be the first and last paired NTU-

mg/L data collected during a sampling event. All of this paired data was removed and a few more outliers were removed in order to develop a regression between turbidity (as NTU) and sediment concentration (mg/L).

The new regressions can be seen in Figures 36 and 37. The correlation improved but it still is not strong for NTU-S or NTU-T,  $R^2=0.726$  and  $0.774$ , respectively. The equation for each regression was then used to convert NTU to mg/L. Each NTU reading, taken synoptically with the automatic sampler samplers, was converted to a suspended sediment concentration unit (mg/L). An EMC was created from these converted suspended sediment concentrations and the EMCs from each can be seen in Figure 38. Table 19 contains the “n”,  $R^2$  values for each regression along with the equation of the lines of best fit from Figures 36 and 37.

Figure 36: Turbidity Regression with SSC Data After Outlier Removal

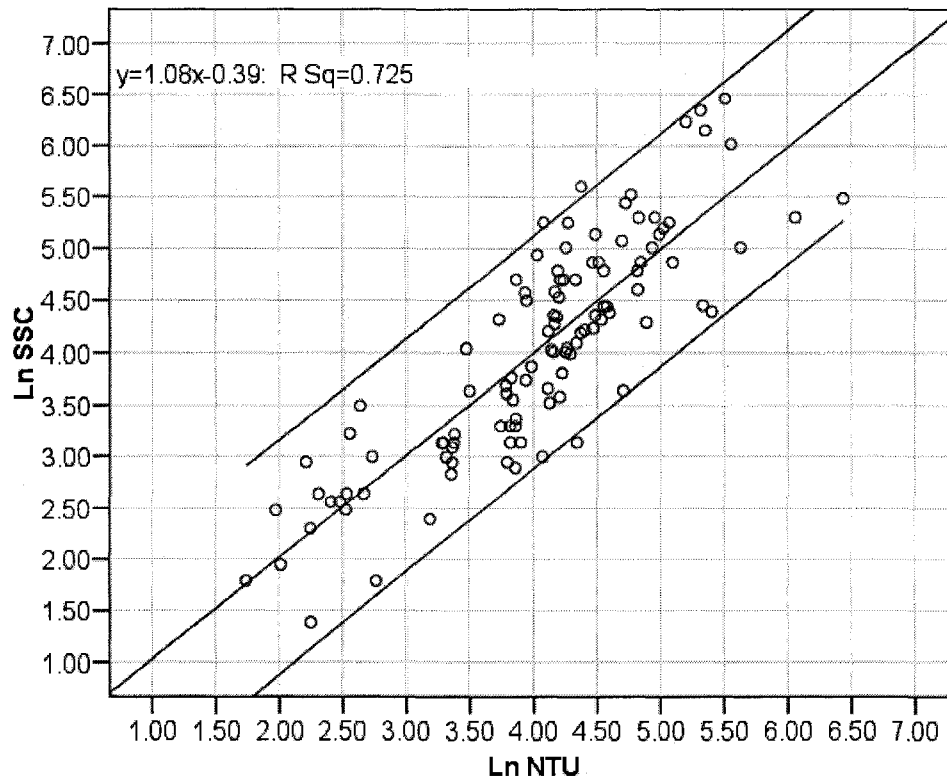


Figure 37: Turbidity Regression with TSS Data After Outlier Removal

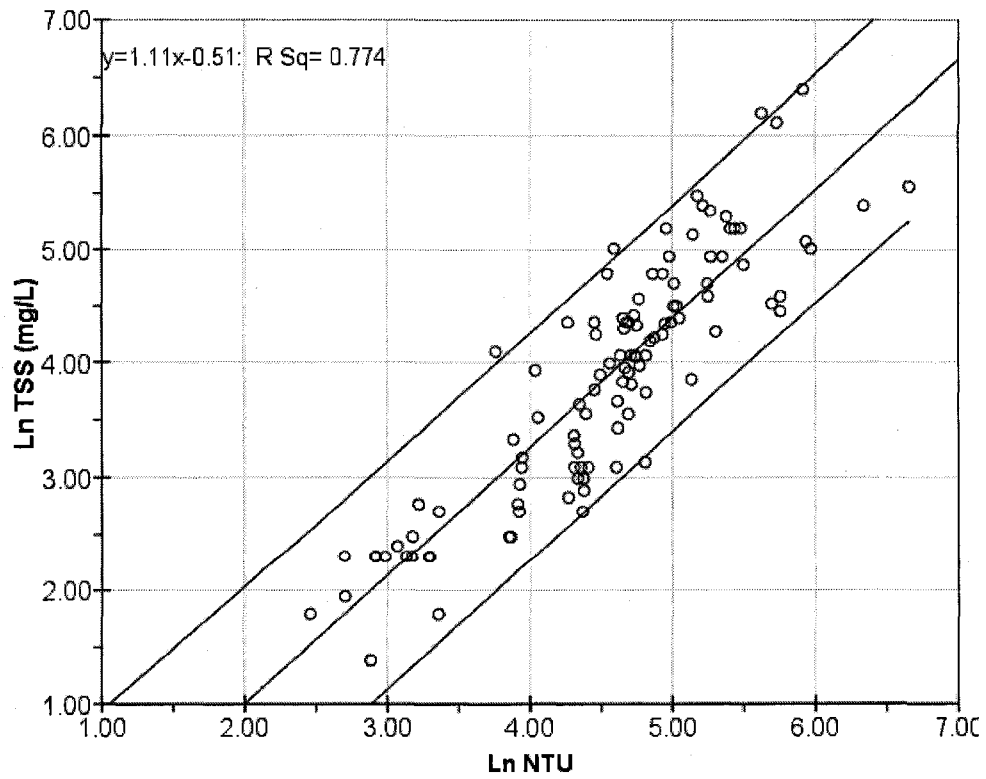
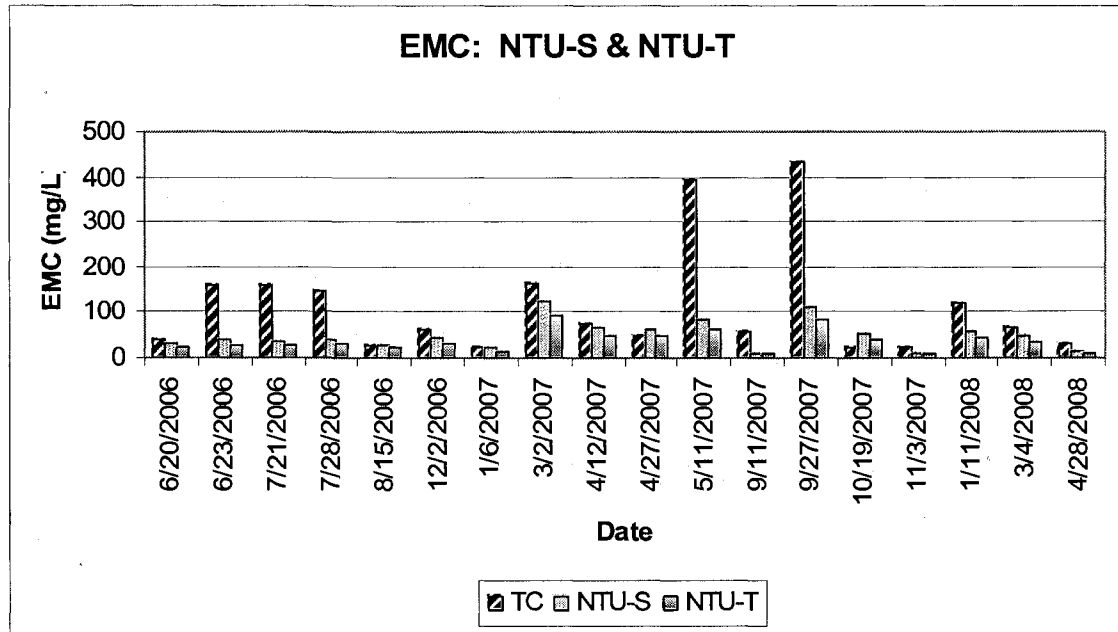


Table 19: Regression Coefficients and R<sup>2</sup> Values For Turbidity After Outlier Removal

Method	n	R <sup>2</sup>	Equation
NTU-S	109	0.726	$y=1.10x-0.97$
NTU-T	109	0.724	$y=1.13x-1.26$

Figure 38: Calculated EMCs using Turbidity Techniques



The EMC results for turbidity are surprising because the events which had higher and lower EMCs were not the same as events with high and low Total Capture EMC values as seen in Figure 31. It seems the variability with turbidity data reduces the ability to accurately monitor suspended sediment EMCs. The turbidity meters were verified in the field and in a controlled lab setting to assess their capability to read “0” NTU. This shows the turbidity meters could read “0” NTU correctly in an environment without the physical constraints of the 15” pipe. However, the regressions from the suspended sediment concentration and turbidity data put the y-intercept (at “0” NTU) much higher than at zero suspended sediment concentration. This gives the impression that the



turbidity meter could not accurately read zero or very low suspended sediment concentrations accurately in the 38.1 cm (15in) pipe. A possible cause for this is the optical viewing area surrounding the meter could have been compromised by the pipe wall. The pipe wall could be reflecting backscatter light to the meter causing false readings of turbidity.

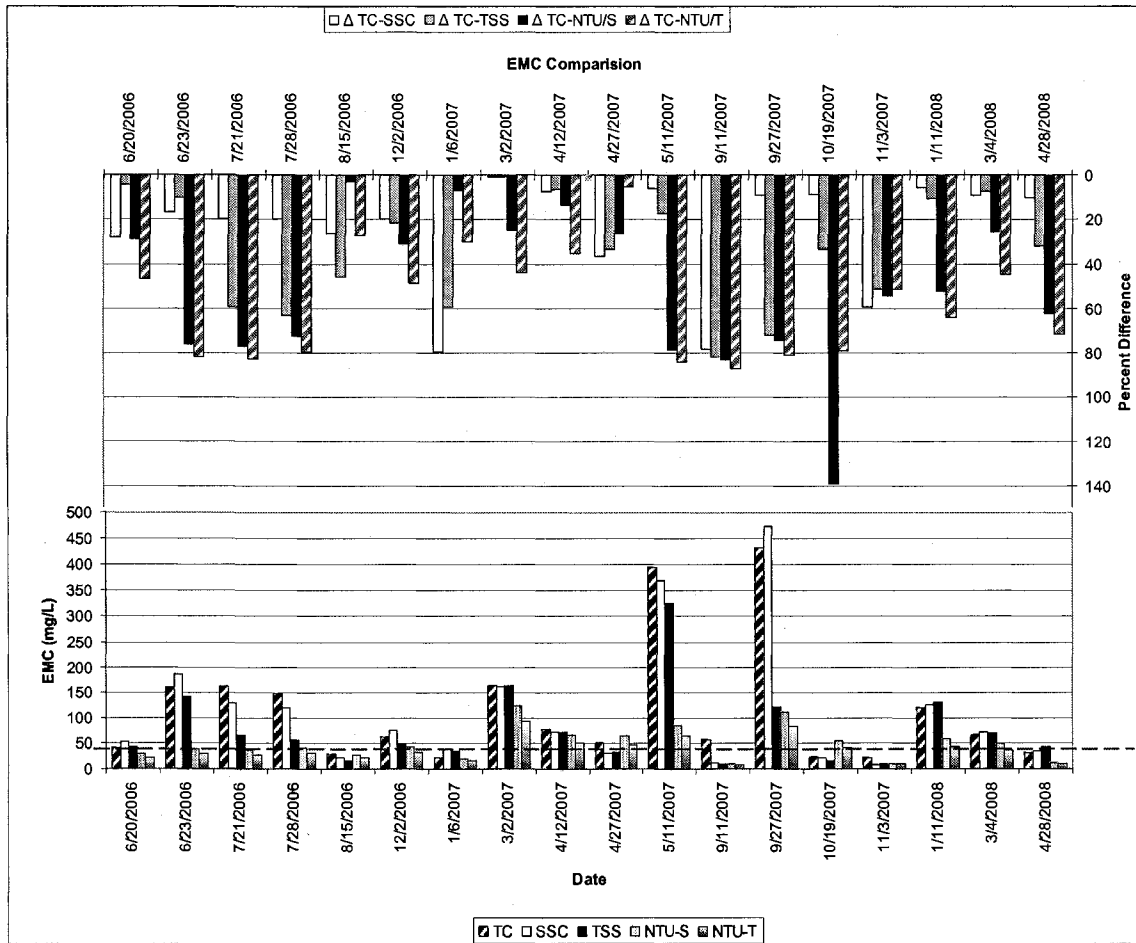
The blank sampler verification is a one point verification check and does not describe the turbidity meters capability to measure different turbidity levels in stormwater. To address this uncertainty, a known turbidity verification check could have been completed on the turbidity meter in the pipe.

Turbidity meters have been used in previous research to monitor suspended sediment concentration with good results as discussed in section 2.2.5. It is unclear if the turbidity meters inability to measure suspended sediment concentration in a stormwater sewer system is due to the configuration of the turbidity meter in this setting or the meter's inability to accurately read suspended sediment concentration in general.

#### 4.3.4 EMC Comparison

In Figure 39 all five methods are compared side by side to evaluate the similarity of each method's EMC during an event. The TC EMC is presumed to be the actual suspended sediment EMC for each event.

Figure 39: Comparison Bar Graph EMCs by Methods



A linear regression was performed between each individual method and the TC EMC (n=18) and can be seen in Figure 40a-d and summarized in Table 20.

Table 20: Summary of Actual vs. Field Method EMC Regression Coefficients

Method Comparison	Y-intercept			Forced through zero intercept		
	R <sup>2</sup>	Slope of Line	y-int	R <sup>2</sup>	Slope of Line	y-int
SSC & Total Capture	0.972	1.03	-6.03	0.970	1	0
TSS & Total Capture	0.620	0.507	19.65	0.585	0.591	0
NTU-S & Total Capture	0.477	0.184	27.36	0.083	0.301	0
NTU-T & Total Capture	0.477	0.137	20.81	0.065	0.223	0

Figure 40a: Actual EMC and SSC EMC Regression (n=18)

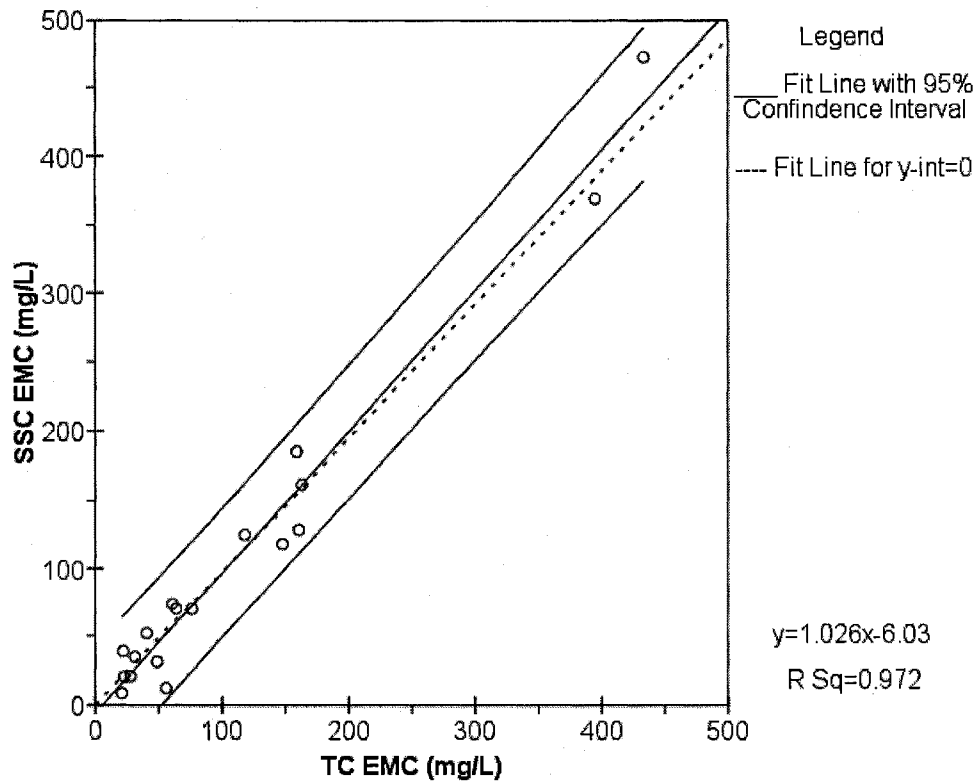


Figure 40b: Actual EMC and TSS EMC Regression (n=18)

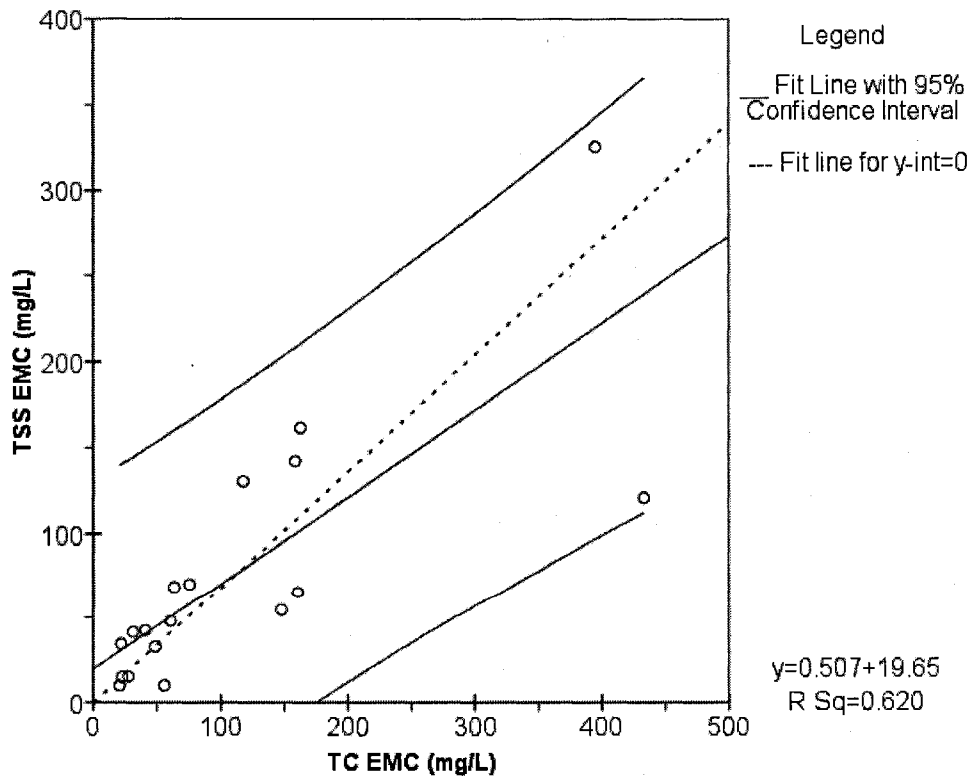


Figure 40c: Actual EMC and NTU-S EMC Regression (n=18)

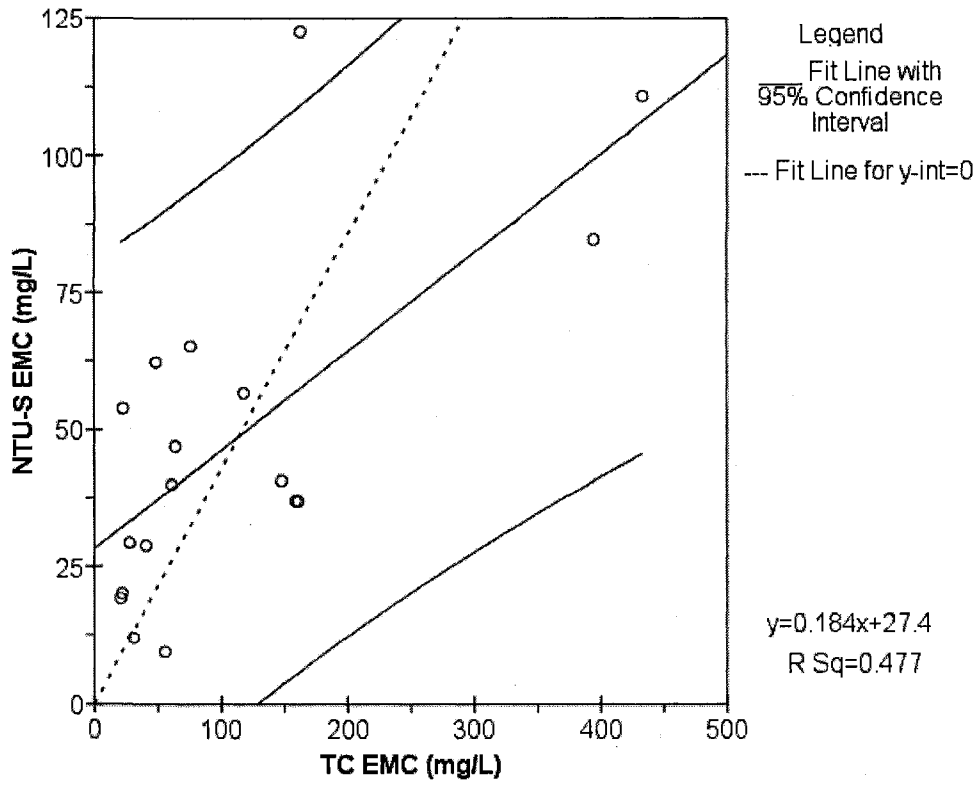
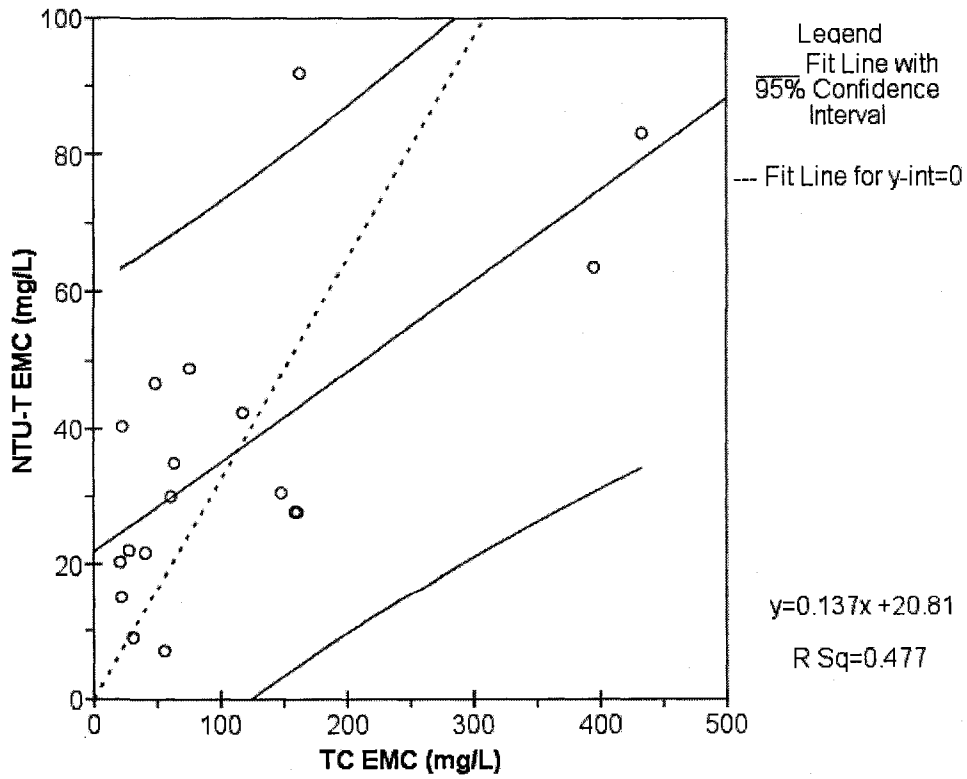


Figure 40d: Actual EMC and NTU-T EMC Regression (n=18)



The R<sup>2</sup> values, slope of lines can be seen in Table 20. The strongest correlation was between the TC EMC and the SSC EMC (R<sup>2</sup>=0.972, slope=1.03). The TC EMC - TSS EMC has a weaker correlation (R<sup>2</sup>=0.620 slope=.501) and the turbidity methods even less.

To test to see if each method was an accurate method to estimate suspended sediment EMC, the Wilcoxon signed rank test was used to test each method's EMC value for a statistically significant difference between it and the TC EMC. This test was selected because the differences between the EMCs were non-normally distributed as seen in the P-P plots for the test of normal distribution Figure C-4a-d. If the differences are normally distributed then the observed cumulative probability should have a linear relationship (slope of one) with the expected cumulative probability meaning the observed values are symmetrically distributed (bell curve).

The "n" for all the tests was 18. A statistical difference exists if the significance value (p value) is less than 0.05. The results of this test may be found in Table 21.

Table 21: Statistical Test Results for Method EMCs and Total Capture EMCs

<b>Method-Actual</b>	<b>Confidence Level</b>	<b><math>\alpha</math></b>	<b>Z</b>	<b>p-value</b>	<b>STD</b>
SSC TC	0.95	0.05	-0.457	0.647	NO
TSS TC	0.95	0.05	-2.461	0.014	YES
NTU-S TC	0.95	0.05	-2.983	0.003	YES
NTU-T TC	0.95	0.05	-3.506	0.00	YES

The only monitoring method used to estimate an EMC for suspended sediment which did not have a statistical difference from the actual suspended sediment EMC was the method using an automatic sampler and the SSC analytical method. The EMCs generated from the method using the automatic sampler and the TSS analytical method

did have a statistical difference between the actual suspended sediment EMCs. This means this method combination is not an accurate way to measure suspended sediment EMC. Max discharge was shown to influence the disparity between SSC and TSS EMCs as seen in Figure 33. Also Figures 26a-d, showed if a sample was taken at times of higher discharge then the disparity between SSC and TSS results were greater than for samples collected at lower discharge levels. During these conditions, larger sediments are present in the water column and are pulled into the grab samples by the automatic sampler. Coarse sediments have shown to cause the disparity between the two analytical methods (Gray J. et al. 2000). This means during all flow conditions, the SSC analytical method accurately measures suspended sediment concentration while the TSS analytical method is not as accurate during times of high discharge.

The statistical test was completed again, removing the results from 9/27/07 since the difference between the TSS and SSC EMCs was a consistent outlier in Figures 33-35. The value of the difference for this event's SSC-TSS EMCs was outside of the 95 confidence interval of individuals for all four regressions. The removal of this event from the data set used for statistical analysis did not change the fact that the TSS EMCs are statistically different than the TC EMC.

## **4.4 Particle Size Distribution**

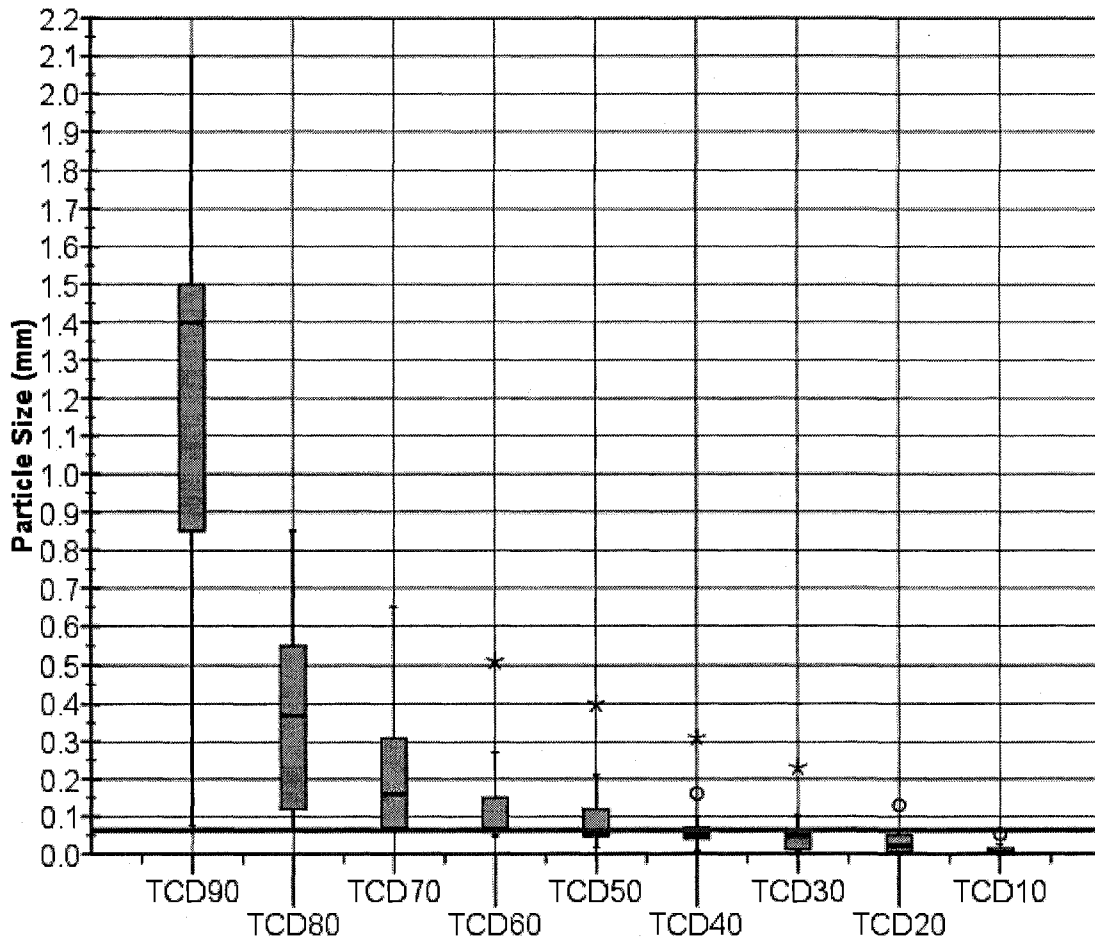
### **4.4.1 Total Capture**

Understanding the particle size distribution of the suspended sediments in the total capture sample is important because it can identify if the automatic sampler possess the ability to extract a representative particle size distribution of suspended sediments passing by. By determining the presumed actual particle size distribution of the

suspended sediments in the total capture sample, this PSD can be compared to the PSD of the suspended sediments in the composite samples taken by the automatic sampler. If the PSDs are different then it can be said the automatic sampler can not collect suspended sediments with a representative PSD from the passing stormwater discharge.

A box and whisker plot for the representative particle sizes from 14 events is seen in Figure 40. This figure shows the Interquartile Range (IQR) of the distributions for each particle size fraction in which the major particle size fractions ( $D_{90}$ ,  $D_{80}$ ...etc.) can be seen. No particle larger than 4.5 mm was recovered during this research and all organic matter such as leaves larger than 4.5 mm was not included in the event's PSD. The PSD for the first four events in this research were performed using a dry step in the sieve analysis and this methodology has been shown to increase aggregate size (Krein A. et al. 2000). The PSD for the events 6/20-8/15/06 were not included in Figure 40 because the PSD for these events were completed using the drying step. PSD from later events were completed using the wash sieving methodology. The two PSDs (dry versus wet techniques) should not be compared because the PSDs were completed using two different methods.

Figure 40: Box and Whisker Plot of Major Size Fractions in TC Sample



The individual PSDs for each event are found in the Figures D-1. Descriptive statistics for each size fraction are shown in Table 22. It is important to note that the median value for all the  $D_{50}$ s is sand size. This is important because the presence of sand size fractions at the  $D_{70}$  size fraction causes disparity between the TSS and SSC analytical methods (Gray J. et al. 2000). The presence of sand size particles at the  $D_{50}$  level ensures suspended sediment conditions exist in which PSD will influence the disparity between SSC and TSS analytical methods.



Table 22: Descriptive statistics for Major Particle Size Fractions of 13 TC PSDs

(mm)	90	80	70	60	50	40	30	20	10
Median	1.400	0.370	0.160	0.065	0.058	0.052	0.048	0.022	0.004
Mean	1.127	0.389	0.213	0.136	0.101	0.077	0.055	0.031	0.010
St. Dev	0.636	0.269	0.173	0.131	0.104	0.080	0.061	0.036	0.016
Max	2.100	0.850	0.650	0.510	0.400	0.310	0.230	0.130	0.054
Min	0.075	0.065	0.060	0.049	0.017	0.008	0.005	0.000	0.000

The standard deviation of the  $D_{90}$  and  $D_{80}$  values are greater than any other size fraction. Large organic gross solids such as pine needles, small leaves, and garbage were present in some events and not others, which could explain this large standard deviation.

. There is an outlier (°) and an extreme outlier (\*) in the  $D_{60}$  and finer fractions. An extreme outlier is an outside value three times the width of the IQR (Ott R. 2004). These outliers are from the 9/27/07 event. A reference line at 0.063 mm was added to the plot to delineate the sand size sediment. Values above this line are sand size or coarser. As can be seen, the median value of the  $D_{40}$  and coarser fractions are sand size and greater. This is important to note since previous research has shown the influence of sand-sized particles on the accuracy of the TSS analytical method. Also the presence of a wide range of particle sizes in the passing stormwater discharge tests the ability of the automatic sampler to extract a representative suspended sediment PSD.

Two regressions were made evaluating the influence of maximum discharge on particle size. Two particle size were choose for these two regression models, the  $D_{70}$  and the  $D_{50}$  and can be seen in Figure C-3a and b. The  $R^2$  values for the  $D_{70}$  and  $D_{50}$  are 0.626 and 0.818 respectively. As the discharge increases, so does the particle size. This is intuitive because high rainfall intensities can sweep coarse sediments into the sewer and can be brought to the outlet. The  $D_{70}$  regression does not have as a strong a correlation as the  $D_{50}$  because the presence or lack of larger organic material.

#### 4.4.2 Automatic Sampler

The major particle size fractions for the sediments captured by the automatic sampler can be seen in Figure 41 (n=11). The use of automatic samplers to measure PSD did not occur until later in this investigation beginning on 12/01/06 hence a lower “n” value than the total capture PSD. During the event on 3/2/07, an equipment malfunction prevented the collection of sample with the automatic sampler and the sample from the 3/4/08 event was damaged and could not be used.

Individual events’ PSDs can be seen in Figure D-1. Descriptive statistics can be seen in Table 22. Three outliers (°) are present in the  $D_{80}$ ,  $D_{70}$  and  $D_{60}$  are from the same event 12/1/06, the first event in which the PSD was measured by the automatic sampler.

Figure 41: Box and Whisker Plot of Major Size Fractions in Automatic Sampling Samples

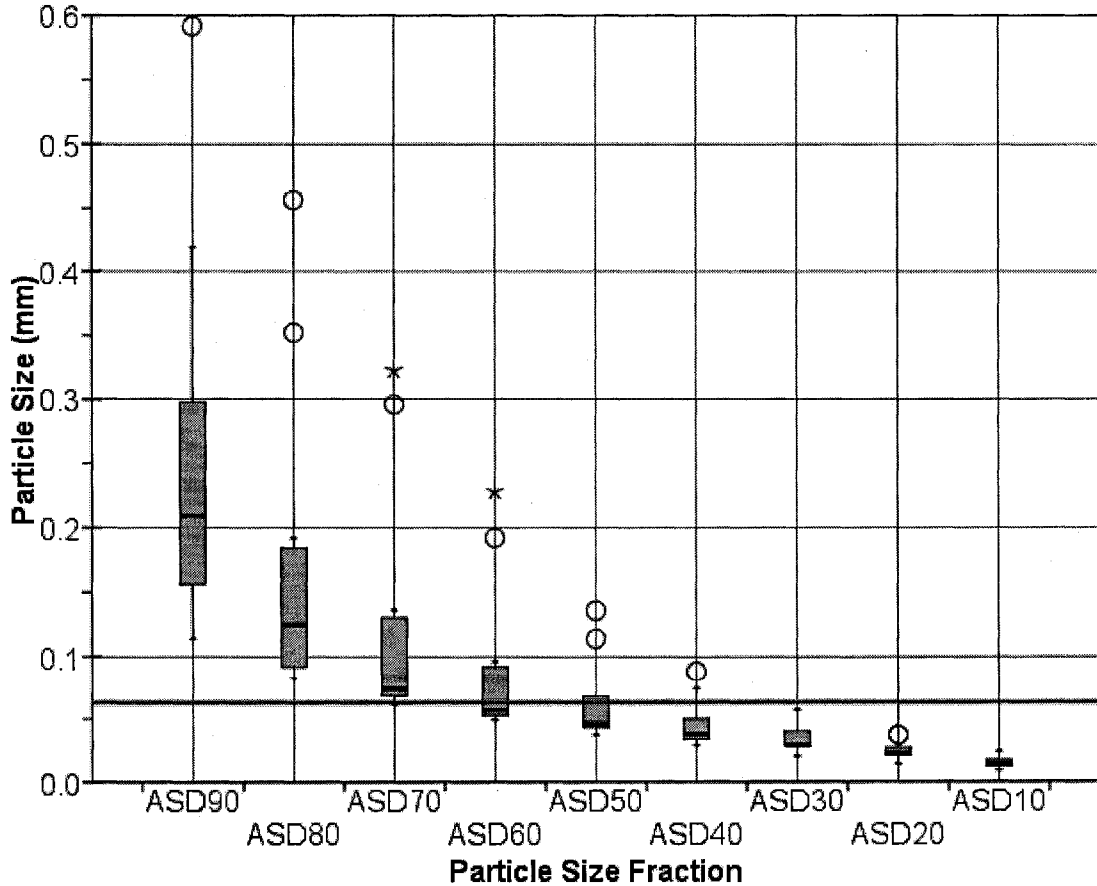


Table 23: Descriptive Statistics of Major Size Particle Fractions in Automatic Sampling Samples (all values in mm)

<b>% Finer</b>	<b>90</b>	<b>80</b>	<b>70</b>	<b>60</b>	<b>50</b>	<b>40</b>	<b>30</b>	<b>20</b>	<b>10</b>
Median	0.209	0.125	0.074	0.057	0.046	0.038	0.029	0.023	0.014
Mean	0.258	0.176	0.127	0.091	0.063	0.046	0.035	0.025	0.015
St dev	0.143	0.121	0.094	0.062	0.033	0.019	0.011	0.007	0.005
max	0.592	0.457	0.323	0.228	0.136	0.088	0.057	0.037	0.024
min	0.114	0.082	0.061	0.049	0.037	0.029	0.020	0.014	0.009

The median of all  $D_{60}$  values in the samples captured by the automatic sampler are sand size or coarser. This is an indication the PSDs of the suspended sediments in the samples captured by the automatic sampler which were sent to the lab for TSS and SSC analysis could possess enough sand size particles which can influence the accuracy of the TSS analytical method. Previous research has shown if the  $D_{70}$  value is sand size or coarser in a sample than a difference between SSC and TSS occurs (Gray J. et al. 2000).

The composite sample created by the automatic sampler was made from sub samples taken throughout the entire sampling event. The measured PSD from the composite is a representation of the PSD of all the suspended sediments passing by the automatic sampler during a sampling event. This PSD is an indication of what size suspended sediments the automatic sampler can extract and this is the PSD that can be compared to the actual suspended sediment PSD in the total capture sample.

#### 4.4.3 Comparison of Particle Size Fractions

Three major size fractions were selected to test if a statistical difference existed between the sediment sizes in the TC sample (presumed to be the actual suspended sediment size distribution) and that from the automatic sampler (AS). The methodologies to determine PSD for both these methods were different and this potentially introduces

bias in itself. This potential bias will be discussed in the QA/QC section, 4.7.2. The following sizes were tested for a statistically significant difference:  $D_{70}$ ,  $D_{50}$ ,  $D_{30}$ .

The distribution (box plot) and median values of three particle sizes can be seen in Figure 42. The range of all the particle size fractions for the total capture samples is quite large when compared to the size fractions of automatic sampler samples. The outliers present are discussed in the previous sections. The “n” for both the box and whisker comparison plot and for the statistical test is 11. This is the total number of events which had a composite sample made by the automatic sampler to allow for a comparison with the suspended sediments in the total capture sample.

Figure 42: Comparison of Particle Size Fractions by Method

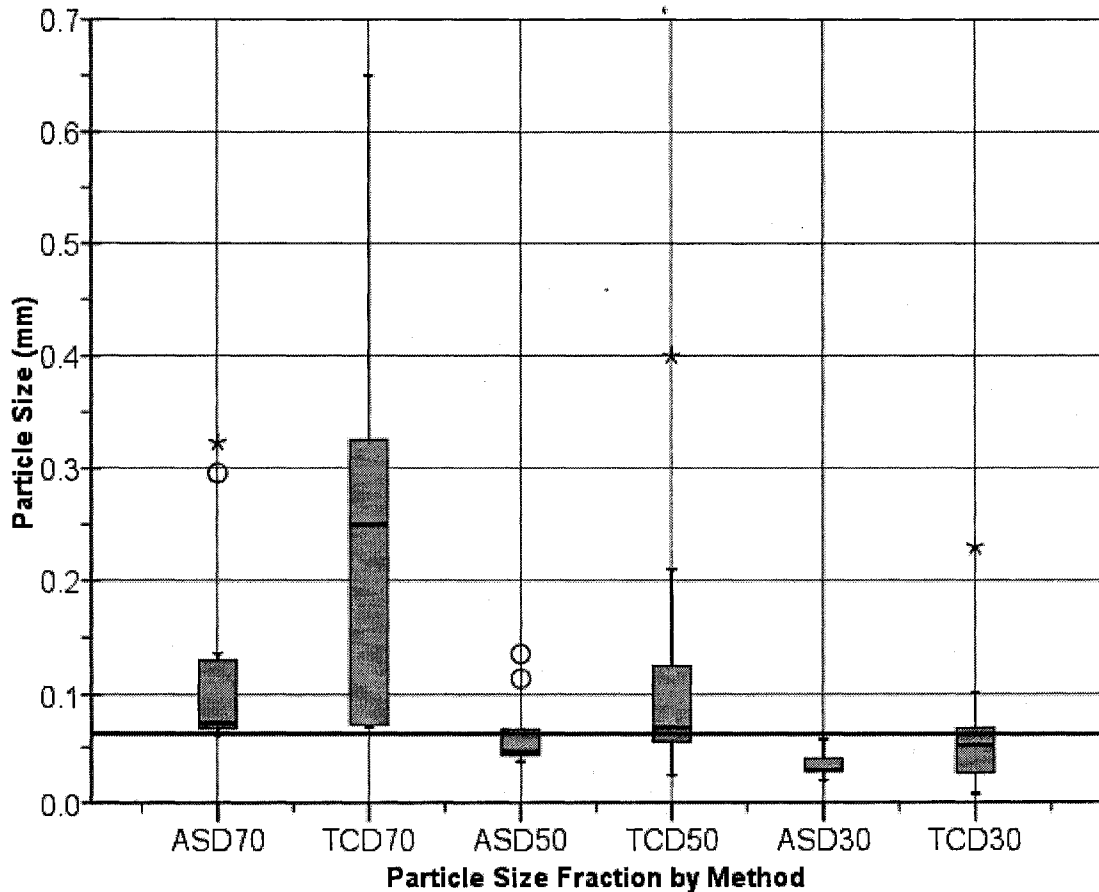


Table 24: Descriptive Statistics for D70, D50 and D30 values by method (all values in mm)

Particle Size	Method	Min	Max	Mean	Median	Std. Deviation
D70	TC	0.060	0.650	0.213	0.160	0.131
	AS	0.061	0.323	0.127	0.074	0.094
D50	TC	0.017	0.400	0.101	0.058	0.104
	AS	0.037	0.136	0.063	0.046	0.033
D30	TC	0.005	0.230	0.048	0.058	0.061
	AS	0.020	0.057	0.035	0.029	0.011

Table 24 shows the median values are quite different between the D<sub>70</sub> between the two methods. The median values of the D<sub>50</sub> and D<sub>30</sub> data are quite close. To test for a statistical difference, the Wilcoxon signed rank test was used with a 95% confidence interval (p-value is 0.05). If a statistical difference exists, then the p-value will be less than 0.05. The results of the test are listed in Table 25.

Table 25: Statistical Test Results for D<sub>70</sub>, D<sub>50</sub> and D<sub>30</sub> Comparison

Fraction Size	Confidence Level	$\alpha$	Z	p-value	STD
D <sub>70</sub>	0.95	0.05	-2.05	0.041	YES
D <sub>50</sub>	0.95	0.05	-1.60	0.110	NO
D <sub>30</sub>	0.95	0.05	-1.65	0.100	NO

The results show there is a statistical difference between the presumed actual and the field method D<sub>70</sub> particle size fraction. For the D<sub>50</sub> and D<sub>30</sub> size fraction there was not a statistical difference despite the visual presence of a large difference between the median values. The Wilcoxon signed-rank test detects differences in the distributions of two related variables. It accomplishes this by looking at the difference between the pairs of each event to assess if the number of negative and the number of positive differences are the same, which would mean the median is at zero. It also considers the magnitude of the differences between pairs (Statistical Package for the Social Sciences 2008). The

result of the statistical test for the  $D_{70}$  is not visually surprising because the difference between the median values of all the  $D_{70}$  values for the TC and AS methods was so large. Table 26 shows the differences between the TC and AS size fractions.

Table 26: Differences between TC and AS Size Fractions (all values in mm)

<b>Date</b>	<b>D70</b>	<b>D50</b>	<b>D30</b>
1/6/07	-0.020	-0.020	-0.007
1/11/08	-0.004	0.018	-0.013
4/12/07	0.001	0.013	-0.005
4/27/07	0.181	0.029	0.020
4/28/08	0.009	-0.016	-0.016
5/11/07	0.198	0.086	0.053
9/11/07	0.002	0.014	0.020
9/27/07	0.545	0.348	0.201
10/19/07	0.214	0.052	0.014
11/3/07	0.014	-0.044	0.005
12/1/06	0.017	0.074	0.044

In Table 26 there are three negative and eight positive differences between the  $D_{50}$  values and four negative and seven positive differences between the  $D_{30}$  TC and AS values. The median values of the differences for the  $D_{70}$ ,  $D_{50}$  and  $D_{30}$  are 0.014mm, 0.018mm and 0.014mm. Given the magnitudes of the distribution of the differences and the small sampler size could explain why there is no statistically significant difference between the  $D_{50}$  and  $D_{30}$  size fractions because the median values are close to zero. However because of the visual disparity between the  $D_{50}$  and  $D_{30}$  values, another statistical test was used to assess if the field method could accurately sample sediments with a representative size fraction.

The one sample Komolgorov-Smirnoff test determines if a sample's distribution fits a certain type of distribution such as: normal, Poisson, etc. For this investigation, if the distribution of the field method's (AS)  $D_{50}$  or  $D_{30}$  values were different than the distribution of the Total Capture (TC) values for the same size fractions, than the field did

not accurately obtain a representative particle size distribution. The results for the test of the  $D_{50}$  and  $D_{30}$  are listed in Table 27 and show the KS statistic ( $\Delta$ ) and the critical value ( $\Delta_0$ ) at a confidence level of 0.95 ( $\alpha=0.05$ ). The KS statistic is the maximum difference between the actual cumulative distribution values (empirical non-exceedance) and the theoretical cumulative distribution values of a normal distribution (Yevjevich V. 1972). If the  $\Delta$  is greater than  $\Delta_0$ , then the distribution of the  $D_{50}$  or  $D_{30}$  values are not normally distributed (a “no” in column 6). If one of the method’s values is normally distributed and the other method’s is not, than the methods’ values are different and the field method does not sample sediments with a representative size distribution.

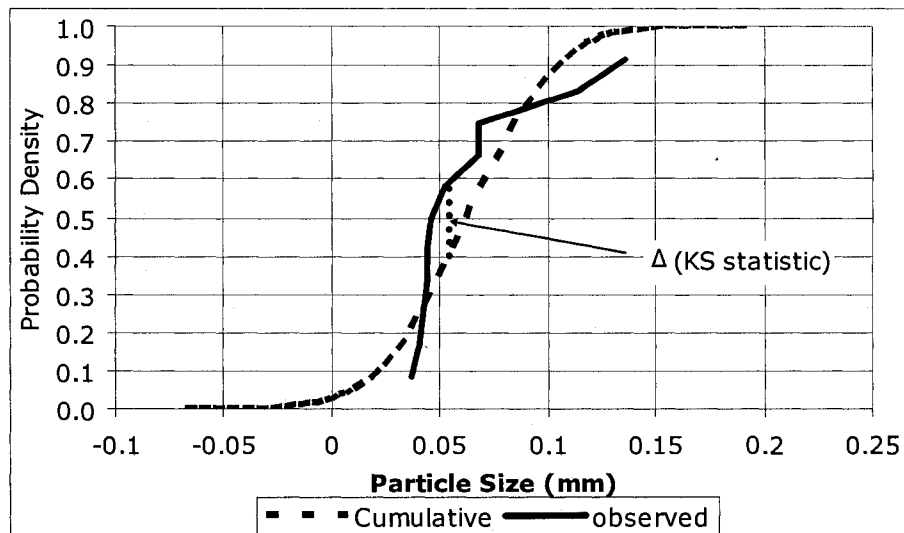
Table 27: Test Results of the Komolgorov-Smirnov test for  $D_{50}$  and  $D_{30}$  Values

1	2	3	4	5	6
Particle Size Fraction	Method	$\Delta$	$\Delta_0$	$\alpha$	Goodness of Fit
$D_{50}$	AS	0.263	0.424	0.05	Yes
	TC	0.275	0.424	0.05	Yes
$D_{30}$	AS	0.235	0.424	0.05	Yes
	TC	0.269	0.424	0.05	Yes

The results from the KS test show that the distributions of all the  $D_{50}$  and  $D_{30}$  values have the same distribution. This does not confirm that the field methods’  $D_{50}$  and  $D_{30}$  values are the same as the TC because this test only assesses the distribution of the data but it would have confirmed if the distribution of the data were different. The results of this test were surprising since visually in Figure 42, the distributions of the field method’s  $D_{50}$  and  $D_{30}$  look abnormally positively skewed. Figure 43 shows the empirical cumulative distribution with the theoretical cumulative distribution of the field method’s (AS)  $D_{50}$  values. The KS test statistic is also shown on the plot. The slope of the empirical line appears to be steeper than the slope of the line of the normal cumulative

distribution, a characteristic of an abnormal distribution but the sample size appears to be too small for the KS test to distinguish if the distributions are different.

Figure 43: Theoretical and Observed Cumulative Distribution of Field Method's  $D_{50}$  values



To further evaluate if the  $D_{50}$  and  $D_{30}$  values are similar or different, a test of variance was completed. This test was used to determine if the values' variance (standard deviation) was the same or different. If the ratio of variance, the calculated "F" value ( $\sigma_1^2/\sigma_2^2$ , column 4 and/or 5) exceeds the critical "F<sub>c</sub>" (column 6 and 7) than the variance of each method was not equal (Dowdy S. et al. 1991). Table 28 shows the results of this test for the evaluation of the  $D_{50}$  and  $D_{30}$  values. If the variances are different than a "Reject" was recorded in column 8.



Table 28: Test of Variance for D<sub>50</sub> and D<sub>30</sub> Particle Size Fractions

1	2	3	4	5	6	7	8
Size Fraction	Method	$\sigma^2$	Calc. F (TC/AS) ( $\alpha=0.05$ )	Calc. F (AS/TC) ( $\alpha=0.95$ )	F <sub>c</sub> ( $\alpha=0.05$ )	F <sub>c</sub> ( $\alpha=0.95$ )	Variance
D <sub>30</sub>	AS	0.0040	2.96	0.338	2.98	0.336	Reject
	TC	0.0117					
D <sub>50</sub>	AS	0.0001	29.36	0.034	2.98	0.336	Reject
	TC	0.0039					

From the results in the variance test, the variance between the field methods and actual values for both the D<sub>50</sub> and D<sub>30</sub> values were different.

The Wilcoxon Signed Rank test found a statistical difference between the D<sub>70</sub> values. The KS Test to determine the distribution type of the D<sub>50</sub> and D<sub>30</sub> values showed there was not a difference between the field method and the presumed actual distribution of values. The results of these tests contradict the visual appearance of the results in Figure 42 which showed a large disparity between distribution types. Small sample size was believed to have prevented a difference from being calculated. However, the assessment of the variances did show that the variance within the distribution of the field method's D<sub>50</sub> and D<sub>30</sub> values were different. The results of all three of these statistical tests appear to show the method using the automatic sampler and tri-laser diffraction does not appear to be able to accurately collect representative amounts of coarse sediments. It is unclear if either the field method or the laboratory research or both contributes to this phenomenon.

#### 4.4.4 Assessment of Decanted Sediments

During the decanting steps of processing the total capture sample, grab samples were obtained to determine if sediments were being pumped off prematurely. The weight of all sediments pumped off prematurely was added to the total weight of

sediments in the total capture sample. However, this weight was added in for EMC calculations only and not for PSD calculations because these sediments were never measured by sieve or hydrometer. The influence of the weight of the sediments on PSD was assessed. The assumptions used in Equation 3 stated all the sediments, 2  $\mu\text{m}$  or coarser should have settled out of the water column onto the tarp below so any sediments pumped prematurely were presumed to be finer than 2  $\mu\text{m}$ .

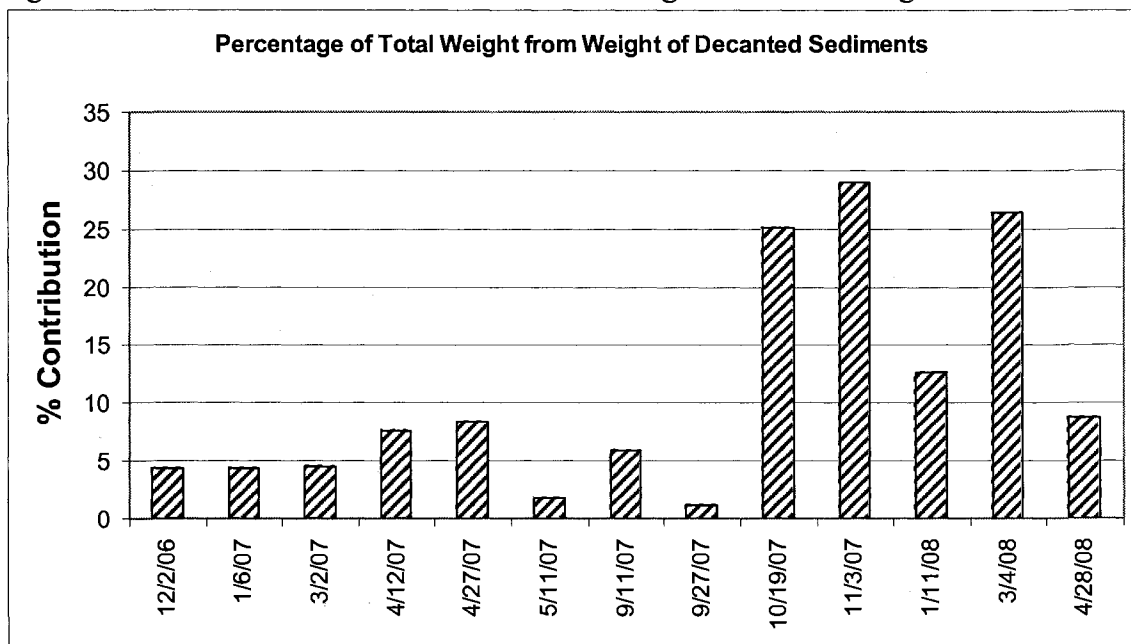
The weight of the sediments finer than 2  $\mu\text{m}$  would have influenced the TC PSDs by shifting the plots to the left (making them finer) but what was not understood was how dramatic this shift could have been. This was important to evaluate because the TC Pads were used to compare the field method's ability to accurately sample a representative PSD. If the TC PSDs were indeed finer because of the added weight of the pumped off sediments, then this could have effected the evaluation of the field method's ability to sample sediments with a representative PSD.

All of the TC sample PSDs which were compared to the field method PSDs were assessed to see if this influence existed. Table 29 lists: the sampling events in which this PSDs comparison was made, the total weight of sediments in the TC sample (Total Weight), the weight of sediments pumped off prematurely (Dec. Weight) and the percentage this weight contributed to the over all weight (% Contr.). The latter is visually displayed seen in Figure 44.

Table 29: Contribution of Decanted Sediment Weight to Overall TC Weight (n=11)

Date	Total Weight (g)	Dec. Weight (g)	% Contr.
12/01/2006	532	23.4	0.04
1/06/2007	246.4	10.9	0.05
4/12/2007	502.7	37.8	0.08
4/27/2007	393.9	32.7	0.08
5/11/2007	3837.6	69.3	0.02
9/11/2007	373.9	21.9	0.06
9/27/2008	3655.3	43.9	0.01
10/19/2007	237.9	59.7	0.23
11/03/2007	195.6	56.7	0.29
1/11/2008	745.2	93.4	0.13
4/28/2008	369.4	32.2	0.09

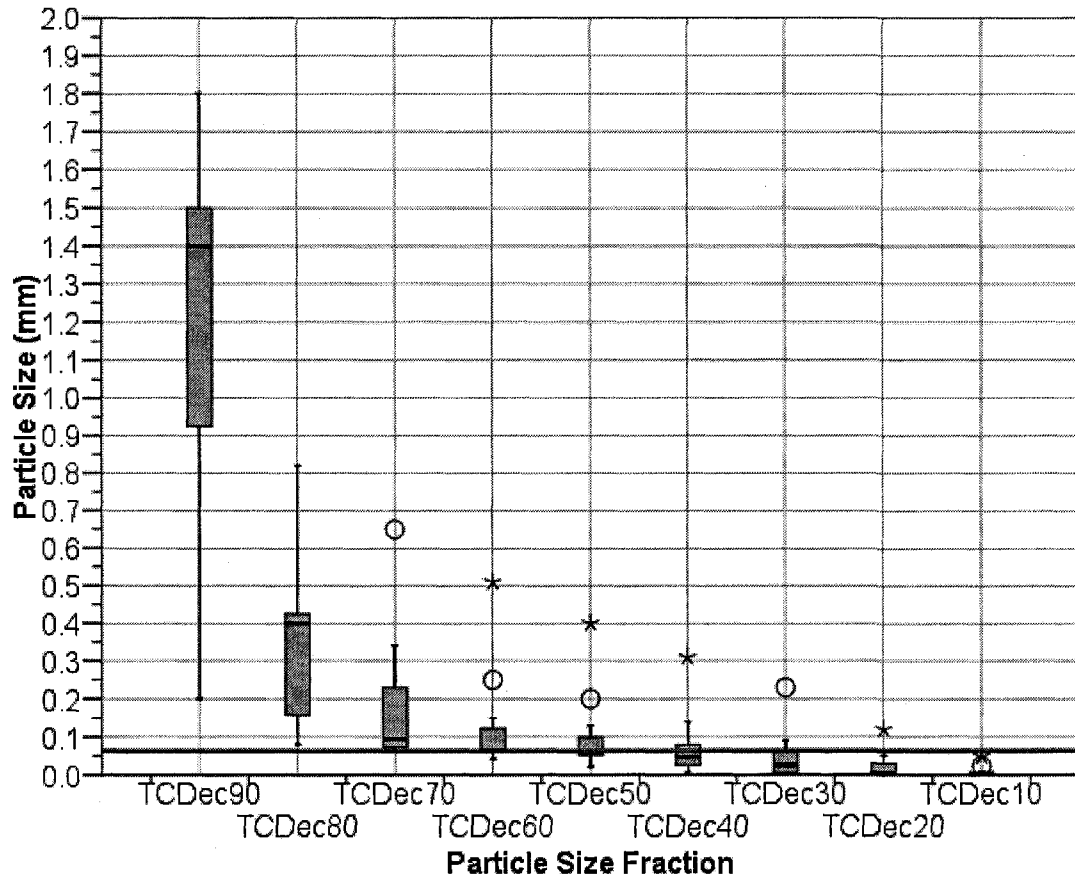
Figure 44: Contribution of Decanted Sediment Weight to Overall Weight



The TC PSDs were recalculated by categorizing the pumped off sediments as fine and medium clays whose size ranges were 0.5-2.0  $\mu\text{m}$  (Gordon N. et al. 2004). The weight of the sediments was then added to this range of particle size and the PSDs were recalculated. The major size fractions of the adjusted TC PSDs (TC Dec) are seen in

Figure 45 and all the adjusted TC PSDs are plotted with the original PSDs in Figures D4-a-k.

Figure 45: Major Particle Size Fractions of Adjusted TC PSDs (n=11)



The particle size fractions from the 9/27/07 event are the extreme outliers (\*) and the larger of the regular outliers (o). The red reference line is at 0.063 mm to designate where sand size sediments are present within the size fractions of the adjusted PSDs. The sand size sediments are found consistently in the size fractions down to the D<sub>50</sub> fraction.

The mean and median values of each size fraction can be seen in Table 30

Table 30 Mean and Median Values for Adjusted PSD Size Fractions (all values in mm, n=11)

% Finer	90	80	70	60	50	40	30	20	10
Median (mm)	1.400	0.400	0.095	0.065	0.058	0.047	0.026	0.005	0.002
Mean (mm)	1.134	0.346	0.190	0.132	0.103	0.075	0.049	0.023	0.009
St. Dev.	0.538	0.223	0.179	0.139	0.110	0.087	0.067	0.037	0.015
Max (mm)	1.800	0.820	0.650	0.510	0.400	0.310	0.230	0.120	0.048
Min(mm)	0.200	0.080	0.064	0.042	0.022	0.007	0.004	0.000	0.000

To assess what the difference is between the original TC PSDs and the adjusted TC PSDs, the median values of all the major particle size fractions were plotted in Figure 46 (n=11) to develop a PSD for each.

Figure 46: PSD of the Median Values for TC Sample and TC Sample with Decanted Sediments

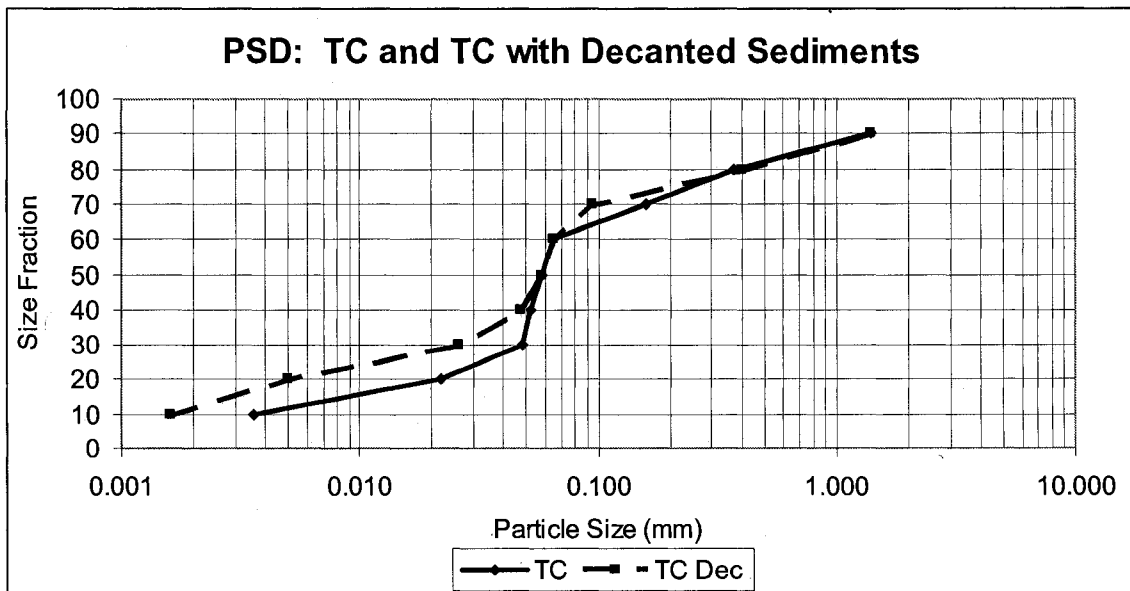


Figure 46 does show a finer shift of the adjusted TC PSD. However, the adjusted PSD was developed from the median values of all the events and was susceptible to a few events whose individual PSD shifted more dramatically than others such as the 10/19/07 and 11/03/07 events. Table 31 supports this statement by summarizing the differences between the TC PSD and the adjusted TC PSD (TC Dec.).

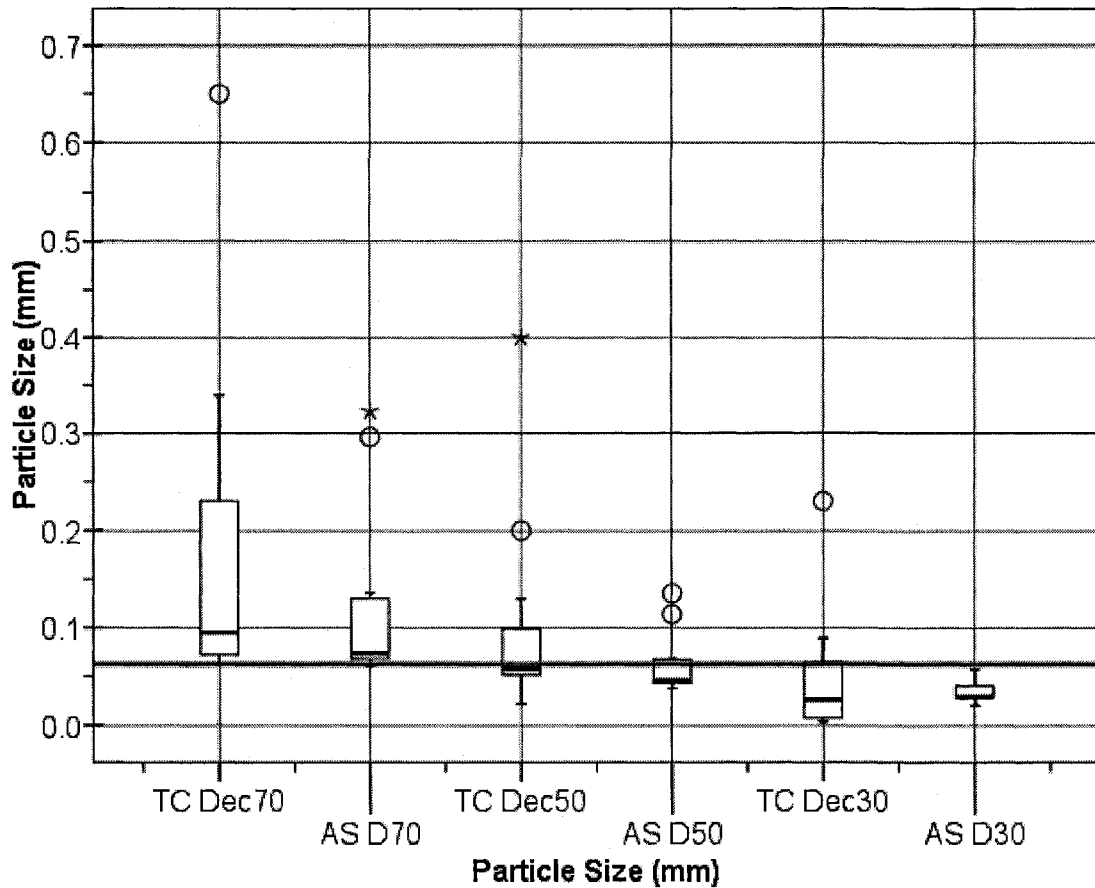
Table 31: Medians For TC and TC Dec. Size Fractions and Differences per Event

	<b>D<sub>70</sub></b>	<b>D<sub>50</sub></b>	<b>D<sub>30</sub></b>
<b>TC Median value (mm)</b>	0.160	0.058	0.048
<b>TC Dec. Median Value (mm)</b>	0.095	0.058	0.026
<b>Date</b>	<b>Δ (TC-TC Dec)</b>	<b>Δ (TC-TC Dec)</b>	<b>Δ (TC-TC Dec)</b>
1/6/2007	0.010	0.004	0.003
1/11/2008	0.005	0.005	0.003
4/12/2007	0.000	0.002	0.011
4/27/2007	0.050	0.007	0.004
4/28/2008	0.006	0.003	0.002
5/11/2007	0.000	0.000	0.000
9/11/2007	0.000	0.000	0.022
9/27/2007	0.000	0.000	0.000
10/19/2007	0.150	0.062	0.049
11/3/2007	0.234	0.015	0.053
12/1/2006	0.000	0.010	0.012
<b>Median Δ</b>	<b>0.005</b>	<b>0.004</b>	<b>0.004</b>

Table 31 shows the median value of the D<sub>50</sub> did not change after the shift but the values of the D<sub>70</sub> and D<sub>30</sub> did. However, most events were not dramatically affected by the shift of the PSDs.

The findings in section 4.4.3 showed there was no statistical difference between D<sub>50</sub>, and D<sub>30</sub> size fractions of the actual and field method PSDs despite the appearance of a large difference between the median values of the size fractions as seen in Figure 42. The D<sub>70</sub> value was found to have a significant difference. To assess if the adjusted PSDs will have an affect on these findings, the three major size fractions of interest in section 4.4.3 were plotted with the field method's and can be seen in Figure 47 (n=11).

Figure 47: Comparison of Field Method (AS) and adjusted TC Major Size Fractions



The median values of the adjusted TC size fractions in Figure 47 are closer to the median values of the field method size fractions, more so than in Figure 42. This is explained by the shift to the left (finer) of the PSDs from the 10/19/07, 11/03/07 and 1/11/07 events (Figures D4h, i, j respectively). To assess if these shifts will affect the results of the Wilcoxon Signed Rank test used in section 4.4.3, which did not find a statistical difference between the  $D_{50}$  and  $D_{30}$  size fractions, the tests were rerun. The results of these tests are found in Table 32 (n=11).

Table 32: Wilcoxon Signed Rank Test Results using Adjusted PSD Size Fractions

Fraction Size	Confidence Level	$\alpha$	Z	p-value	STD
$D_{70}$	0.95	0.05	-1.16	0.248	NO
$D_{50}$	0.95	0.05	-1.07	0.286	NO
$D_{30}$	0.95	0.05	-0.44	0.985	NO

The shift of three total capture PSDs (the presumed actual PSDs) did not change the results of the statistical test for the  $D_{50}$  and  $D_{30}$  size fractions, however the results of the  $D_{70}$  size fraction did change and a statistical difference was not found. This is due in part to the shift of the  $D_{70}$  values in the 10/19/07 and 11/03/07 events. The addition of the decanted sediment weight did not appear to impact the results of the statistical tests used to determine if the field method could measure a representative particle size fraction.

#### 4.4.5 Influence of Particle Size on Methodologies

The above mentioned particle size fractions ( $D_{70}, D_{50}, D_{30}$ ) were used in a regression to examine the influence particle size has on the difference between SSC and TSS EMCs. These regressions can be seen in Figure D-2 and the coefficients are seen in Table 33. It appears that as particle size increases in these particle size fractions the disparity between the analytical methods increases. Each linear regression has a positive correlation with increasing particle size and an increase in the difference. The strongest correlation occurring with the  $D_{50}$  particle size ( $R^2=0.818$ ).

Table 33: Regression Coefficients of PSD Influence on ([SSC]-[TSS])

<b>Particle Size Fraction</b>	<b>Slope</b>	<b>R<sup>2</sup></b>
$D_{70}$	1.02	0.535
$D_{50}$	2.16	0.797
$D_{30}$	3.45	0.667



#### **4.5 Suspended Sediment Load**

Actual suspended load for each event was determined by the total weight of suspended sediments recovered in the total capture sample. To determine the total suspended sediment load for each event using the other methods, each method's EMC was multiplied by a total water volumetric amount. Two water volumetric amounts were used in conjunction with the other method's EMCs. The first, the total water volumetric amount as measured by the automatic sampler, was used because this is a standard field monitoring method. The second total water volumetric amount was the total volume in the total capture sample which is presumed to be the actual total water volume. Table D-1 list the following for each event: total water volume recorded by automatic sampler (AS volume), total water volume in total capture sampler (TC volume), actual suspended sediment load in TC sample (TC Load), suspended sediment load determined using a SSC EMC and AS water volume (SSC-AS), suspended sediment load determined using a TSS EMC and AS water volume (TSS-AS), load determined using a SSC EMC and total capture water volume (SSC-TC) and load determined using a TSS EMC and total capture water volume (TSS-TC). The methods using turbidity measurements to create an EMC were not evaluated because these two methods were not a good predictor of suspended sediment concentration.

In Table 34, mean, median and standard deviation statistics for each of the methods used to calculate load can be found (n=18). It is surprising that the suspended sediment load calculated using the automatic sampler water volume and a SSC EMC (SSC-AS) had lower median and mean values than the actual total capture load (TC). This is surprising because the SSC EMC was not statistically different than the TC EMCs

which means load calculations using this method should have similar results assuming accurate volumetric measurements by the sampler. However, when the volume from the total capture sample was used (SSC-TC), the mean and median values were more similar. The water volume measured by the automatic sampler was not the same as the volume in the TC. Generally these volumes were less, leading to lower load values.

Table 34: Descriptive Statistics of Sediment Load By Method

	SSC-AS (kg)	TSS-AS (kg)	SSC-TC (kg)	TSS-TC (kg)	TC (kg)
Mean	0.591	0.431	1.01	0.692	1.053
Median	0.336	0.322	0.541	0.460	0.509
St. Dev.	0.637	0.462	1.18	.766	1.162

To test for a significant difference between the four calculated loads and the presumed actual load (TC) the Wilcoxon Signed Rank test was used and the results are seen in Table 35. Each mass which used the total volume as recorded by the automatic sampler was statistically different to the actual mass.

Table 35: Statistical Test Results for the Comparison of Actual and Monitored Sediment Load

Load Comparison	Confidence Level	$\alpha$	Z	p-level	St. Difference
SSC-AS	0.95	0.05	-3.51	0.00	YES
TSS-AS	0.95	0.05	-3.46	0.01	YES
SSC-TC	0.95	0.05	-0.806	0.420	NO
TSS-TC	0.95	0.05	-2.72	0.006	YES

From the test results in Table 35 the only method for predicting load which was not statistically different from the actual load was the SSC EMC with the TC volume method. This implies that the volume recorded by the sampler was not correct. Both loads using the TSS EMC were statistically different which was not surprising since the

TSS EMCs were not a good predictor of the TC EMCs. Regardless, if the ISCO samplers were not recording discharge correctly, it appears this inaccuracy does not affect the SSC EMC because the suspended sediment load calculations using the total capture water volume (SSC-TC) was not statistically different. Table 36 shows mean, median and standard deviation statistics of the volumes recorded by the automatic sampler and the total capture samples from Table D-1.

Table 36: Descriptive Statistics of Actual and Measured Volumes

	<b>Water Volume (L) Sampler (AS)</b>	<b>Water Volume (L) TC</b>
Mean	5698	8621
Median	5664	8444
St. Dev.	2654	2404

Table 36 shows that the automatic samplers do not measure discharge correctly. Due to this inaccuracy, the current method, using automatic samplers to monitor volume, is not an accurate method to evaluate total suspended sediment load. This inaccuracy does not affect EMCs. This is shown by the lack of a statistical difference between the SSC EMCs and the TC EMCs. Also, the suspended sediment loads using the SSC EMC and total capture volume (SSC-TC) were not different either. Revisiting the EMC equation from Equation 1, the error in recording volume in the numerator is the same as the error in recording volume in the denominator assuming the error is linear.

$$EMC = \frac{M}{V} = \frac{\int_0^T c(t)q(t)dt}{\int_0^T q(t)dt}$$

This statement assumes two things, one that the ISCO bubbler was recording stage correctly. Figure 23 shows the bubbler was recording stage correctly because it had

a very strong correlation with the pressure transducer stage data. Second, it assumes the stage discharge relationship, at the location of the ISCO bubbler, did not fluctuate during an event, meaning different stage values for the same discharge.

#### **4.6 Specific Gravity**

The protocol for testing the recovered suspended sediments for specific gravity was modified because the sediments had a high amount of organic material and finer material that stayed above the water line in the pycnometer. The samples were soaked overnight in order to reduce the amount of material that stayed above the water line, and this soaking procedure was not described in the ASTM protocol. The results of the specific gravity test are listed in Table 37 as densities of the sediments. Ottawa sand with an assumed known specific gravity of 2.65 was used to validate the results.

Table 37: Specific Gravity(s) Results

<b>Event</b>	<b>s (g/cm<sup>3</sup>)</b>
Ottawa Sand	2.67
5/11/07	1.86
3/02/07	2.01
1/11/08	2.07
9/27/07	2.96

These results are lower than some of the findings of previous research (Li Y. et al. 2006a) but are within the range of a more recent publication (Kayhanian 2008).

## 4.7 QA/QC

### 4.7.1 Event Mean Concentration

The storms sampled for this investigation met federal and state monitoring recommendations for NPDES permitting and BMP removal efficiency testing (US EPA 1992; Technology Acceptance Reciprocity Partnership 2003). Field blanks were tested to determine contamination from reagents and laboratory analysis as part of the monitoring recommendations, and the results are listed in Table 38. These results are from the UNHSC quality assurance plan and were measured using the SSC analytical method.

Table 38: Blank Sample Verification for Suspended Sediment Concentration

<b>Date</b>	<b>Concentration (mg/L)</b>
7/18/08	7
7/23/08	<2

Field sample duplicates were sent to the lab to test for laboratory consistency and the results are listed in Table 39.

Table 39: Duplicate Sample Results (all concentration values in mg/L)

<b>Date</b>	<b>SSC</b>	<b>TSS</b>
10/19/07	93	13
	31	15
11/03/07	8	<10
	4	<10
1/11/08	95	94
	90	90
3/4/08	78	82
	80	82

The results of this QA/QC procedure were approximately the same level of concentration except for the SSC result from 10/19/08. This duplicate sample seems to be unusual since the TSS results for these samples were very close to each other (<10%

error). The 11/3/07 SSC results were 100% different (but within 4 mg/L of each other) perhaps because the suspended sediment concentration was so low when compared to the other samples submitted (the rest of the duplicates were consistent (5% and 2.5% error).

To verify if the laboratory could measure suspended sediment concentration accurately, known sediment concentrations were sent to the lab and the results can be seen in Tables 40a-c.

Table 40a-c: Results for Known Sediment Concentration Verification

Table 40a: 80 mg/L

1	2	3	4
Known Con. (mg/L)	Results (mg/L)	% Diff	% Diff. mean
80	57.00	29%	11%
80.7	66.00	18%	3%
81.1	72.00	11%	12%
80.3	67.00	17%	4%
81.3	59.00	27%	8%
mean	64.20	20%	

Table 40b: 300 mg/L

1	2	3	4
Known Con. (mg/L)	Results (mg/L)	% Diff	% Diff. mean
303.3	270.00	11%	2%
304	260.00	14%	6%
300.4	280.00	7%	1%
301.9	290.00	4%	-5%
303.8	280.00	8%	1%
mean	276.00	9%	

Table 40c: 150 mg/L

1	2	3	4
Known Con. (mg/L)	Results (mg/L)	% diff	% diff. mean
150	120.00	20%	13%
150	120.00	20%	13%
150	160.00	7%	16%
150	150.00	0%	9%
150	140.00	7%	1%
Mean	138.00	8%	

The SSC analytical method was used to quantify the lab's capability of measuring suspended sediment concentration. A combination of the SSC and TSS analytical methods were not used because running two analytical methods on the same sample introduces the potential for error due to the removal of a sub sample for TSS analysis. A similar pattern as was shown with the field duplicates occurred with these results because the difference (column 3 in Tables 40a and b) between the known concentration and the reported concentration was lower as the suspended sediment concentration increased from 80 mg/L to 300 mg/L. Each individual test for both concentrations was compared to the result mean to assess the deviation among the results (column 4). The results were consistent, 1% to 12% difference from the mean percent difference.

The cone split results (for the 150 mg/L samples, Table 40c) were within a 20% margin of error from the known concentration. The cone splitter used to split these samples is a USGS approved splitter which can split samples accurately (Gray J. et al. 2000). This instrument does have a limitation when the number of coarse particles is few which could explain why some of the samples had variations in suspended sediment concentration. For example, if there is one large particle, it can only go into one sub sample, which could cause the sub samples to have different concentration values.

The QA/QC results show the lab can consistently repeat results but the amount of error between the known and reported values increased when the sediment concentration was low. The cause of error was either due the creation of the known concentrations that were sent to the lab or a difficulty with the laboratory analysis at low concentrations.

#### 4.7.2 Particle Size Distribution

Two analytical methods were used to determine the particle size distribution (PSD) of the sediments recovered in the total capture and automatic sampling samples. At the present, a standard does not exist for the determination of the PSD of stormwater sediments. Due to the contrasting quantities of recovered sediments from these two sampling methods; the same methodology could not necessarily be used for both samples. The automatic sampling method yielded too little sediment for a sieve analysis, and therefore only the optical technique (tri-laser diffraction) could be performed on these samples. Initially only the sieve analysis could be completed on the TC suspended sediments but after they were all recovered both an optical and sieve analyses could be performed.

To compare the two PSD methodologies (tri-laser diffraction and wash sieve with hydrometer), the sediments from three TC storm events, were reconstituted and resuspended for each event and then analyzed by using both PSD methods. Generally the  $D_{50}$  value of the PSD is used as the characteristic measure of a PSD, this value as well as two other supporting values will be used to demonstrate and assess the influence of these PSD methodologies on the reported PSD. The PSD plots from each resuspended event are seen in Figure E-1a,b,c and the three major particle size fractions for the tri-laser analysis (C) and wash sieve analysis (WS) can be seen in Table 41.

Table 41: Comparison of Particle Size Fractions  $D_{70}$ ,  $D_{50}$ , and  $D_{30}$  Between Tri-Laser (C), and wash sieve (WS) Methods (all values in mm)

Date	D70-C	D70-WS	D50-C	D50-WS	D30-C	D30-WS
12/1/06	0.203	0.280	0.102	0.075	0.043	0.014
9/27/07	0.045	0.098	0.027	0.029	0.016	0.013
5/11/07	0.096	0.380	0.05	0.140	0.026	0.025



The wash sieve method and tri-laser diffraction method appeared to be different at the  $D_{70}$  level because these values for the wash sieve tended to be coarser. The  $D_{50}$  values were more similar with the exception for the 5/11/07 event. The  $D_{30}$  events values were similar as well. If the values between the two methods are similar at the  $D_{50}$  and  $D_{30}$  fraction sizes than it can be assumed the PSDs for both methods can be compared for the  $D_{50}$  and  $D_{30}$  because PSD methodology does not appear to influence the particle at these size fractions. It appears that the  $D_{70}$  values of the Tri-laser diffraction method are finer than the  $D_{70}$  values of the wash sieving analysis, meaning that the optical analysis misses coarser sediments so the  $D_{70}$  particle size fraction should not be used for comparison purposes.

To assess for a statistical difference between each method's size fractions ( $D_{70}D_{50}D_{30}$ ), a simple paired t test was completed using a confidence level of 95% and  $\alpha=0.05$ . If the significance level (p-value) is less than 0.05, a statistical difference exists. Table 42 shows the results of the paired samples t-test. The number of data points is small but a statistical test will help to show if a statistically significant difference exists.

Table 42: Paired Sample t-test for  $D_{70}$ ,  $D_{50}$ , and  $D_{30}$  Between Tri-Laser (C), and Wash Sieve (WS) Methods

Particle Size Fraction	Confidence Level	$\alpha$	T	p-level	St. Difference
$D_{70}$	0.95	0.05	-1.82	0.201	No
$D_{50}$	0.95	0.05	-0.616	0.601	No
$D_{30}$	0.95	0.05	1.22	0.347	No

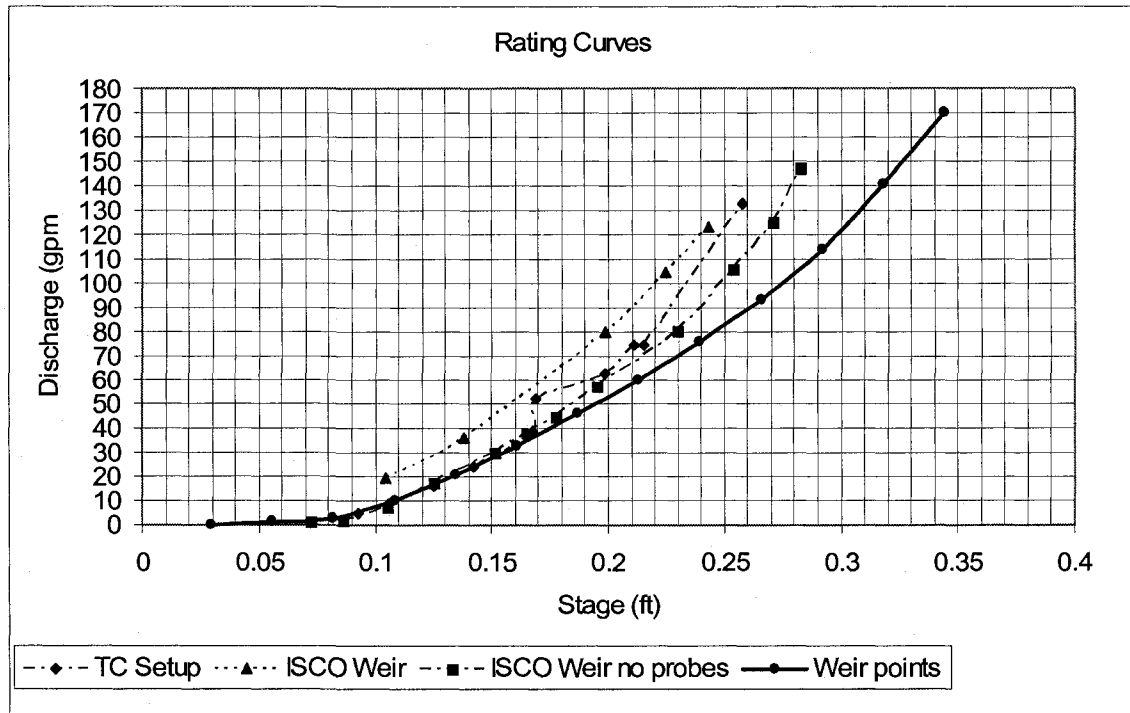
The results of this test show a statistical difference does not exist for any of the size fractions comparing each method.

#### 4.7.3 Evaluation of Weir Rating Curve

To evaluate the difference in water volumes measured by the automatic sampler and the total capture sample, a small test was performed to compare known discharges to measured stage depth as described in section 3.5.3. A known discharge was volumetrically measured over time before each stage-discharge point was measured. After the known discharge was measured, the stage depth was allowed to stabilize and approximately seven minutes of stage data was recorded. These values were averaged and the corresponding discharge was used for the stage-discharge point. Generally 7-12 stage-discharge points were obtained using known discharges from 5.7-681 Lpm (1.5 - 180 gpm). Stage was recorded using an ISCO 720 bubbler which is the same bubbler used during sampling events.

Four scenarios are plotted on Figure 48 including the factory supplied rating curve (Weir Points). An empirical curve for the current sampling setup (TC setup) was created and included on Figure 48. In hopes of identifying possible influences on stage-discharge relations, two other empirical curves were made, ISCO weir and ISCO Weir no probes. These influences will be discussed in the below paragraphs.

Figure 48: Rating Curves for Various Configurations of Stage Recording Device



Reviewing the plots, the empirical curve for the original TC sampling configuration (TC setup) at low flows is the same as the manufacturer's curve provided by ThelMar (Weir points). However for two of the empirical plots (TC Setup and ISCO Weir no probes), at about 40 gpm, the empirical curves begin to separate from the manufacturer's curve. There could be several reasons for this separation. First, the measurement of stage was not measured the same way as the measurement of the stage completed by the manufacturer. The manufacturer measured head directly over the weir but without using an ISCO bubbler which was how stage was measured in this investigation.

Second, the location of the stage recording device was not directly behind the weir. Water depth decreases as it approaches the weir so at different points behind the

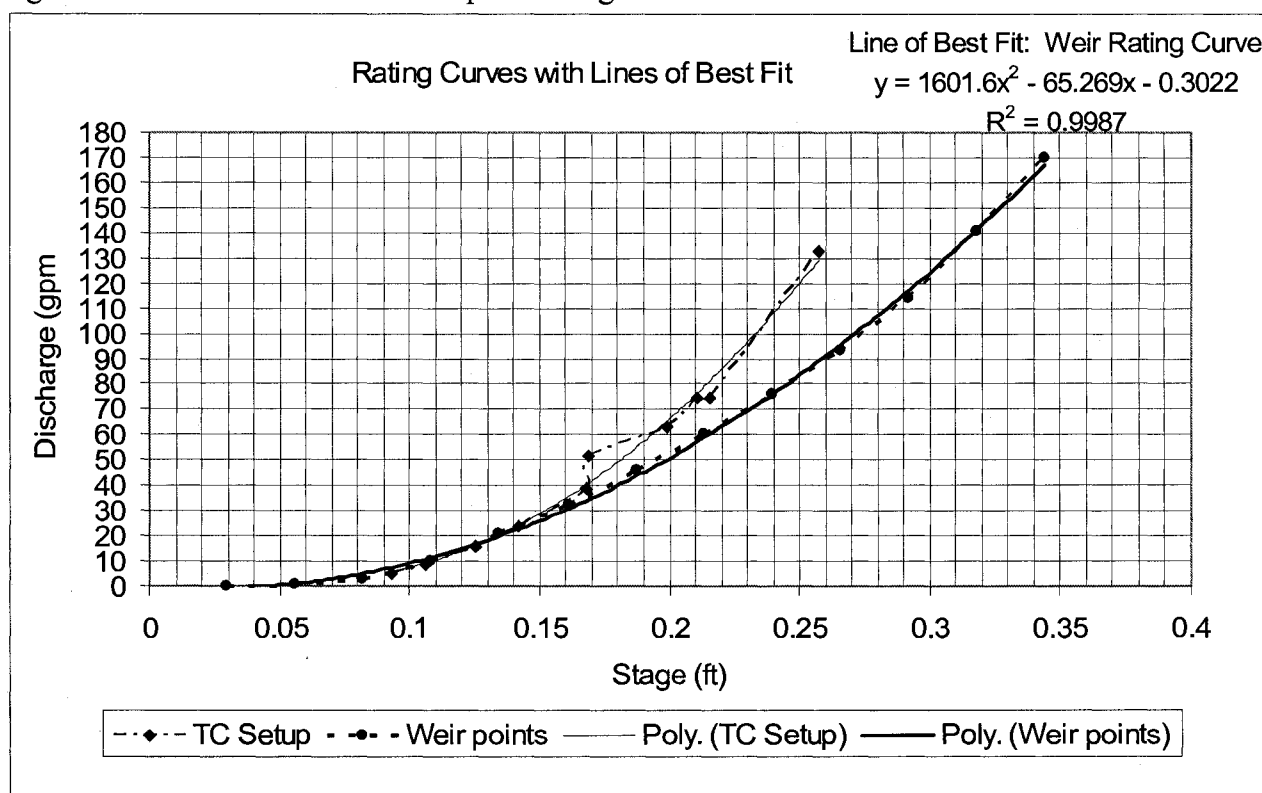
weir the stage could be different at the same discharge. Third, the presence of the automatic sampler sampling intakes, turbidity probe and pressure transducer could be creating an unusual amount of turbulence around the bubbler. The bubbler reads the amount of pressure needed to emit a bubble. More pressure is needed to emit the bubble as the depth of water increases over the opening of the bubble line. Turbulent flows however could be introducing different momentum forces at the bubble line opening, thereby affecting the pressure reading. The manufacturer's curve was not calibrated with probes near the point where stage was recorded.

To investigate the potential reasons why the empirical curve and the manufacturer's curve were not the same, the scenarios shown in Figure 48 were created to isolate these potential influences. The first empirical curve was established to build the curve for the current sampling setup (TC setup). The second empirical curve was measured to determine the curve for the scenario when the bubbler was moved behind the weir but leaving the sampling and monitoring equipment in the same location (ISCO Weir). The third empirical curve was developed when all the equipment was removed with the bubbler left in its location behind the weir (ISCO Weir no probes).

The curves in Figure 48 represent the stage discharge curves for each individual scenario. Each scenario has a different empirical curve meaning that each scenario has a different stage-discharge relationship. To correct the water volumes measured by the automatic sampler so that the total water volume measured by the sampler was approximately the same as the water volume in the total capture sample, the empirical curve of the original setup, (TC setup in Figure 48) was applied to the stage data recorded by the automatic sampler from several events.

. In order to apply the empirical curve, interpolation between stage-discharge points was used. However, the TC setup rating curve in Figure 48 was developed to a maximum stage of 0.2575 ft, a discharge of 135 gpm (510Lpm), due to equipment limitations. To adjust higher stage measurements, a polynomial line of best fit was used. The equation of this line (Equation 11) is listed below and can be seen on Figure 49 which also shows the line of best fit for the weir-point rating curve.

Figure 49: Lines of Best Fit for Adapted Rating Curves



$$y = 3796.2x^2 - 574.8x + 27.03$$

$$R^2 = 0.991$$

Equation 11

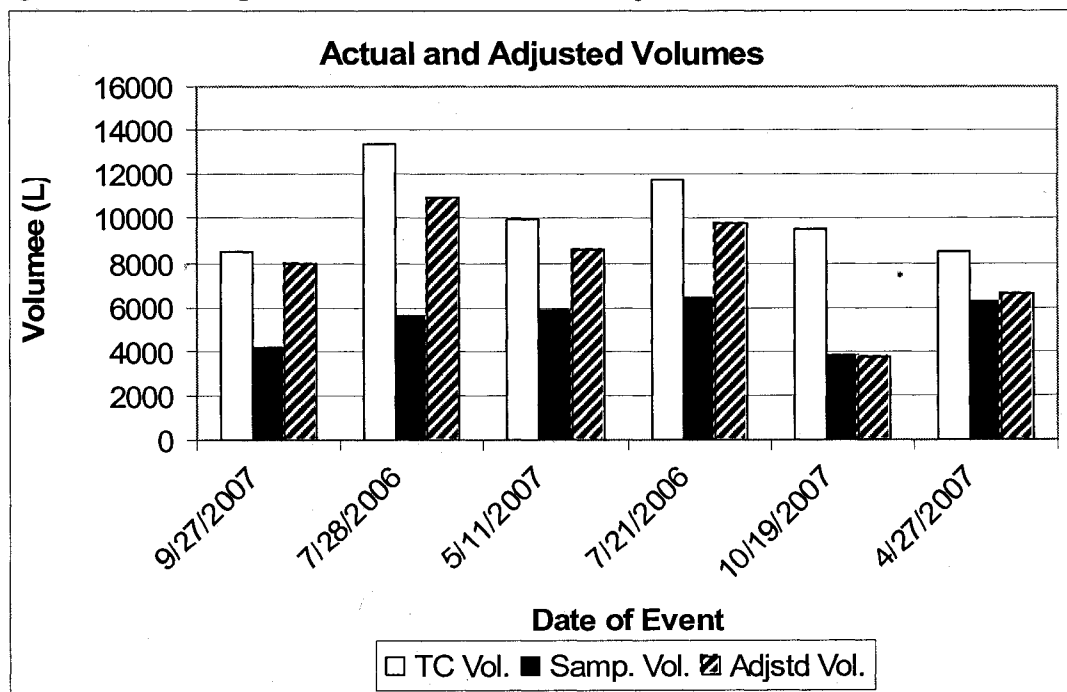
The six events were chosen based on a visual inspection of their hydrographs in Figures B-3a-r for the amount of discharge which was above and below 151 Lpm (40 gpm, column 2 in Table 43). This is the level in which the TC setup empirical curve

began to separate from the manufacturer's curve. Six events were chosen for this evaluation and the discharge levels (column 2), presumed actual water volume from the total capture sample (column 3), water volume from ISCO samplers (column 4), and the readjusted ISCO water volumes (column 5) can be seen in Table 43 and graphically in Figure 50

Table 43: Actual and Measured Water Volumes for Events with Adjusted Volumes

1	2	3	4	5	6	7
Date	Dis. Criteria (Lpm)	TC Vol. (L)	AS Vol (L)	Difference: TC-AS L (1-(AS/TC))	Adjusted Vol (L)	Difference: TC-Adjstd (L) (1-(AS/TC))
9/27/07	>151	8,456	4,163	-4,293 (50%)	8,180	276 (3%)
7/28/06	>151	13,718	5,626	-8,092 (59%)	11,234	2,484 (18%)
5/11/07	< 151	10,149	5,912	-4,237 (42%)	8,777	1,372 (13%)
7/21/06	<151	11,993	6,424	-5,569 (46%)	9,974	2,019 (17%)
10/19/07	<151	9,493	3,795	-5,698 (63%)	3813	5,680 (59%)
4/27/07	<40	8,657	6,224	-2,433 (28%)	6735	1,922 (22%)

Figure 50: Bar Graph of Method Volumes and Adjusted Volumes



Applying the empirical curve of the TC setup adjusted the water volumes as read by the automatic sampler to be approximately the same as the total capture water volumes in the events which had discharge levels over 151 Lpm. The difference between the automatic sampler water volume and the actual water volume decreased when the empirical curve and formula was used as seen in Table 43 (column 7). In the two events with all of the discharge levels in the event less than 151 Lpm, the application of the empirical curve did not bring the water volume measured by the automatic samplers notably closer to the actual volume. In Section 4.5, the implications of volumetric error were discussed and showed that the error in measuring water volume does not affect EMCs. Nor does volumetric measurement affect PSD. Volumetric measurements do affect suspended sediment load calculations, which were discussed in Section 4.5.

## Chapter 5

### V *Conclusion*

#### 5.1 Summary

Several methods used to monitor suspended sediments in stormwater discharge were evaluated over a two year span. The following suspended sediment characteristics were assessed: suspended sediment concentration and particle size distribution. A combination of sampling techniques and analytical methods were assessed for accuracy.

The suspended sediment concentration methods used in this investigation followed federal and state guidance to meet NPDES permit regulations and BMP removal efficiency standards. The turbidity method employed in this research subscribed to USGS-suggested protocol for open channel monitoring. Particle size distributions of sediments recovered by an automatic sampler were completed using tri-laser diffraction. Finally, a “total capture” method was employed to capture a large volume of stormwater discharge and its attendant suspended sediments in order to characterize the suspended sediment size and concentration. This last method was presumed to be the most accurate suspended sediment metrics, to which all other methods were compared.

Eighteen events were monitored, evenly distributed throughout the year. Suspended sediment concentration amounts were found to be just above the expected concentrations from this type of land use (Roseen R. et al. 2006). The range of sediment



particle sizes was within expected values, as found in previous research studies (Furumai H. et al. 2002; Li Y. et al. 2005; Roseen R. et al. 2006; Li Y. et al. 2006a).

Using an automatic sampler with the SSC analytical method is an accurate method to monitor suspended sediment concentration in stormwater discharge.

Automatic samplers collect sand size sediments but the field method using an automatic sampling with tri laser diffraction did not appear to collect a sample with a representative particle size distribution. Coarse particles found in stormwater discharge affect the accuracy of suspended sediment EMCs using the TSS analytical method.

## **5.2 Policy Implications and Recommendations for Future Research**

### **Policy Implications**

- The TSS analytical method, as written in the APHA and AWWA protocol should not be used as a stand alone method to monitor suspended sediment concentration in stormwater runoff to meet NPDES regulations or BMP removal efficiency testing protocol.
- The SSC method can measure suspended sediment EMCs accurately and should be the analytical method of choice
- Automatic samplers can adequately monitor stormwater suspended sediment concentration.
- The inability to accurately measure discharge does not influence EMCs only if the error in the flow measurement, is linear.
- Accurate flow measurement is a requisite in order to determine suspended sediment mass loads. Determining loads is important for the EPA's TDML program.

### **Recommendations for Future Research**

- This investigation was conducted from stormwater discharge from a watershed with a "light transportation" land use and in a northern climate with sanding and salting in the winter. It would be interesting to apply this methodology on stormwater discharge from different land uses and in different climates which do not have winter maintenance to see if these same results are found.
- The application of turbidity meters can reduce financial costs for long term monitoring of suspended sediments in stormwater sewer systems. This incentive should drive a reassessment to determine if a turbidity meter can be used in a stormwater sewer system.

### **5.3 Conclusion**

Monitoring suspended sediment concentration using federal and state recommendations for automatic sampler deployment can be an effective monitoring method when the SSC analytical method is used. The TSS method loses its accuracy when large sediments (sand size or coarser) are present in the water sample which has been proven in previous research with river water samples (Gray J. et al. 2000). The PSD of the suspended sediments in stormwater discharge are coarse enough to cause this inaccuracy. There was a moderate correlation between sediment size and the resulting difference between the two analytical methods. However, the discrepancy between SSC and TSS analytical methods increased when samplers were taken at higher levels of discharge in which coarser particles are present in higher proportion.

The turbidity method was not an effective method to monitor suspended sediment concentration in this investigation using the manufacturer's recommendation for meter orientation in the sewer pipe. It was unclear if the configuration of the probe impacted the turbidity meter to correctly monitor sediment concentration or if the turbidity meter could not accurately measure suspended sediment concentration accurately in a stormwater sewer pipe.

The majority of sampling was conducted in a non-isokinetic environment because the fixed sampling intake velocity was not the same as the fluctuating velocity in the stormwater sewer pipe. This condition did not affect the automatic sampler's ability to monitor suspended sediment concentration.

There was poor to moderate correlation of environmental factors' influence on suspended sediment EMCs for all methods including the total capture method. It appears

max discharge, rainfall intensity and loading period can influence an EMC but the correlations are weak.

The automatic sampler can extract sand size particles from a stormwater sewer. However, there appears to be a disparity between the PSD as determined by the field method and the presumed actual PSD. The results of a statistical test showed there was no statistical difference between the  $D_{50}$  and  $D_{30}$  values of the PSD of the suspended sediments in the samples taken by automatic sampler and the PSD of the total capture samples. There was a statistical difference between the  $D_{70}$  values. An evaluation of the differences between the two particle size fractions ( $D_{50}$ ,  $D_{30}$ ) show there were more positive differences than negative differences between the paired particle size fraction values. The median value of all the differences for the  $D_{50}$ ,  $D_{30}$  was close to zero validating that there was not a statistically significant difference between paired data at that confidence interval with this small sample size. However, further statistical tests did show a difference between the field method PSD and the presumed actual PSD.

There was a difference between the manufacturer supplied stage-discharge rating curve and the empirical curve established for the TC sampling setup. Total water volumes, as measured by the automatic sampler, were chronically lower than the presumed actual water volumes as measured from the total capture sample. When the empirical curve of the TC sampling setup was applied to stage data, measured by the automatic sampler, some sampling events' adjusted volumes were closer to the actual water volume. It was unclear if the location of the bubbler and its proximity to sampling probes affected the stage to discharge rating curve. Since the bubbler chronically measured lower stage values, this lead to lower volumes as measured by the sampler and

consequently lower calculated suspended sediment loads. This error does not affect suspended sediment EMCs or PSD.

Monitoring methods greatly influence the accuracy of characterizing suspended sediments in stormwater discharge. This research shows how unpredictable and unreliable these results can be when different methods are used to monitor for the same characteristic. It is recommended that a standard protocol for the monitoring of each suspended sediment characteristic be implemented.

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1	2	3	4	5	6	7
Date	Dis. Criteria (Lpm)	TC Vol. (L)	AS Vol (L)	Difference: TC-AS L (1-(AS/TC))	Adjusted Vol (L)	Difference: TC-Adjstd (L) (1-(AS/TC))
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10/19/07	<151	9,493	3,795	-5,698 (63%)	3813	5,680 (59%)
4/27/07	<40	8,657	6,224	-2,433 (28%)	6735	1,922 (22%)

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## Appendix A: Figures & Tables For Section 2.2.3-3.3.1

Figure A-1: Diagrams of Various Sample Types

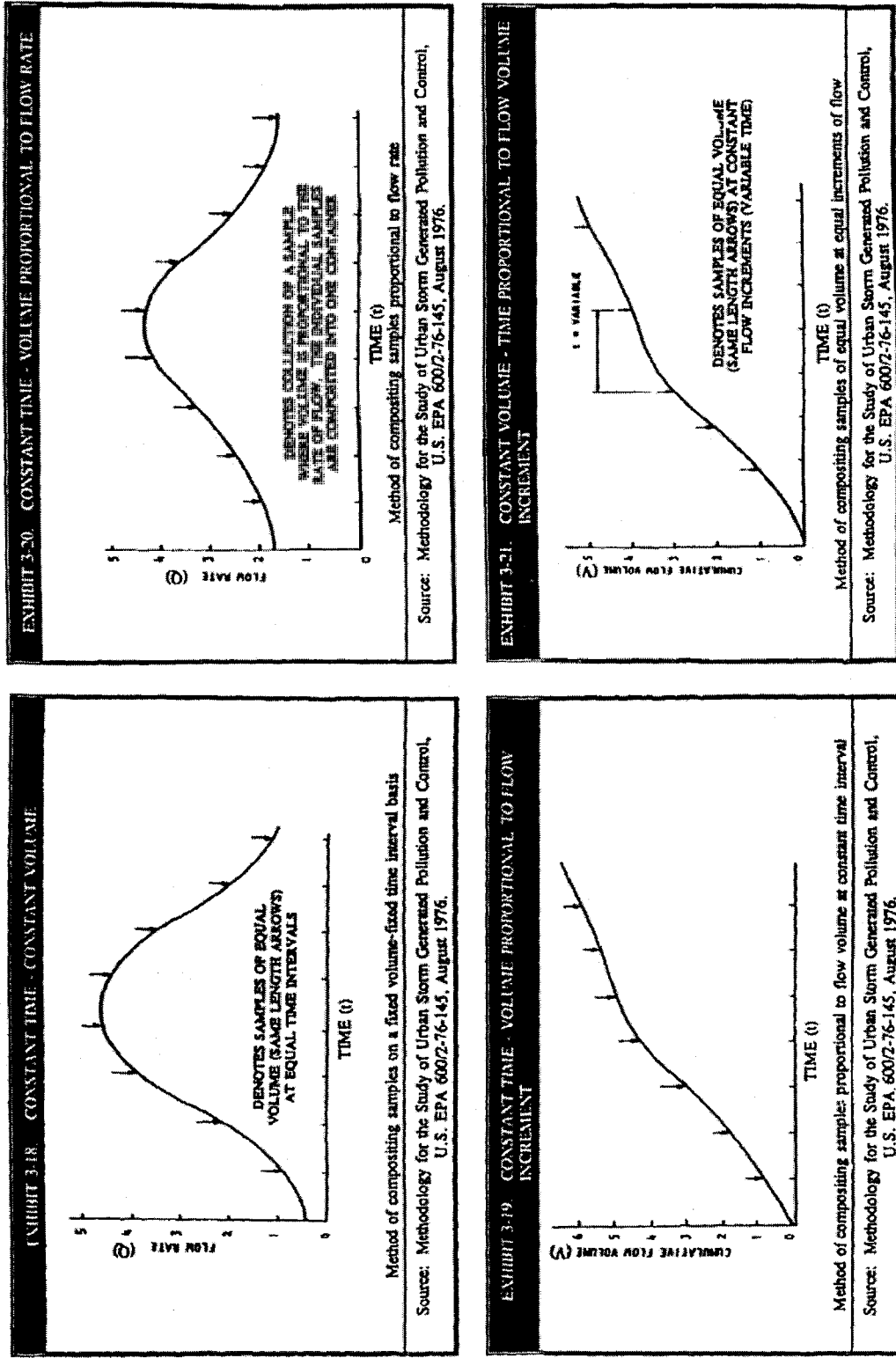
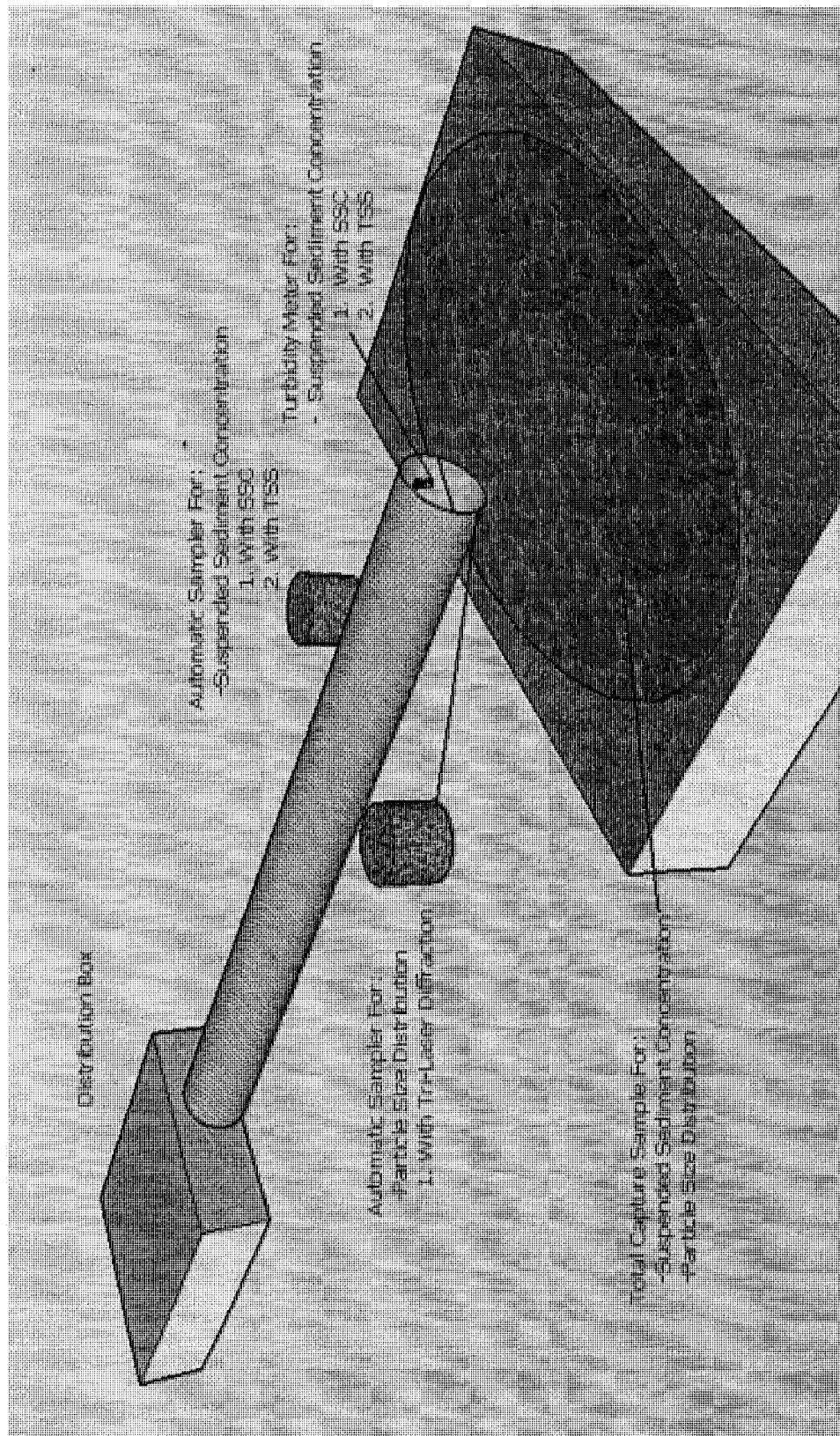


Figure A-2: Sketch of Experimental Design



## Appendix B: Figures & Tables for Sections 4.1.1-4.2.2

Figure B-1: Hyetograph & Hydrograph for All Events

Figure B-1a: 6/20/06

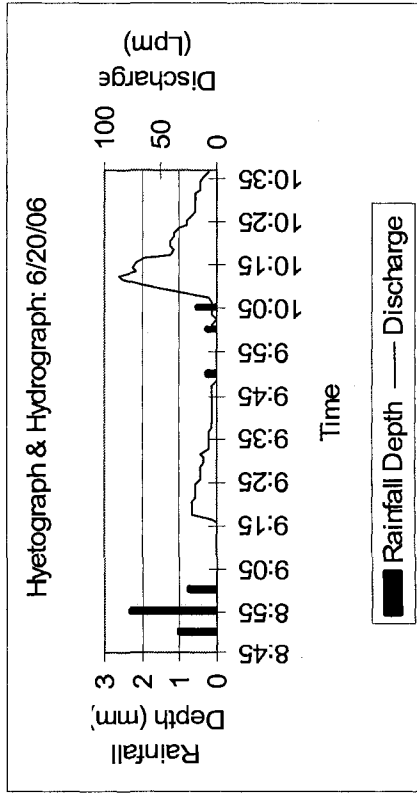


Figure B-1b: 6/23/06

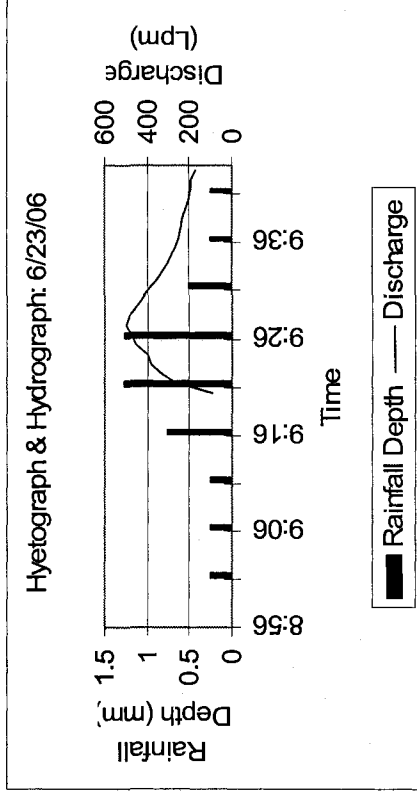


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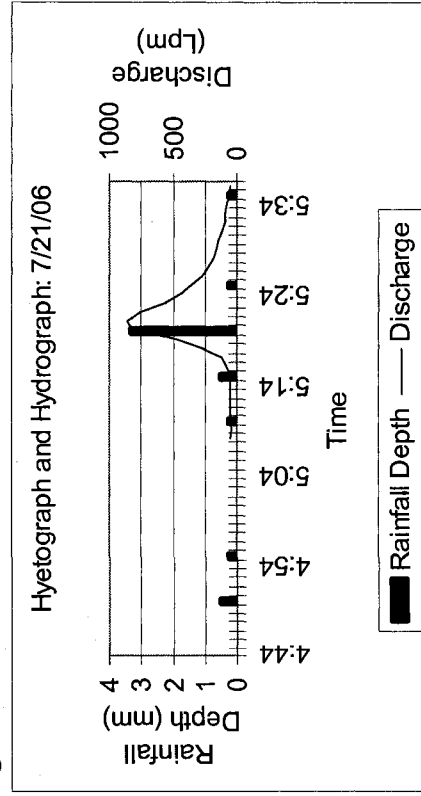


Figure B-1d: 7/28/06

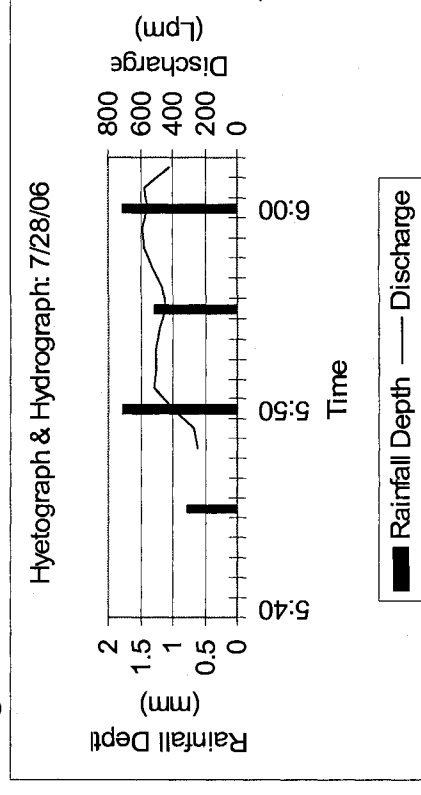


Figure B-1e: 8/15/06

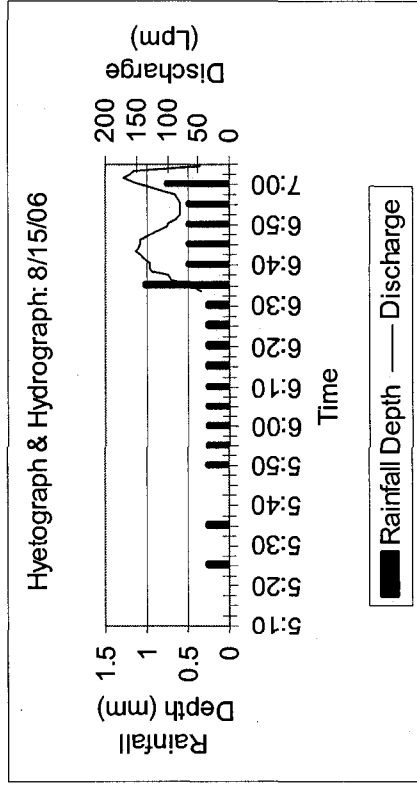


Figure B-1f: 12/01/06

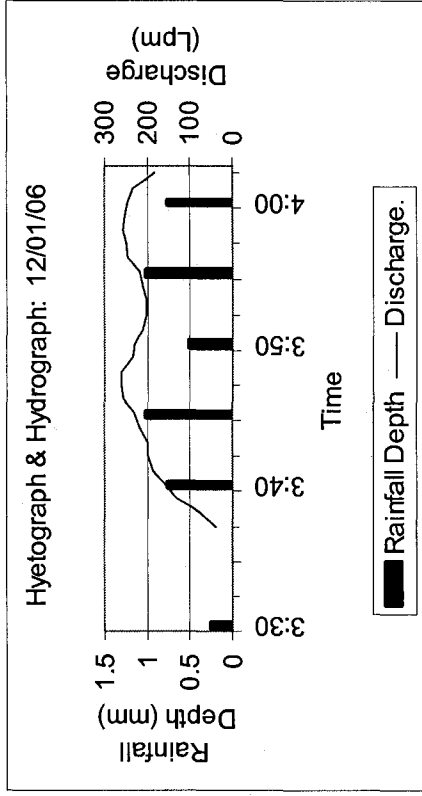


Figure B-1g: 1/6/07

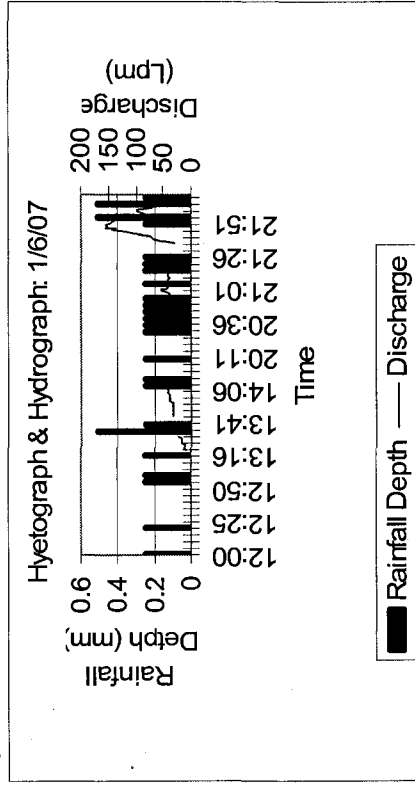


Figure B-1h: 3/2/07

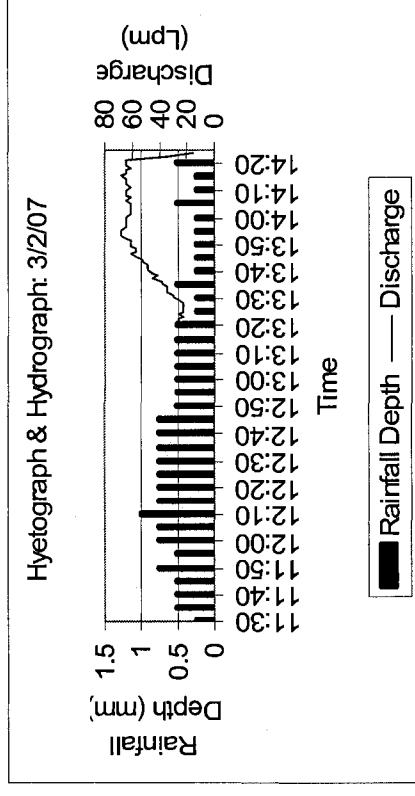


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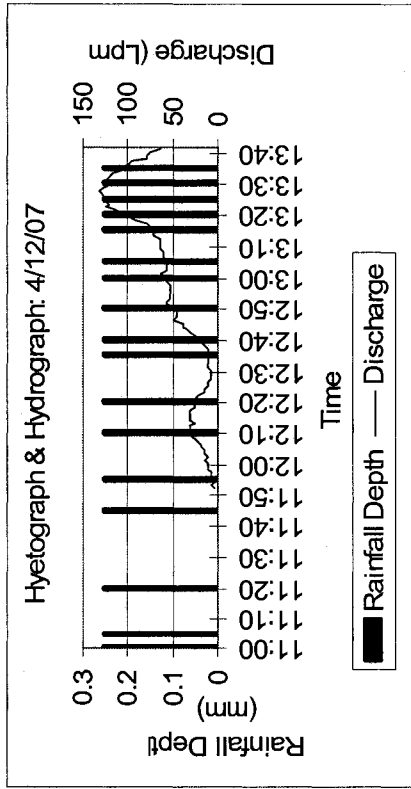


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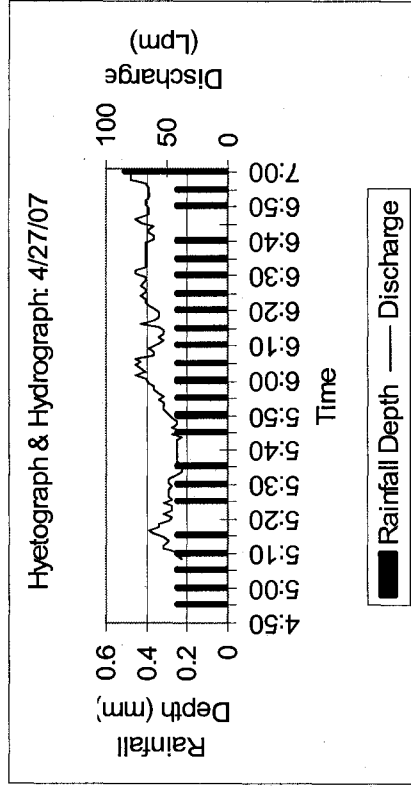


Figure B-1k 5/11/07

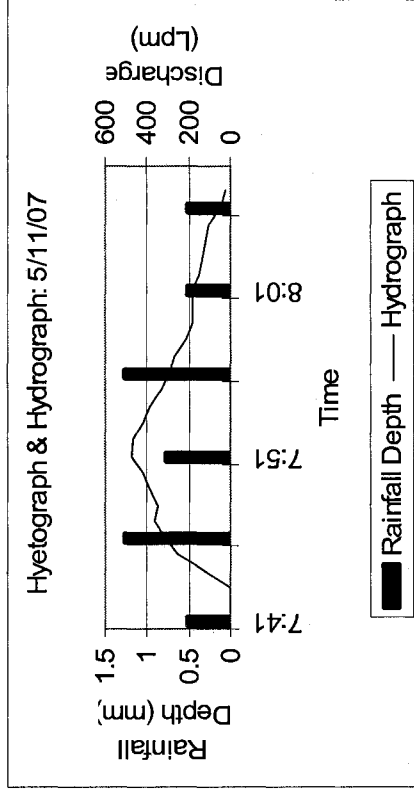


Figure B-1l: 9/11/07

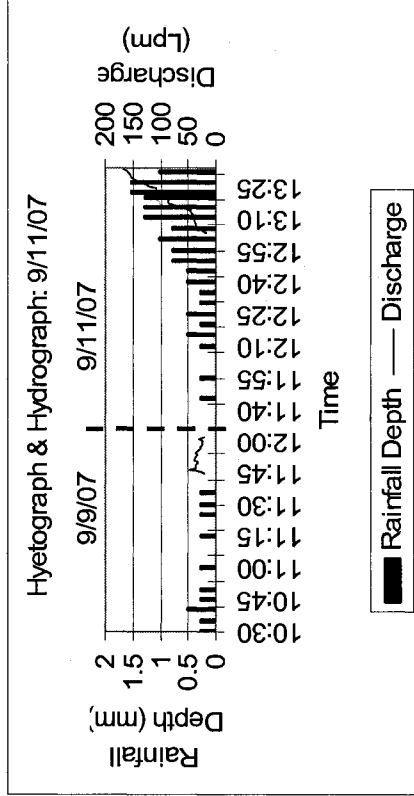


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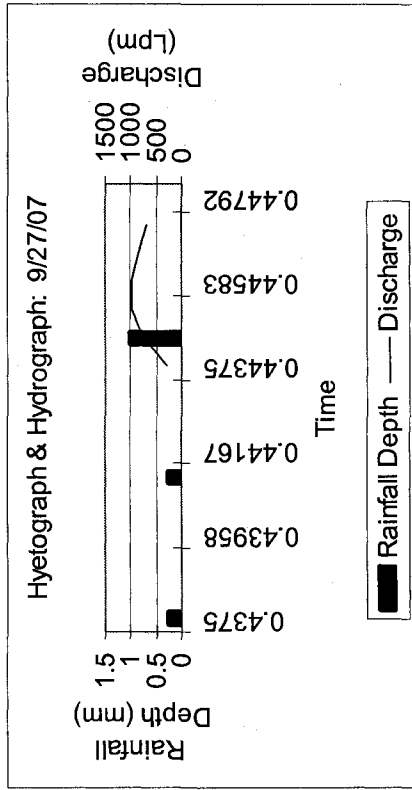


Figure B-1n: 10/19/07

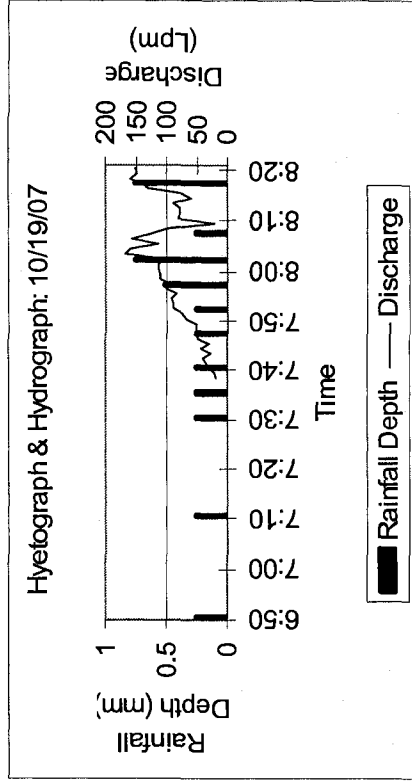


Figure B-1o: 11/03/07

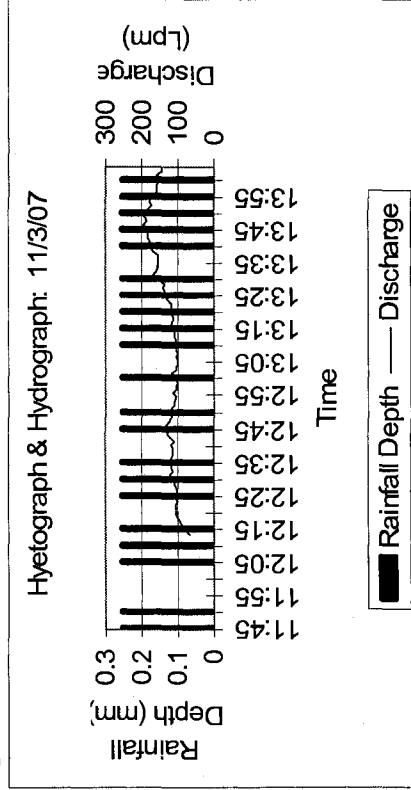


Figure B-1p: 1/11/08

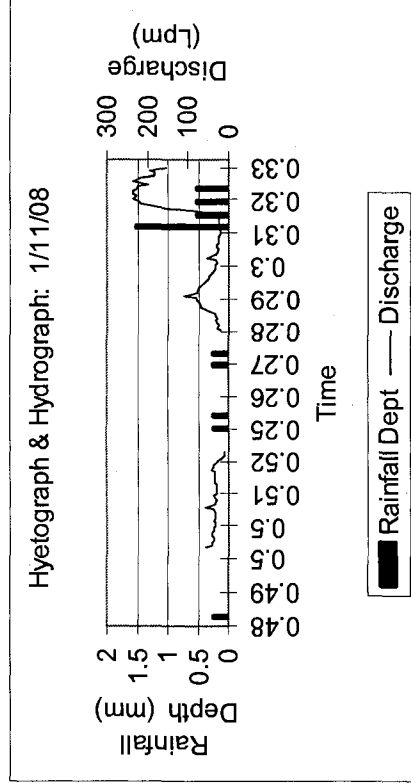




Figure B-1q: 3/4/08

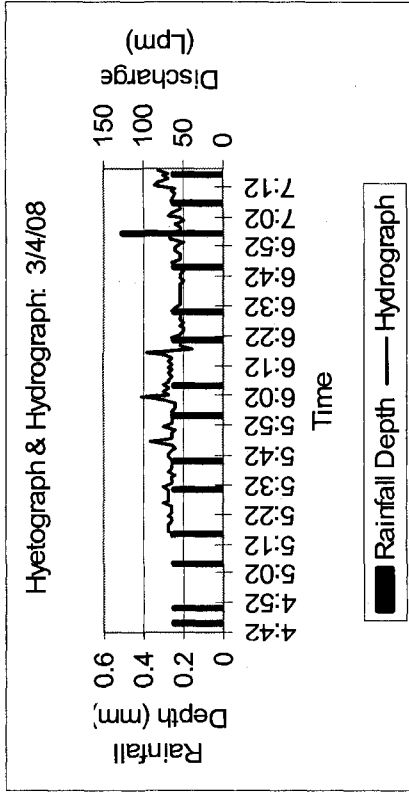


Figure B-1r: 4/28/08

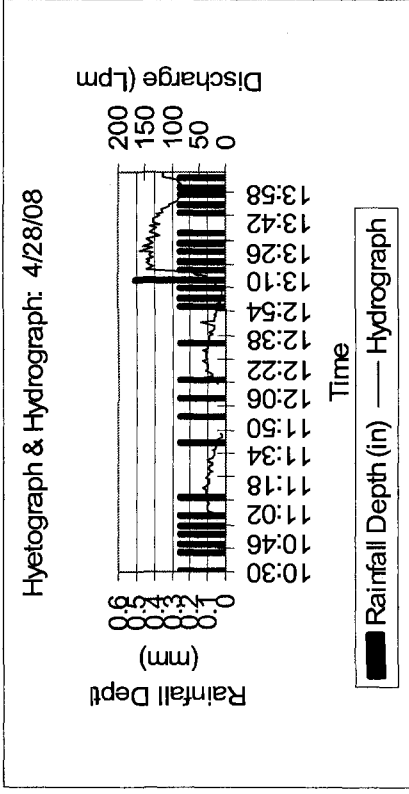


Figure B-2: Cumulative Rainfall Depth for Events to Determine First Flush

Figure B-2a: 6/20/06

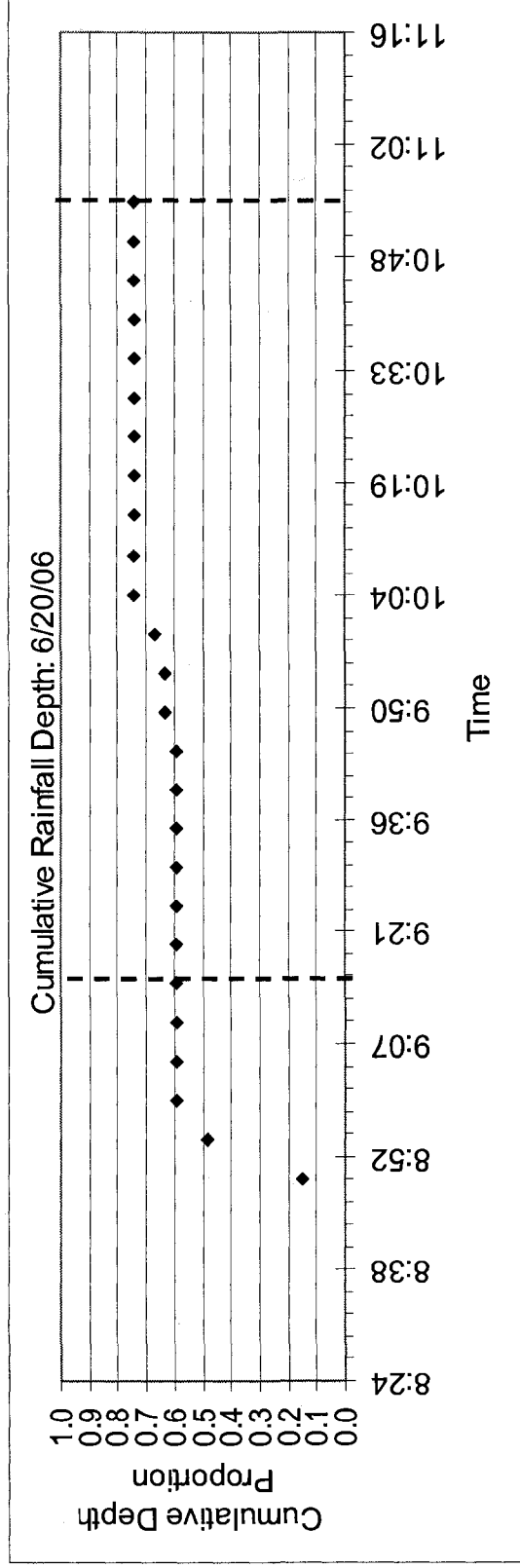


Figure B-2b: 8/15/06

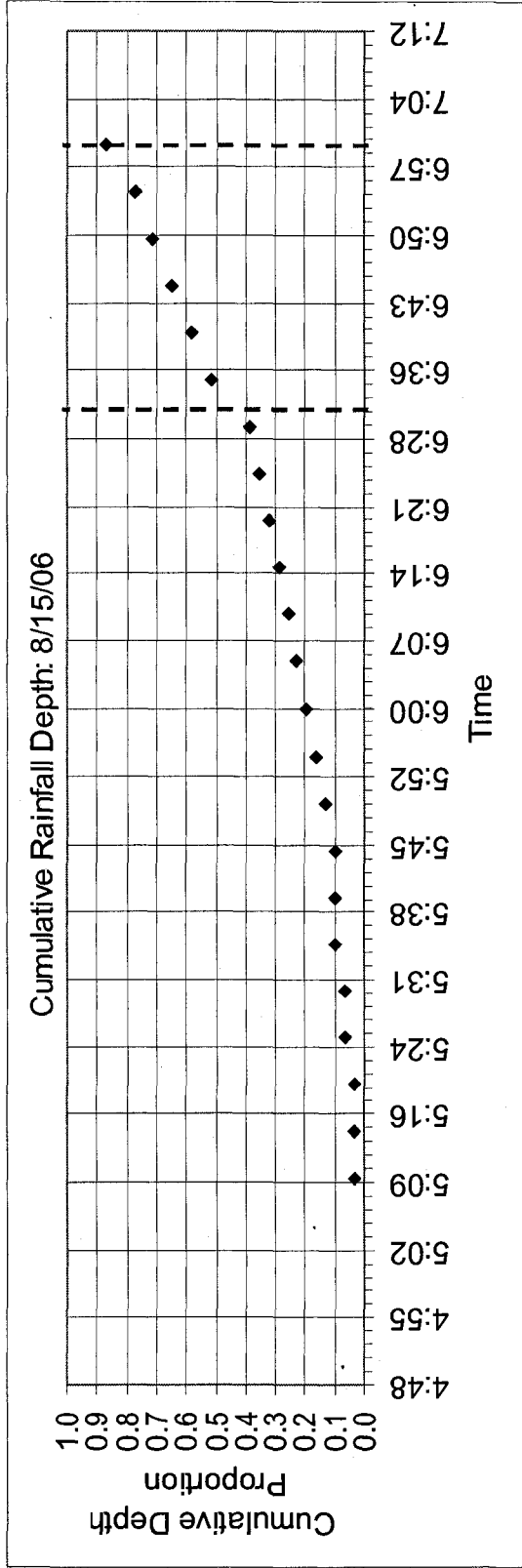


Figure B-2c: 1/06/07

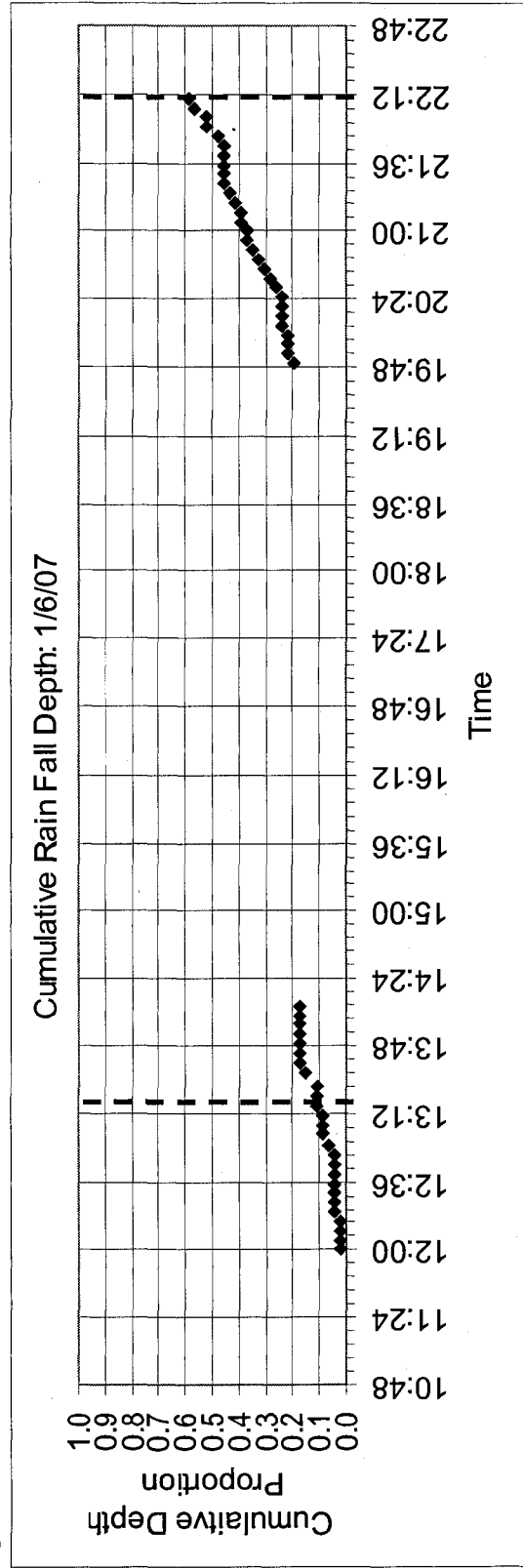


Figure B-d: 4/12/07

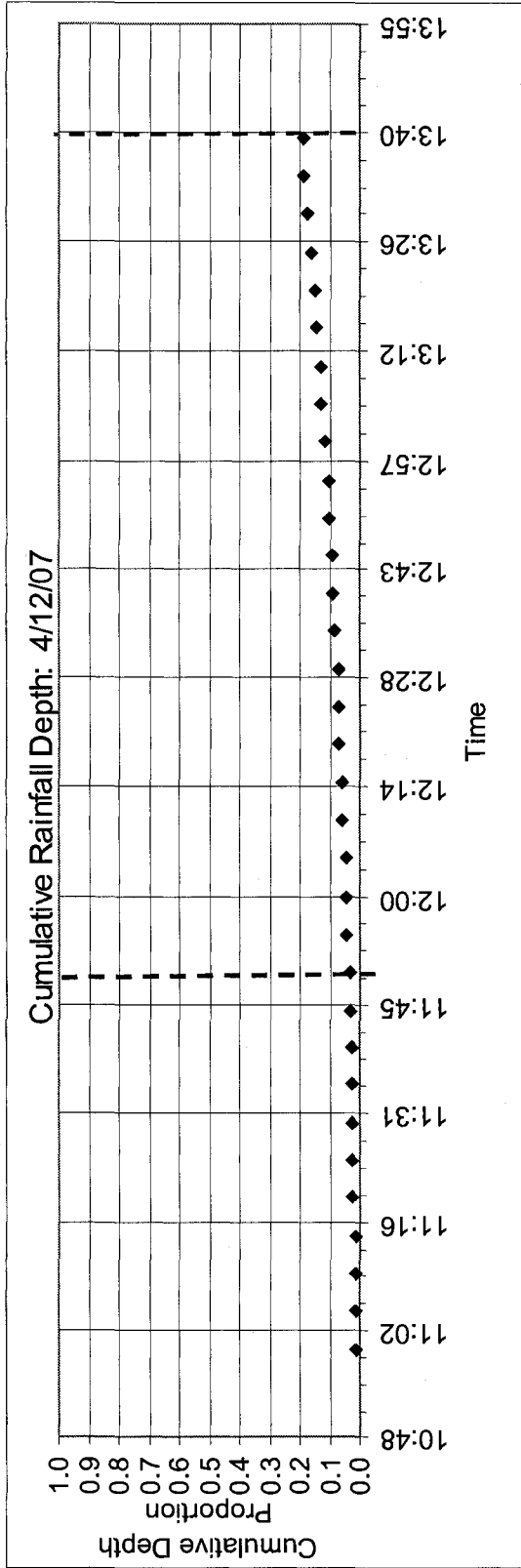


Figure B-3: Hydrographs with Timing of Samples for all Events

Figure B-3a: 6/20/06

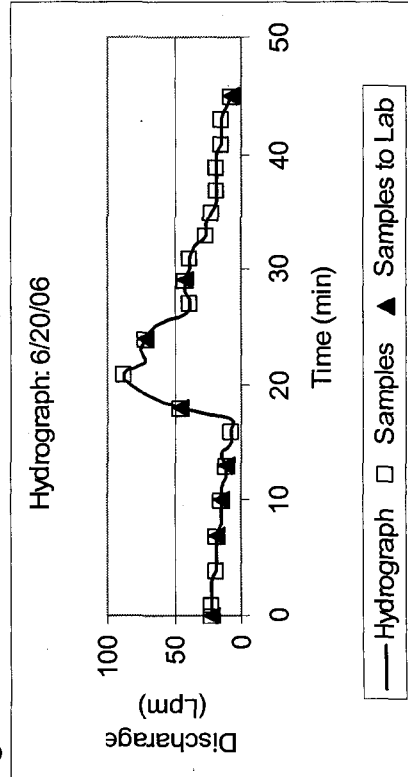


Figure B-3b: 6/23/06

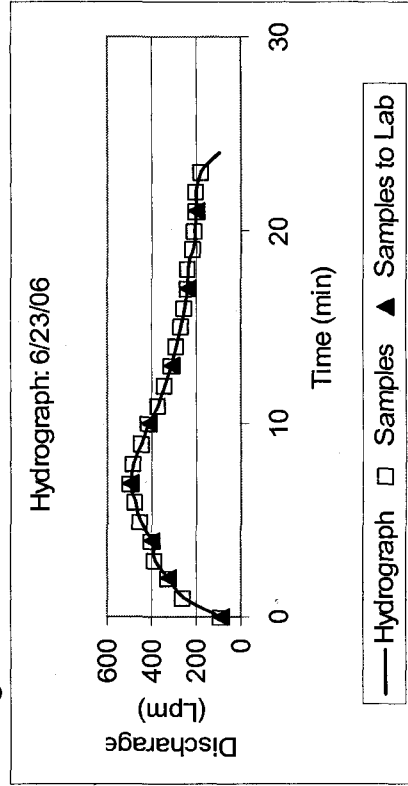


Figure B-3c: 7/21/06

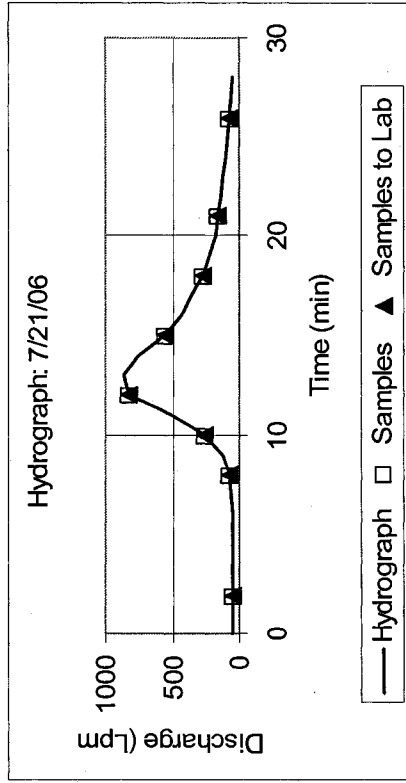


Figure B-3d: 7/28/06

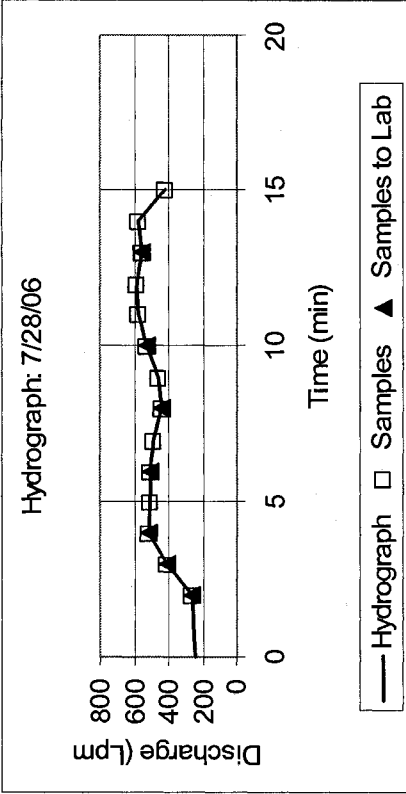


Figure B-3e: 8/15/06

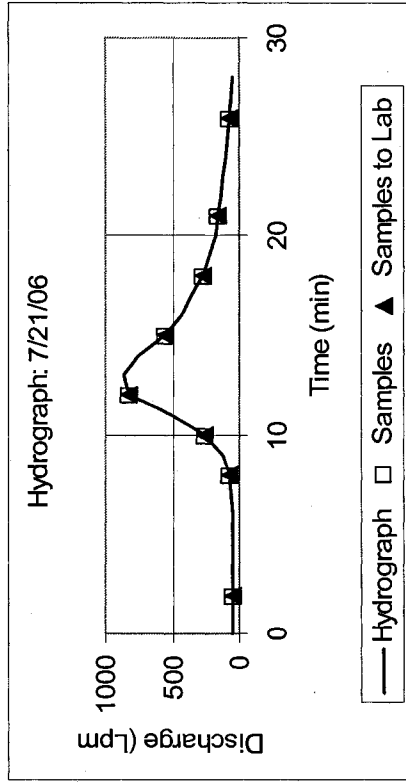


Figure B-3f: 12/01/06

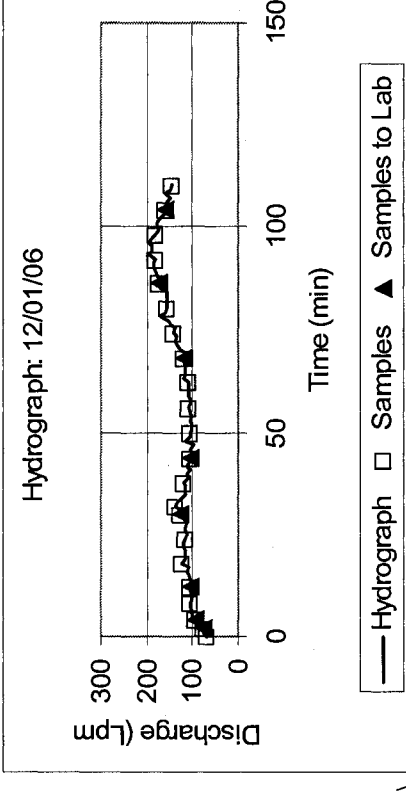


Figure B-3g: 1/06/07

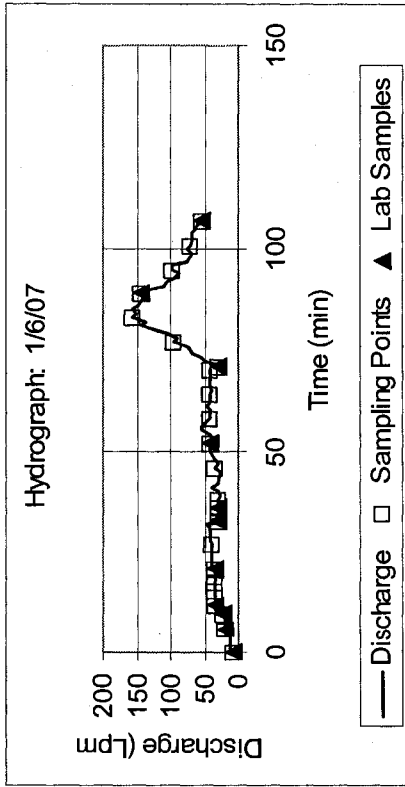


Figure B-3h: 3/02/07

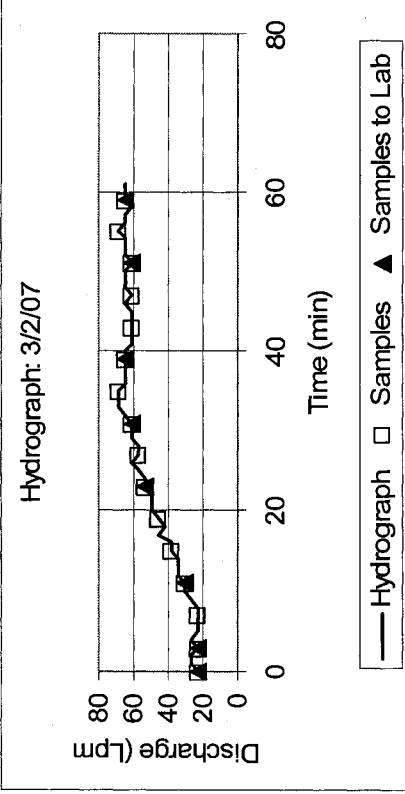


Figure B-3i: 4/12/07

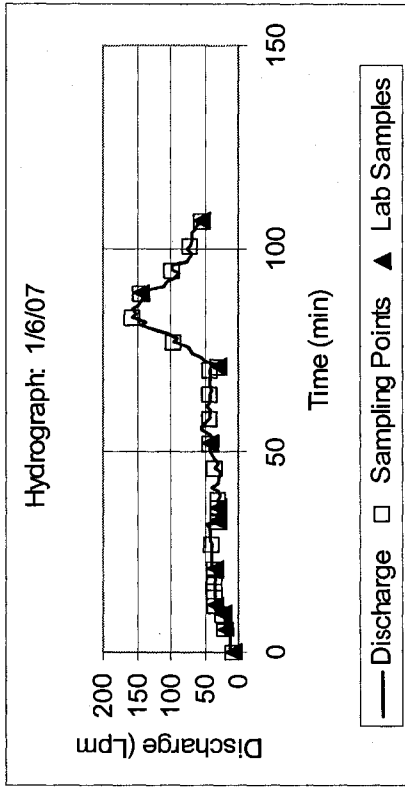


Figure B-3j: 4/27/07

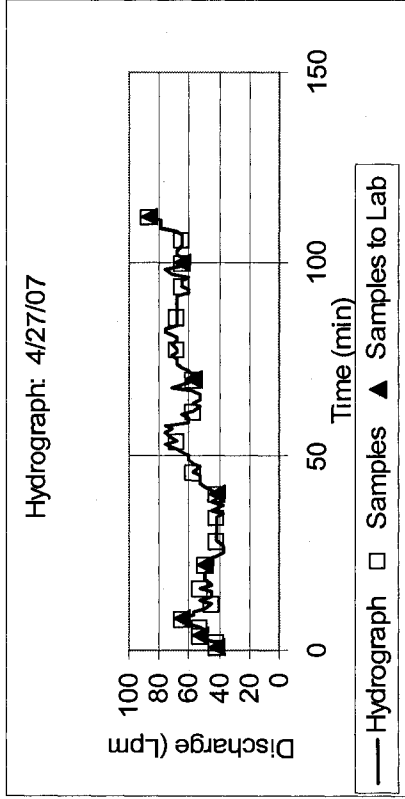


Figure B-3k: 5/11/07

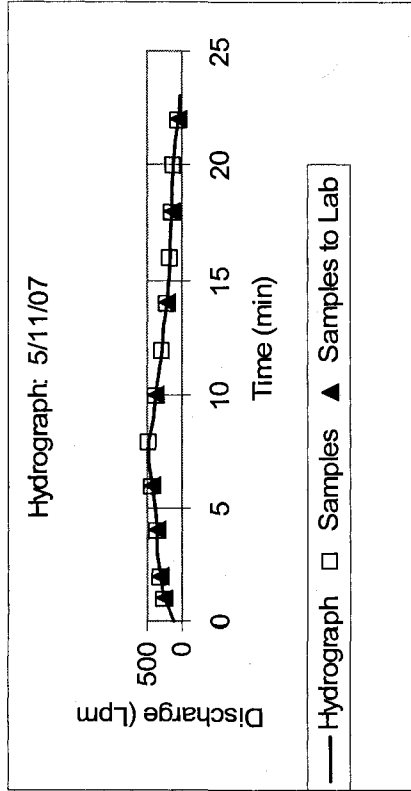


Figure B-3l: 9/11/07

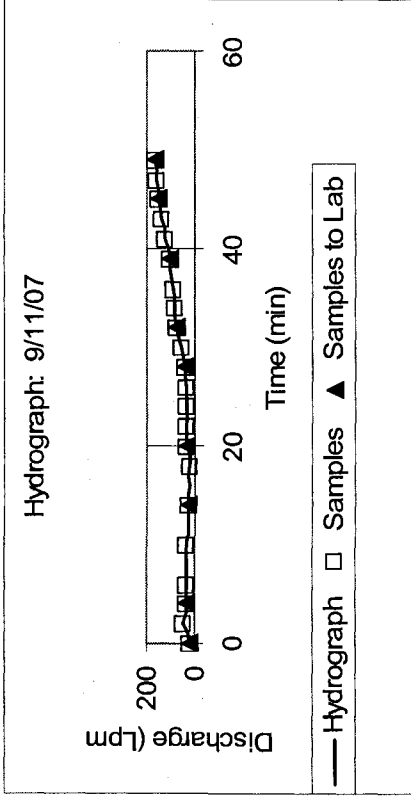


Figure B-3m: 9/27/07

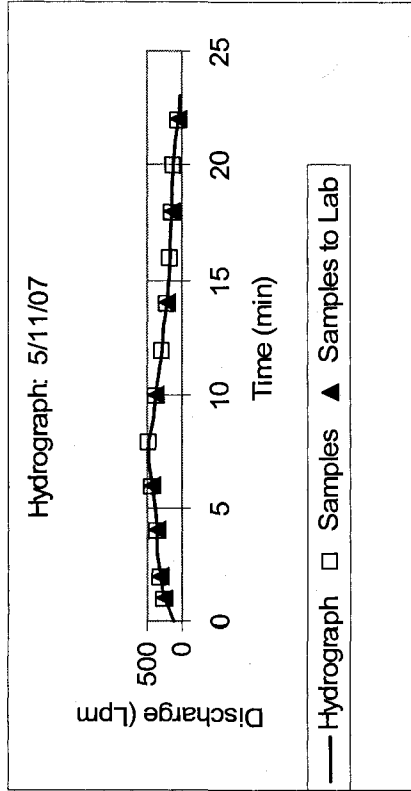


Figure B-3n: 10/19/07

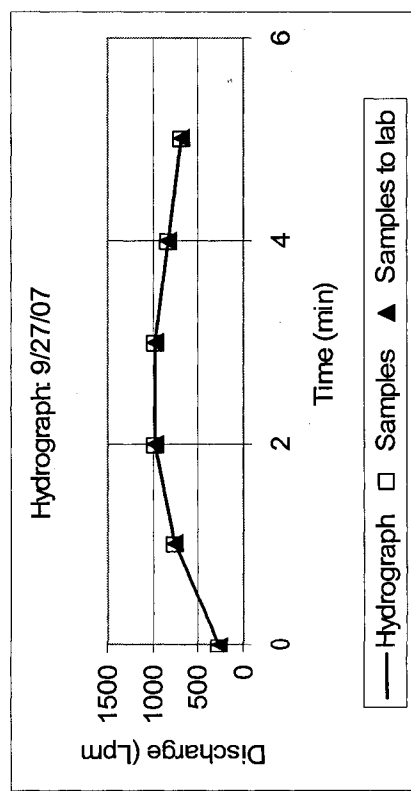


Figure B-3o: 10/19/07

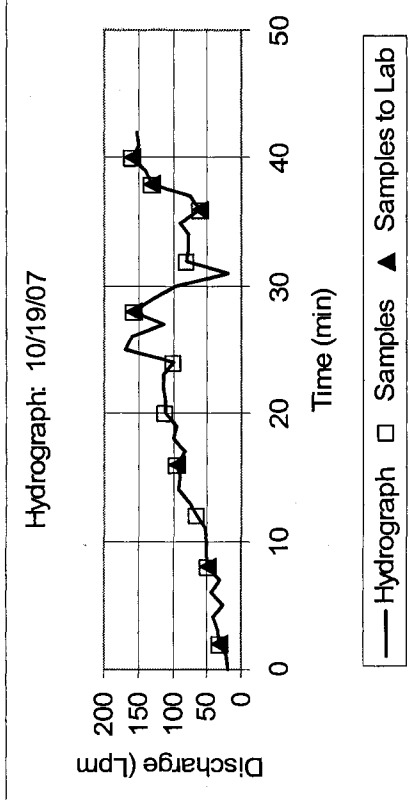


Figure B-3o: 11/03/07

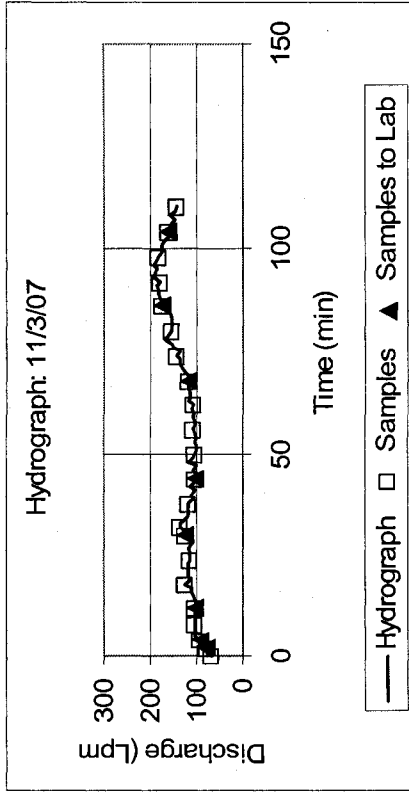


Figure B-3p: 1/11/08

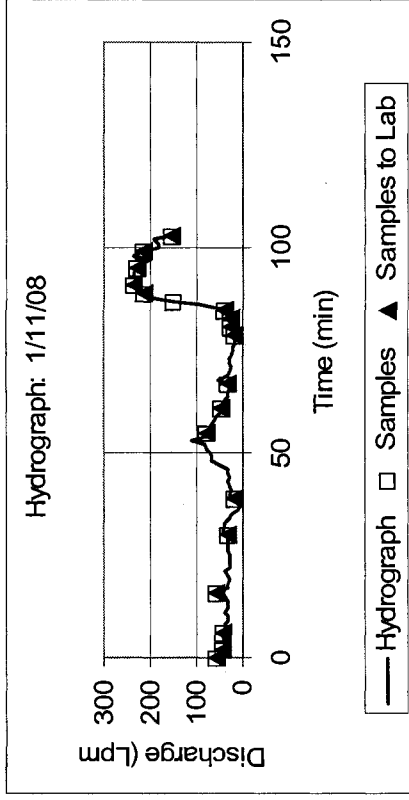


Figure B-3q: 3/04/08

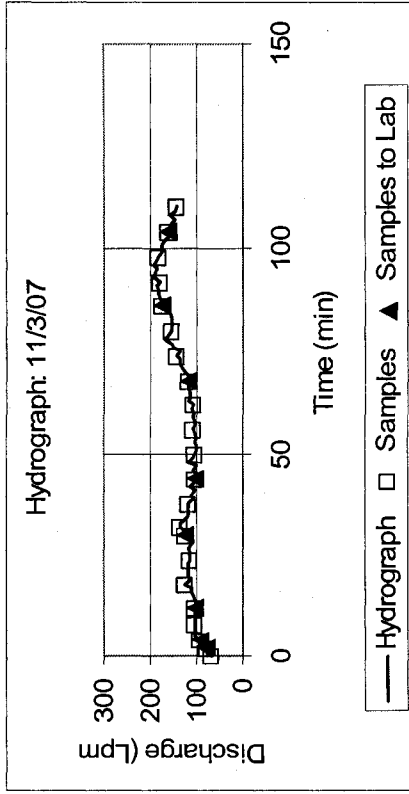


Figure B-3r: 4/28/08

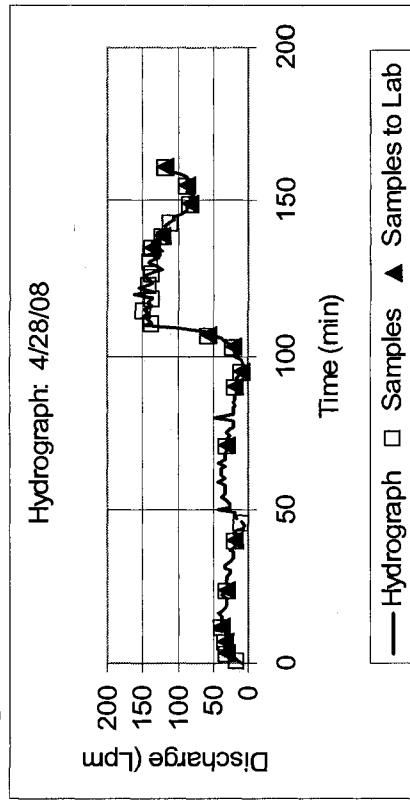


Table B-1: Descriptive Statistics of Discharge for All Events

Date	Mean (Lpm)	Median (Lpm)	St. Dev	Max (Lpm)	Min (Lpm)
6/20/06	20.8	18.9	21.8	87.1	7.6
6/23/06	320.7	300.9	112.4	495.8	90.8
7/21/06	232.6	117.3	246.2	863.0	45.4
7/28/06	498.2	505.3	85.7	582.9	265.0
8/15/06	113.8	111.7	34.7	170.3	45.4
12/01/06	213.0	219.5	55.0	261.2	37.9
1/06/07	56.4	41.6	36.8	155.2	7.6
3/02/07	51.9	60.6	16.2	68.1	15.1
4/12/07	51.1	45.4	37.5	132.5	3.8
4/27/07	59.6	60.6	11.8	87.1	37.9
5/11/07	253.6	253.6	139.7	473.1	3.8
9/11/07	67.0	37.9	46.0	167.7	18.9
9/27/07	769.4	797.5	259.1	980.7	279.7
10/19/07	88.6	88.2	42.8	168.4	18.9
11/03/07	132.3	117.3	29.8	194.2	67.8
1/11/08	68.7	37.9	65.7	235.0	7.6
3/04/08	65.1	64.7	9.4	102.2	40.1
4/28/08	59.6	33.7	47.0	161.2	4.9



Figure B-4: Rainfall Event & Sampling Event Duration

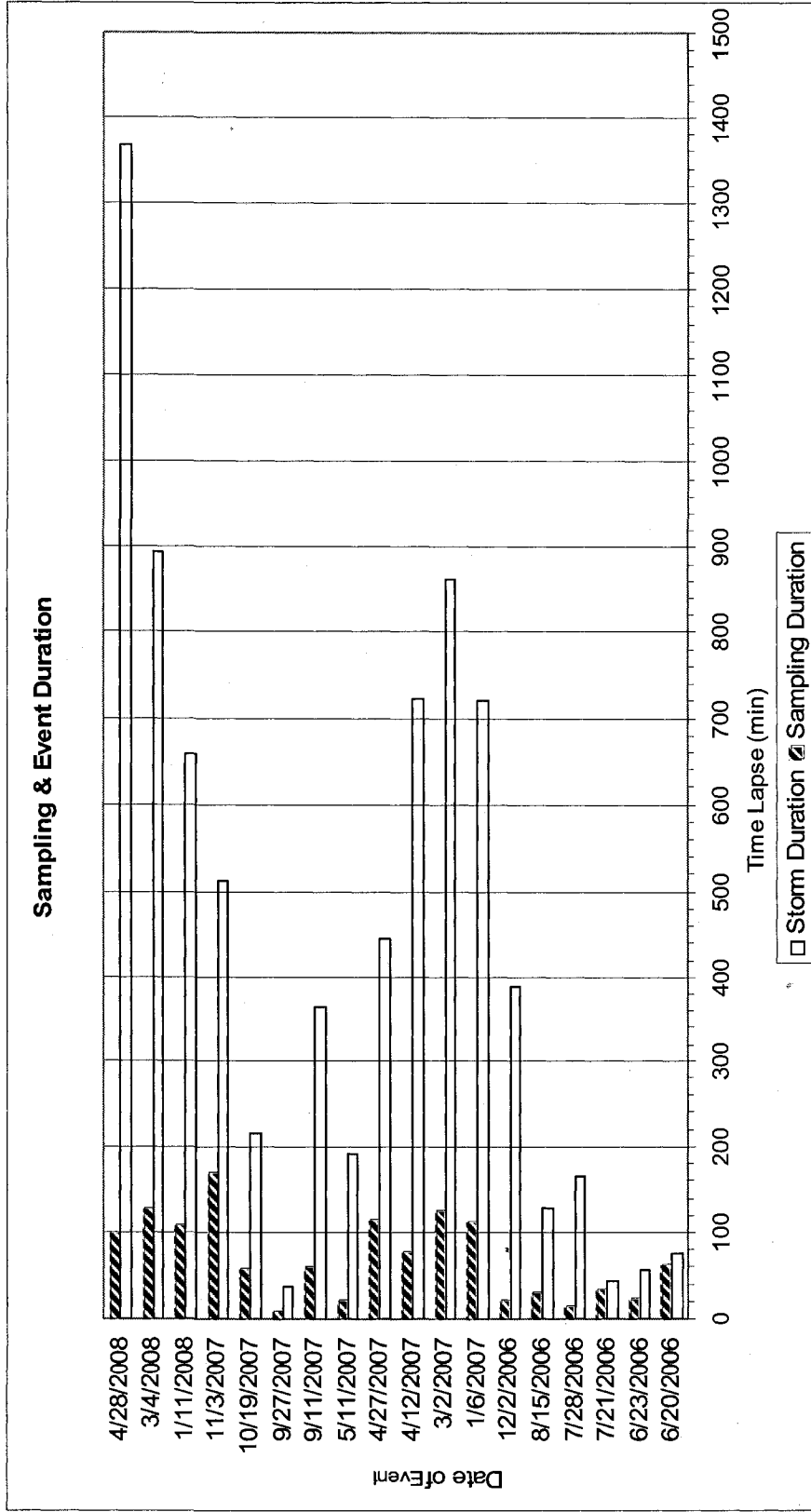


Table B-2: Descriptive Statistics for Pipe Velocity for All Events

	6/20/06	6/23/06	7/21/06	7/28/06	8/15/06	12/01/06	1/06/07	3/02/07	4/12/07	4/27/07	5/11/07	9/11/07	9/27/07	10/19/07	11/03/07	1/11/08	3/4/08	4/28/08	
an	0.26	0.77	1.27	2.41	0.79	1.24	0.54	0.51	0.51	0.54	0.44	0.57	3.38	0.68	0.87	0.10	0.57	0.57	
)																			
lian	0.23	0.95	0.81	2.49	0.79	1.30	0.47	0.55	0.51	0.55	0.40	0.45	3.52	0.69	0.82	0.09	0.57	0.43	
)																			
.	0.16	0.41	1.01	0.32	0.16	0.26	0.17	0.08	0.18	0.06	0.25	0.20	1.01	0.70	0.14	0.07	0.04	0.22	
.)																			
.)	0.68	1.23	3.79	2.73	1.05	1.50	1.00	0.59	0.88	0.68	0.76	1.01	4.31	0.70	1.17	0.54	0.75	1.01	
)																			
)	0.08	0.08	0.49	1.52	0.48	0.45	0.34	0.32	0.28	0.45	0.06	0.35	1.58	0.71	0.59	0.04	0.46	0.28	

Figure B-5: Polytographs for All Events

Figure B-5a: 6/20/06

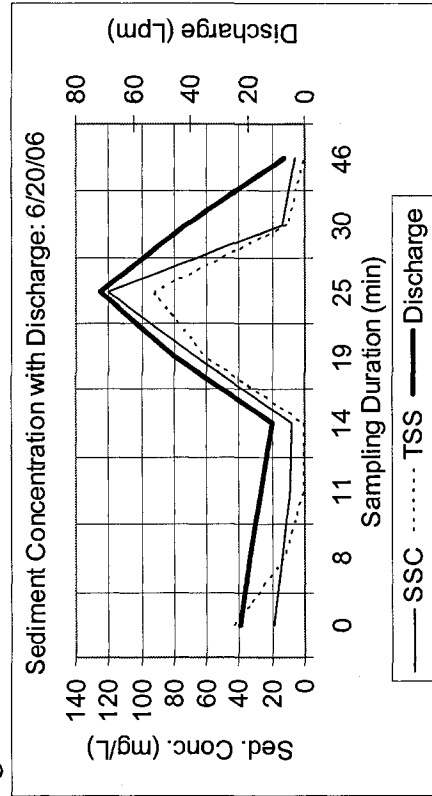


Figure B-5b: 6/23/06

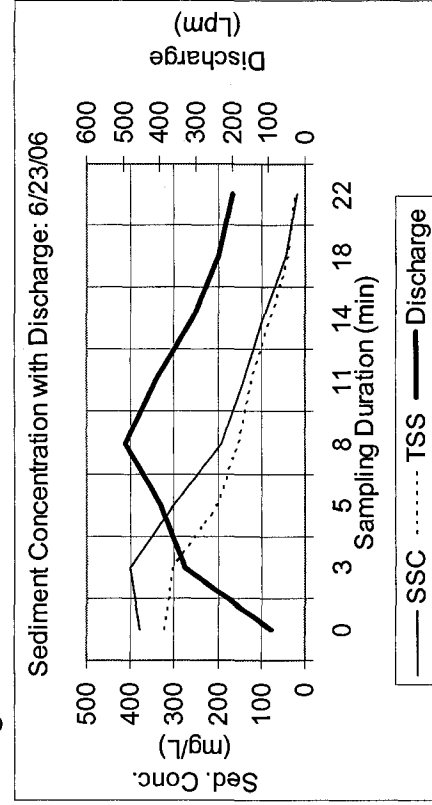


Figure B-5c: 7/21/06

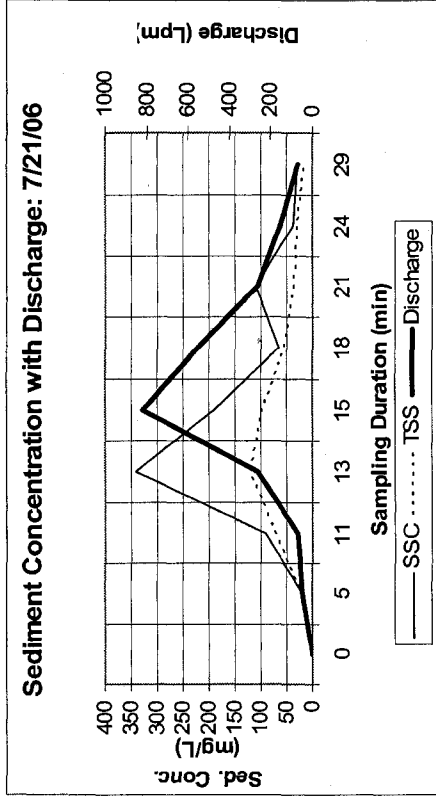


Figure B-5d: 7/28/06

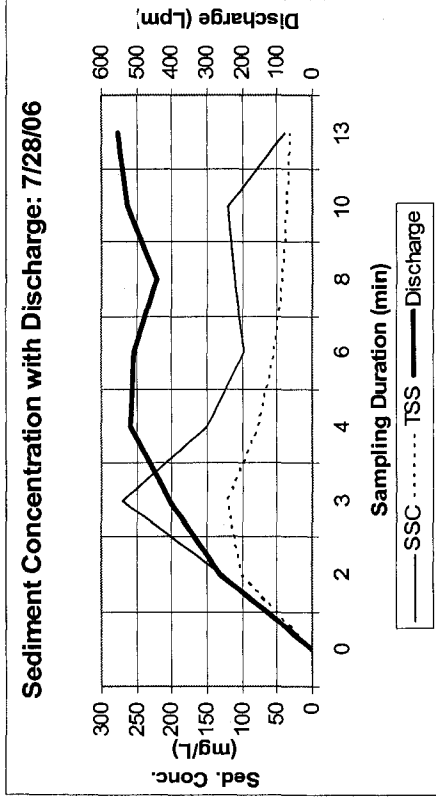


Figure B-5e: 8/15/06

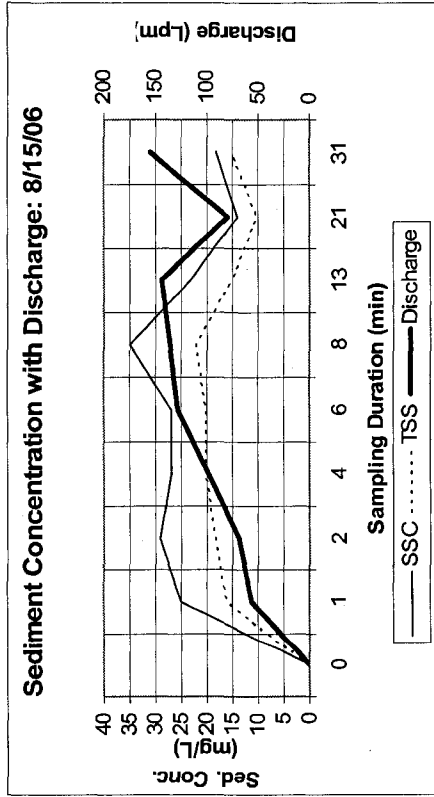


Figure B-5f: 12/01/06

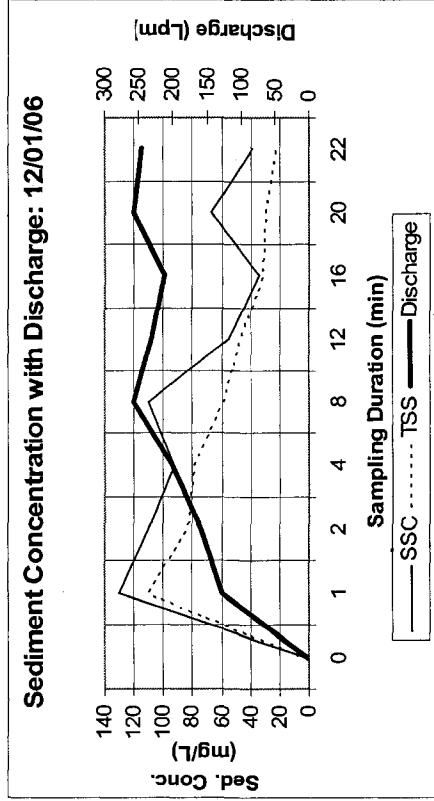


Figure B-5g: 1/06/07

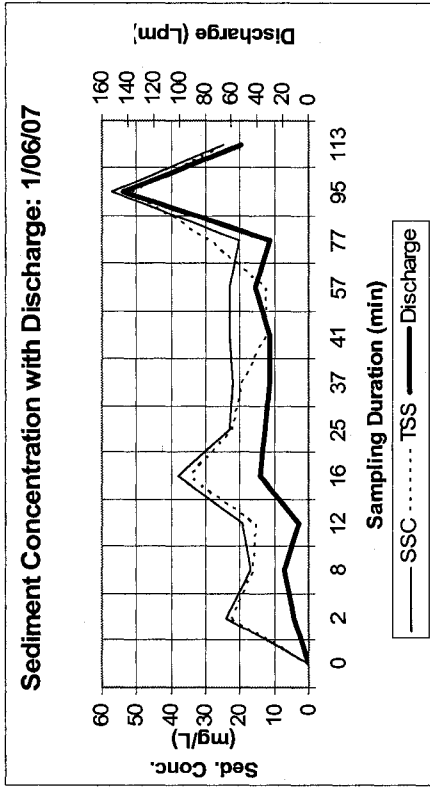


Figure B-5h: 3/02/07

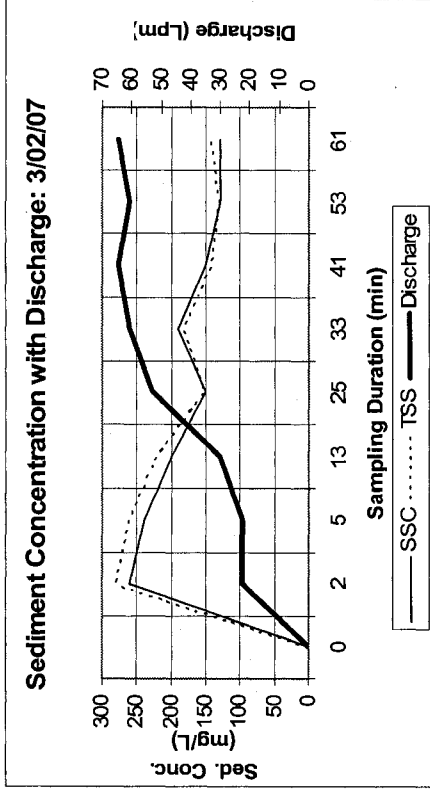


Figure B-5i: 4/12/07

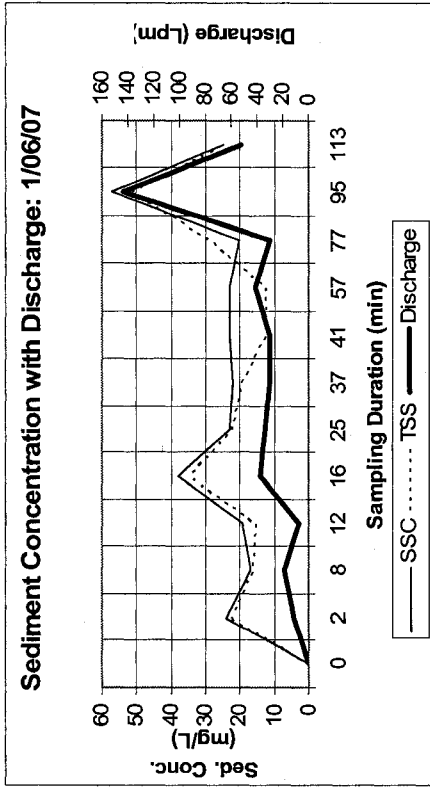


Figure B-5j: 4/27/07

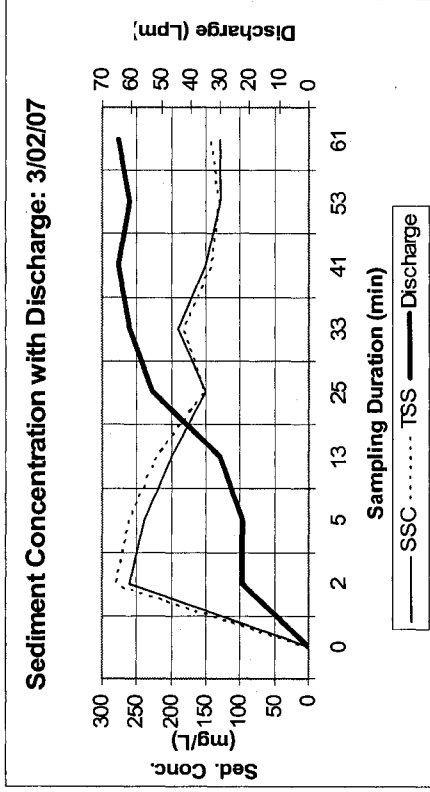


Figure B-5k: 5/11/07

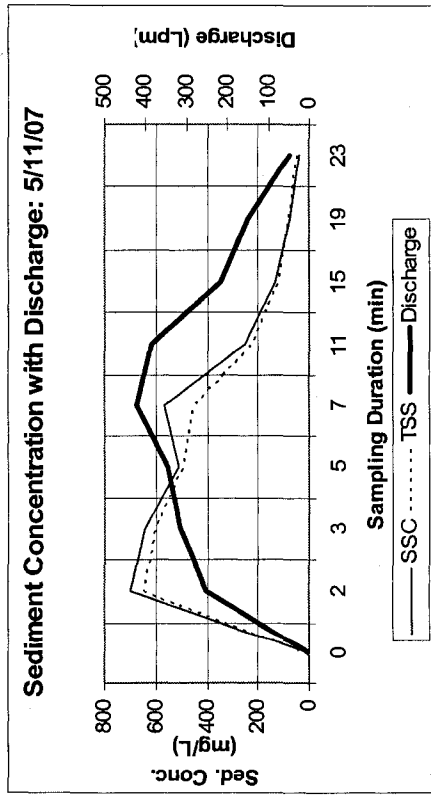


Figure B-5l: 9/11/07

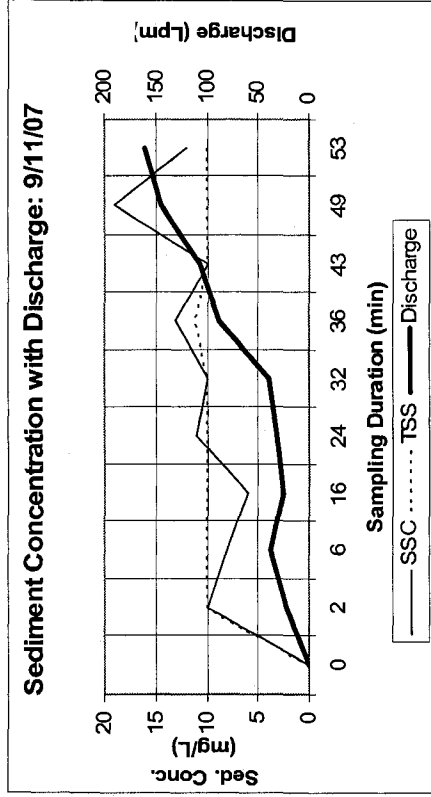


Figure B-5m: 9/27/07

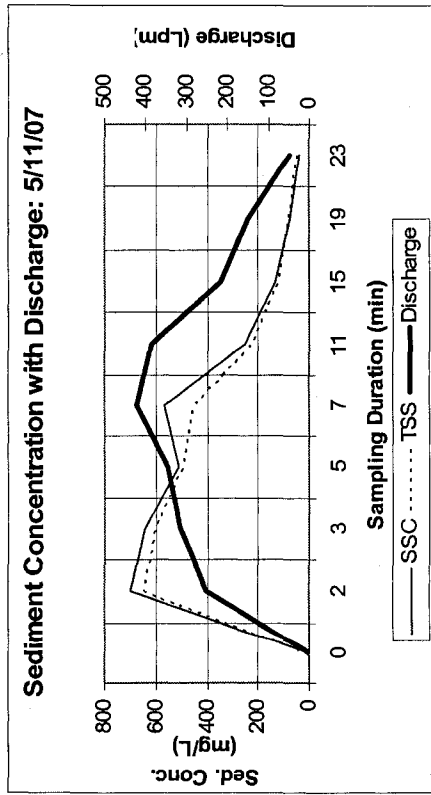


Figure B-5n: 10/19/07

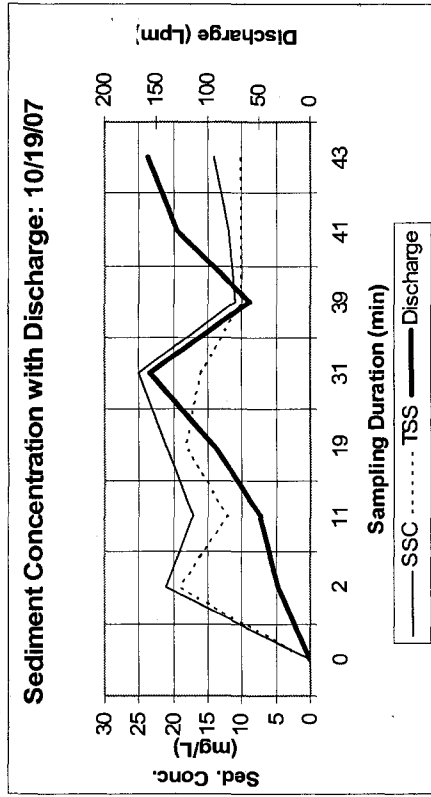


Figure B-5k: 5/11/07

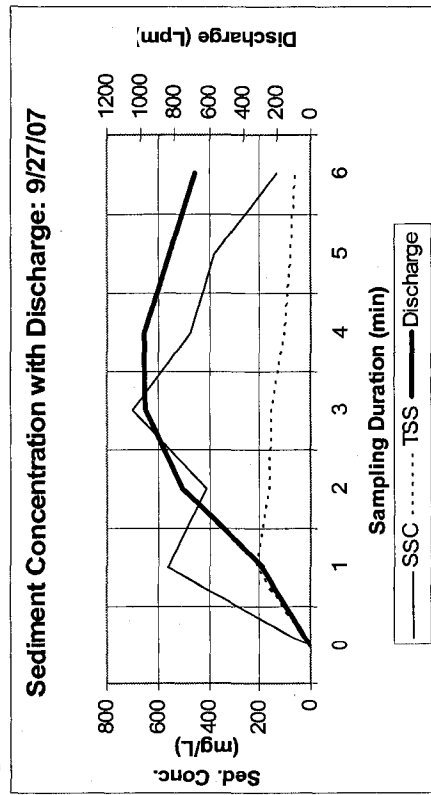


Figure B-5o: 11/03/07

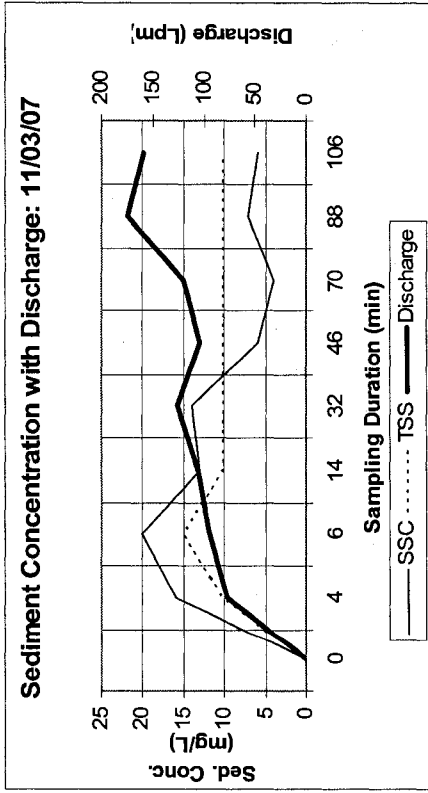


Figure B-5p: 1/11/08

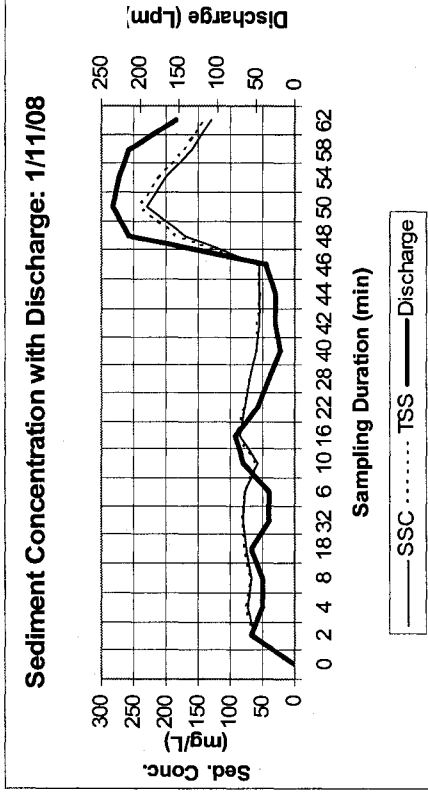


Figure B-5q: 3/04/08

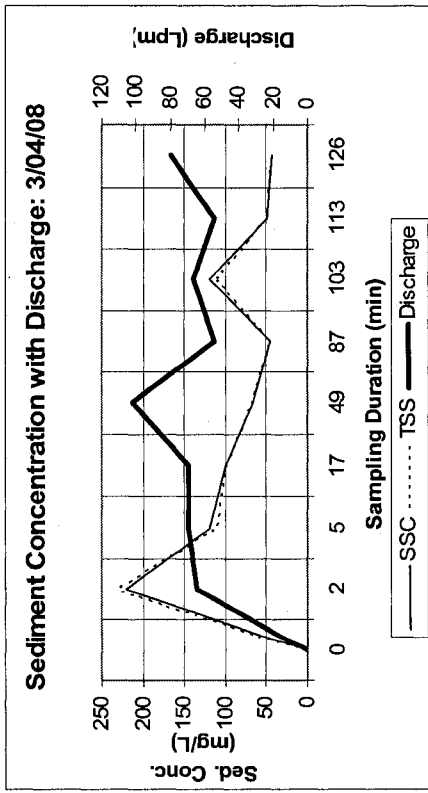


Figure B-5r: 4/28/08

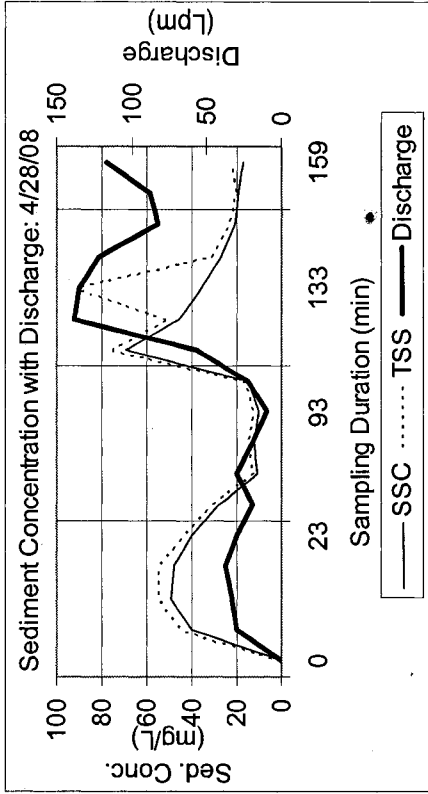


Figure B-6: Summary of Plot of All SSC & TSS Sample Data

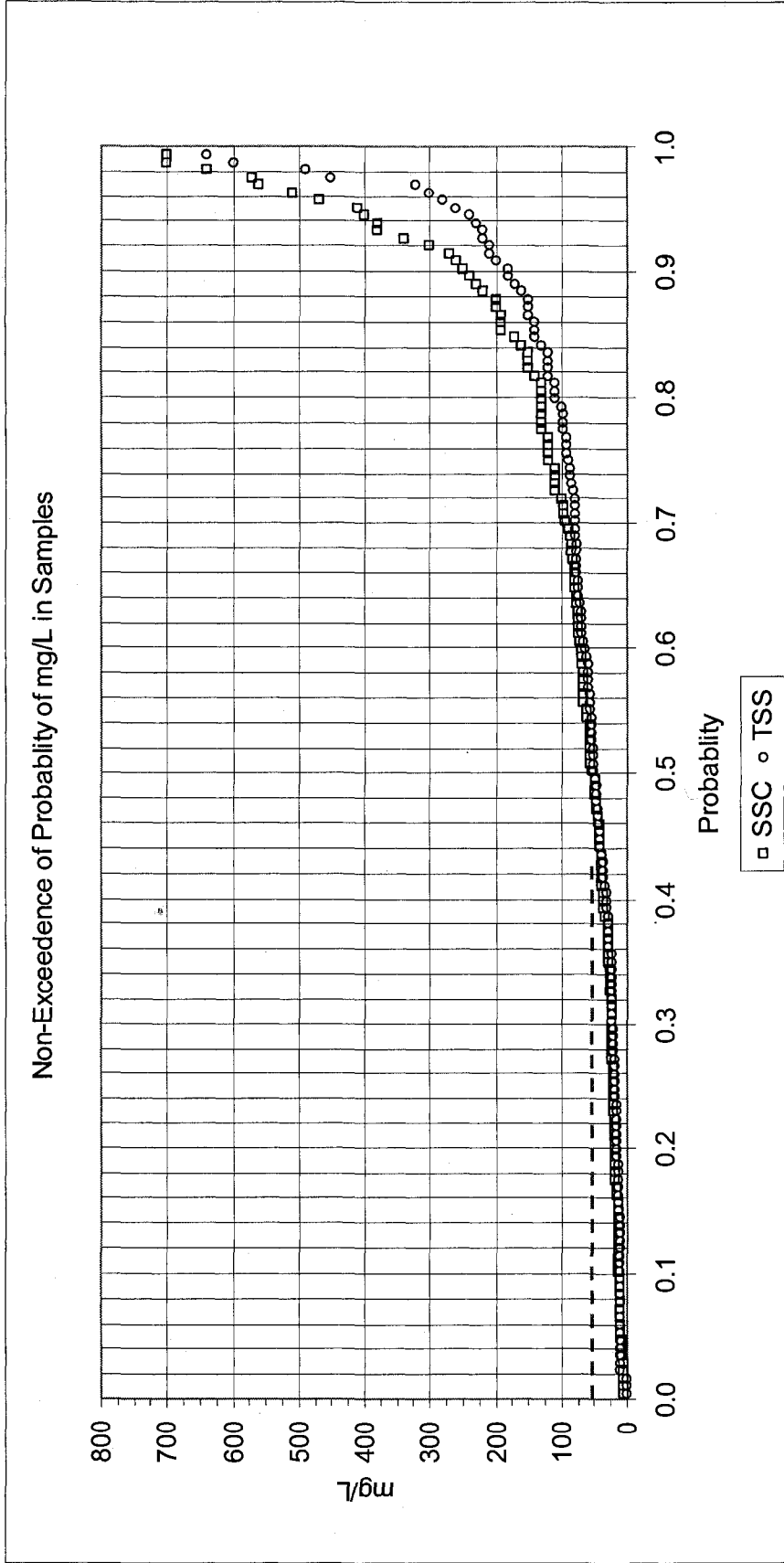
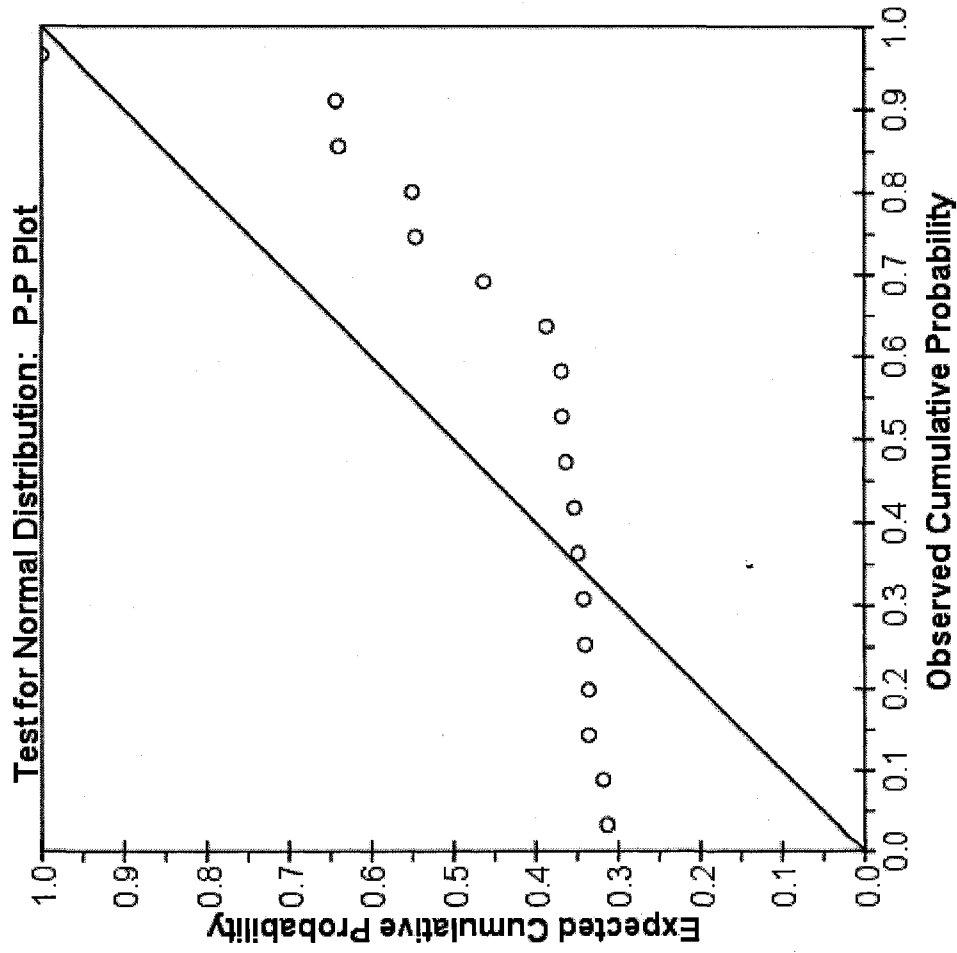


Figure B-7: Test for Normal Distribution between SSC and TSS EMCs





### Appendix C: Figures & Tables for Sections 4.3.1-4.3.4

Figure C-1a: Influence of Max Discharge on Total Capture EMC

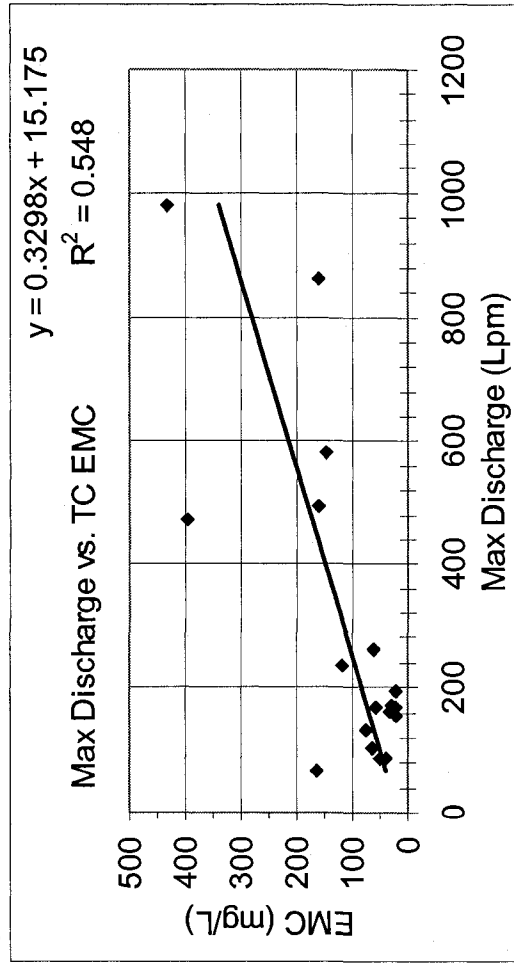


Figure C-1b: Influence of Antecedent Dry Period on Total Capture EMC

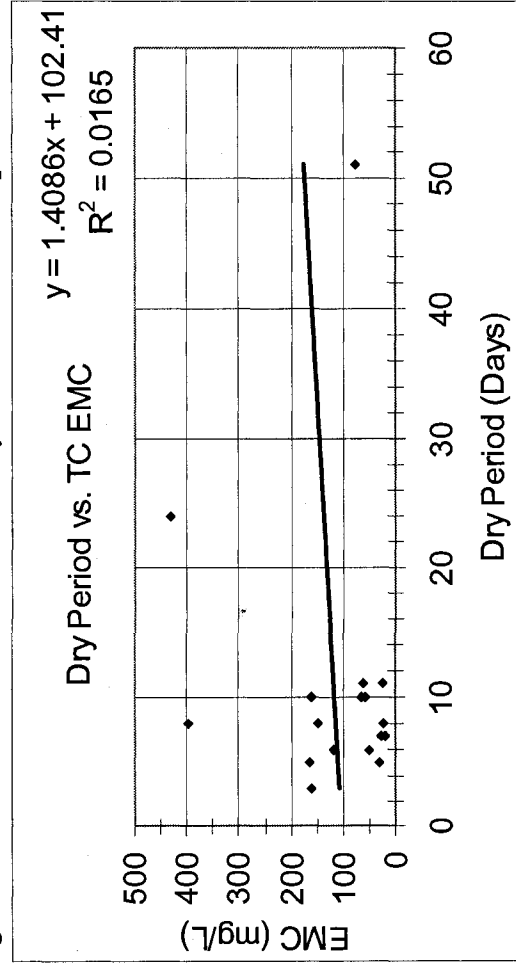


Figure C-1c: Influence of Rainfall Intensity on Total Capture EMC

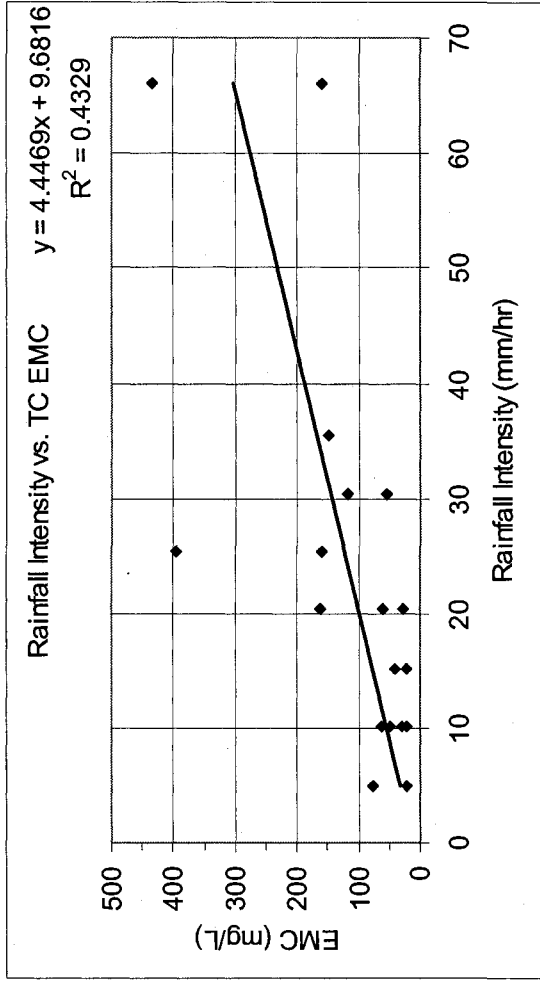


Figure C-2: Non Exceedance Plots for Discharge of Events With a Large SSC & TSS EMC Differences

Figure C-2a: 6/23/06

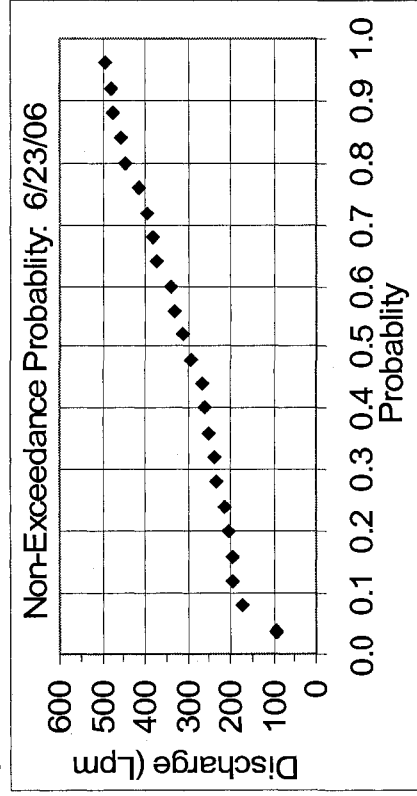


Figure C-2b: 7/21/06

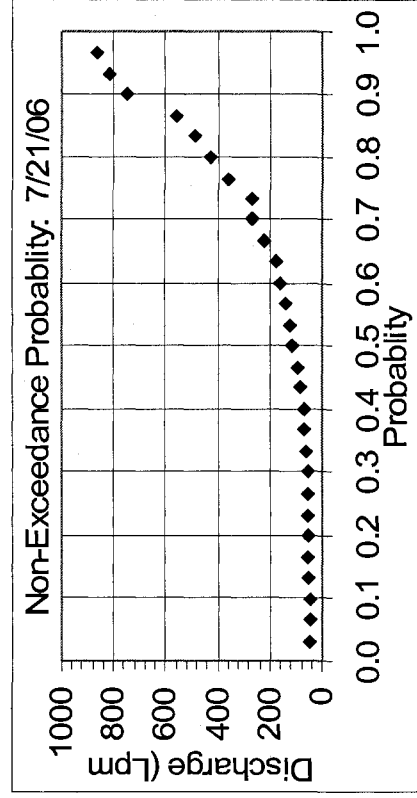


Figure C-2c: 7/28/06

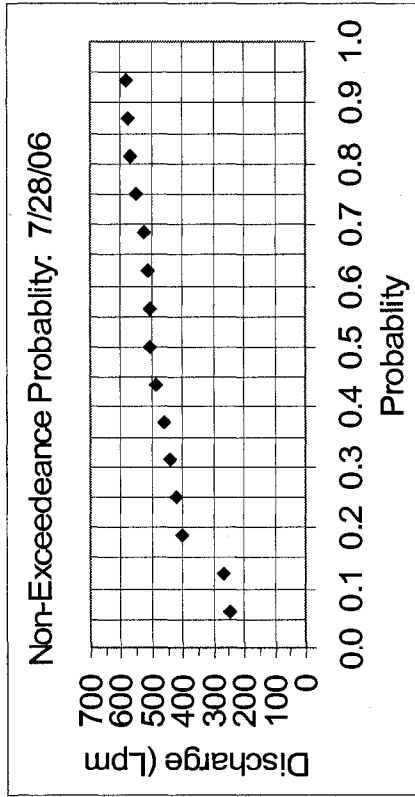


Figure C-2d: 5/11/07

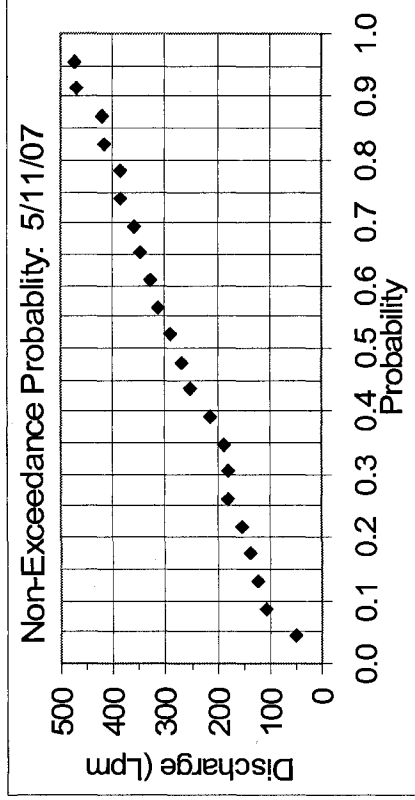


Figure C-2e: 9/27/07

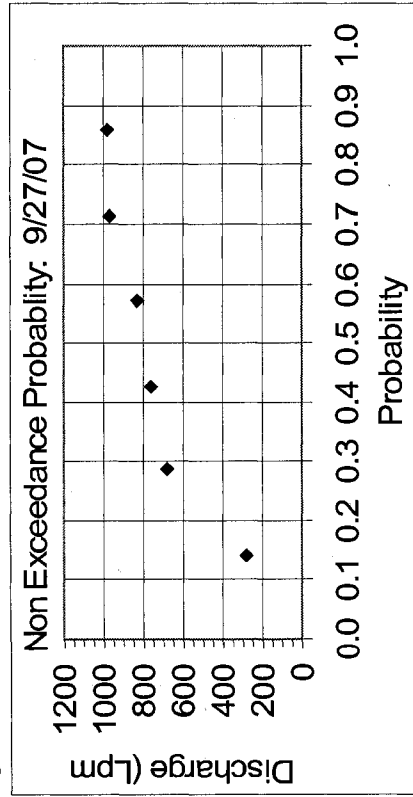


Figure C-3a: Test for Normal Distribution: P-P Plot for EMC (TC-SSC)

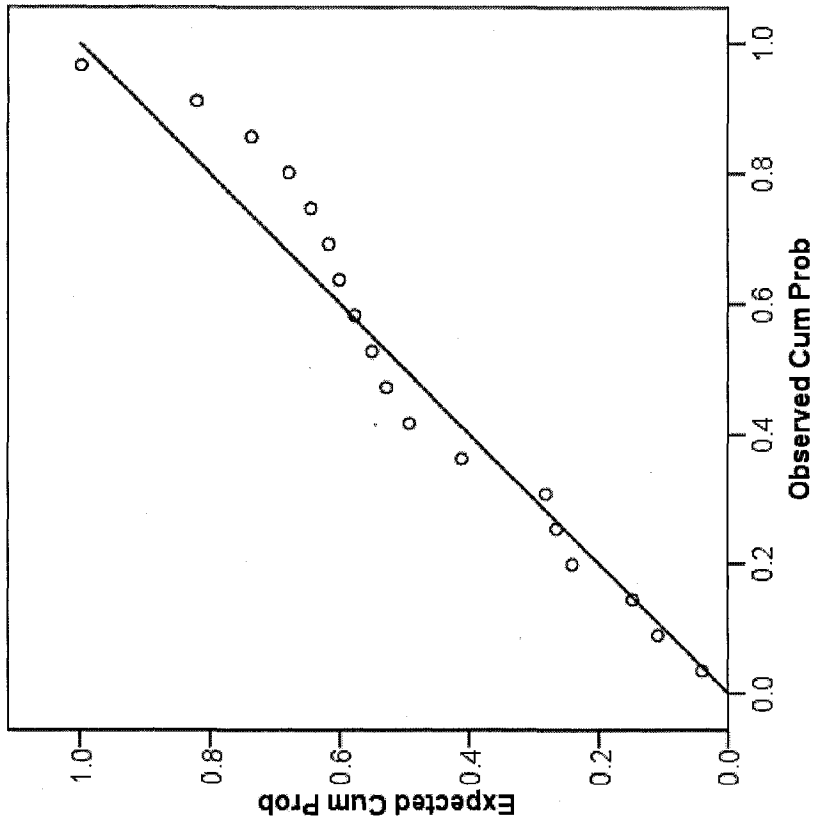


Figure C-3b: Test for Normal Distribution: P-P Plot for EMC (TC-TSS)

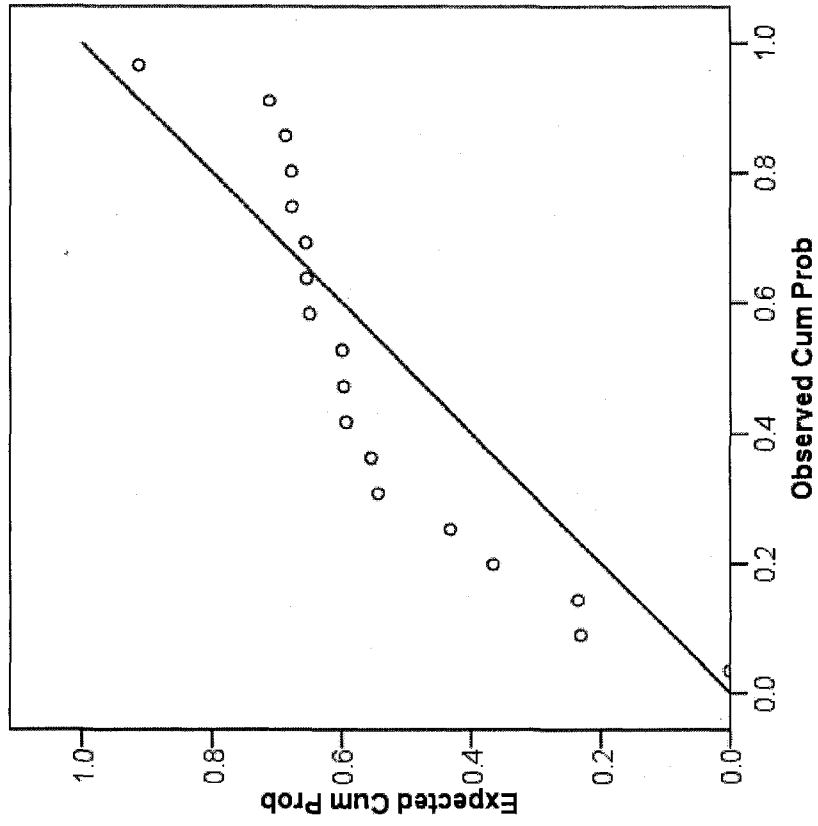


Figure C-3c: Test for Normal Distribution: P-P Plot for EMC (TC-NTU-S)

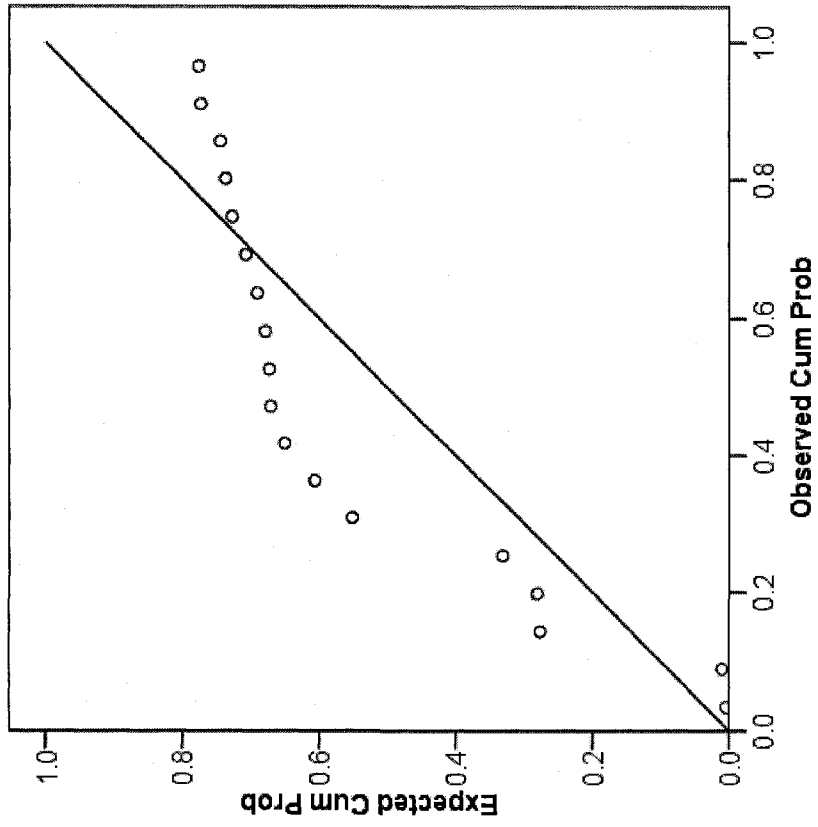
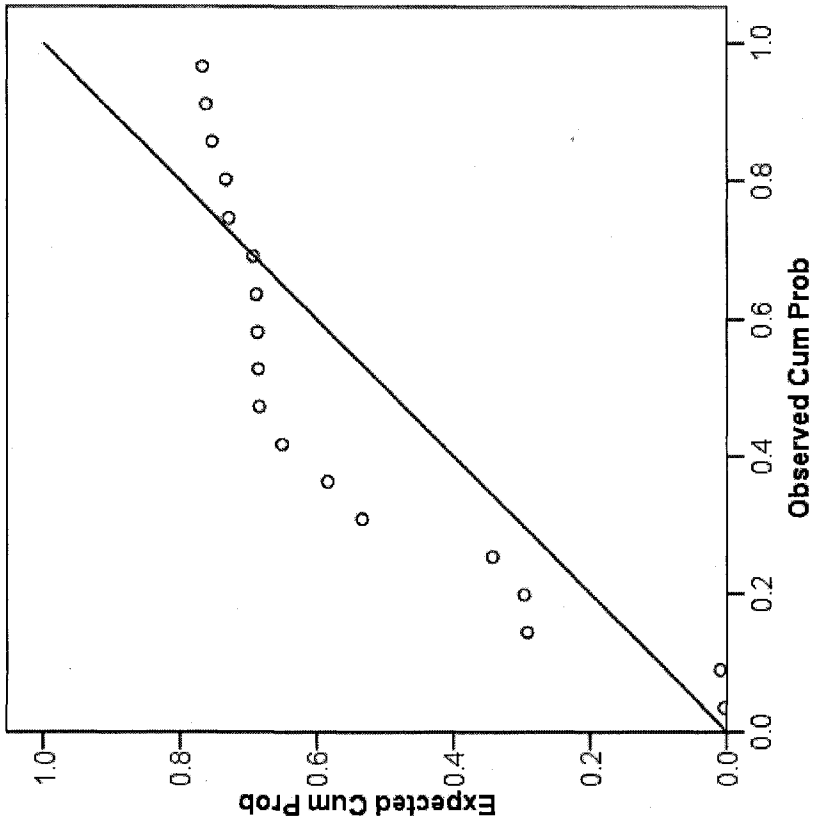


Figure C-3d: Test for Normal Distribution: P-P Plot for EMC (TC-NTU-T)



## Appendix D: Tables & Figures for Sections 4.4.1-4.5

Figure D-1: Particle Size Distribution for All Events

Figure D-1a: 12/1/06

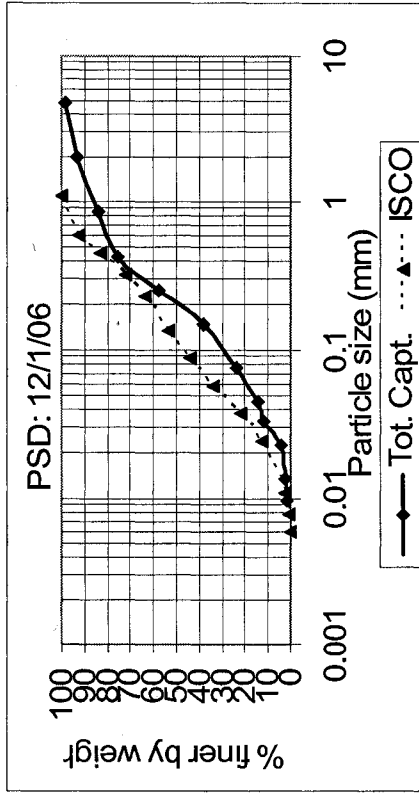


Figure D-1b: 1/6/07

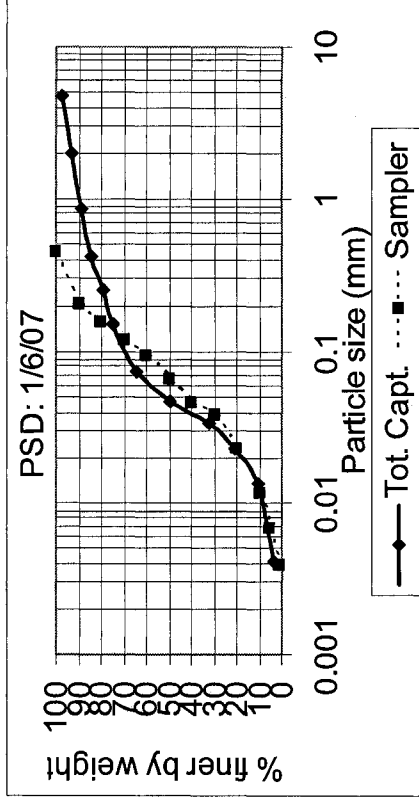


Figure D-1c: 3/2/07

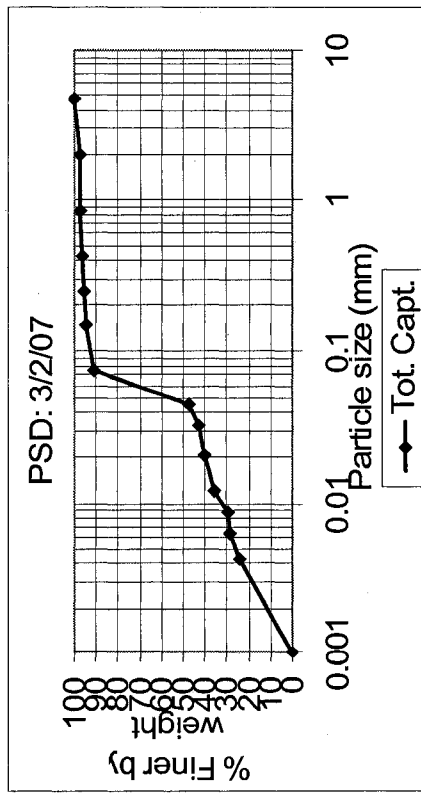


Figure D-1d: 4/12/07

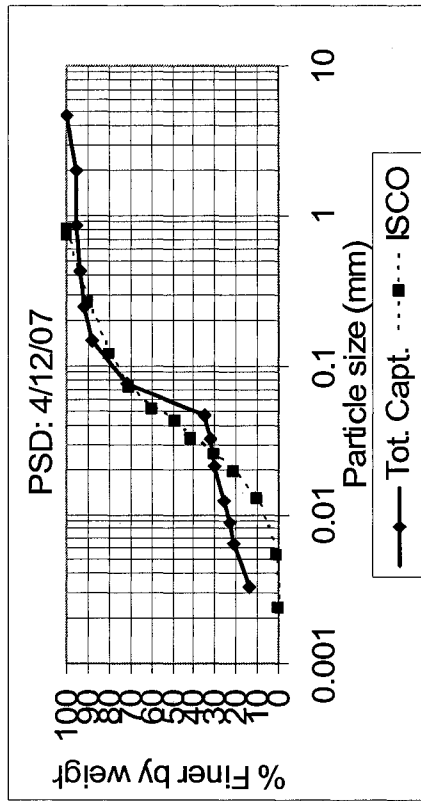




Figure D-1e: 4/27/07

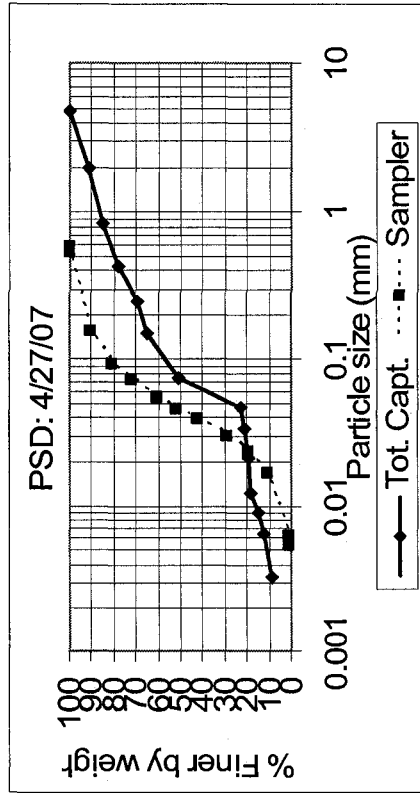


Figure D-1f: 5/11/07

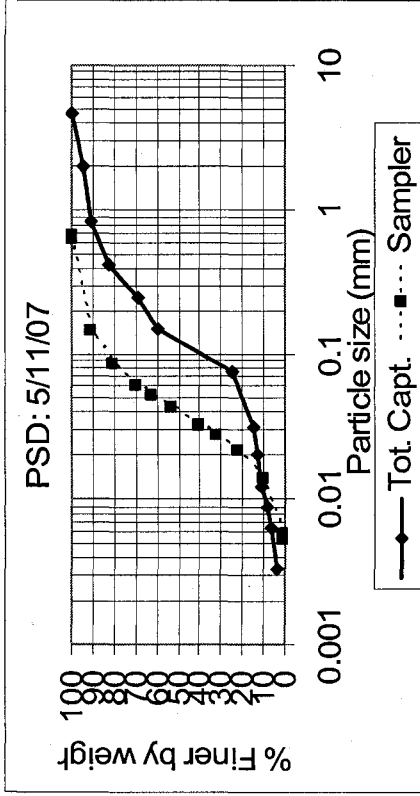


Figure D-1g: 9/11/07

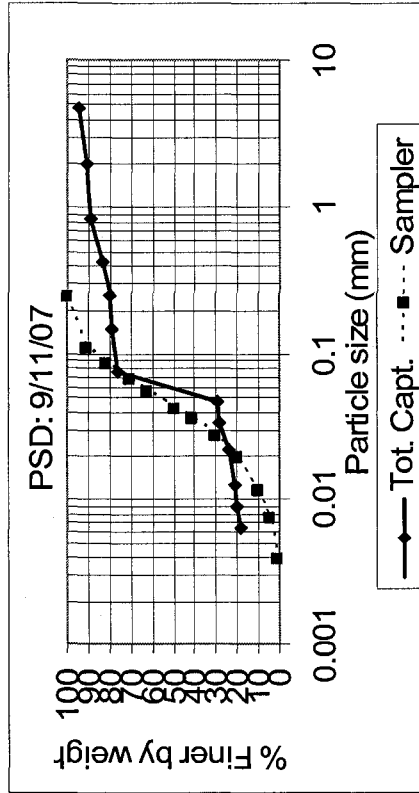


Figure D-1h: 9/27/07

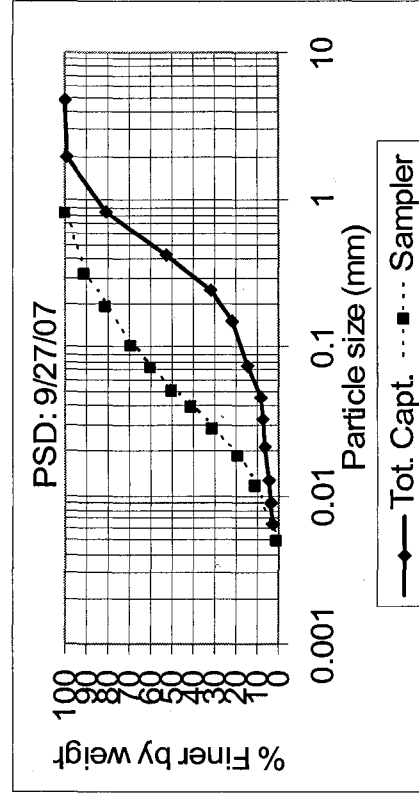


Figure D-1i: 10/19/07

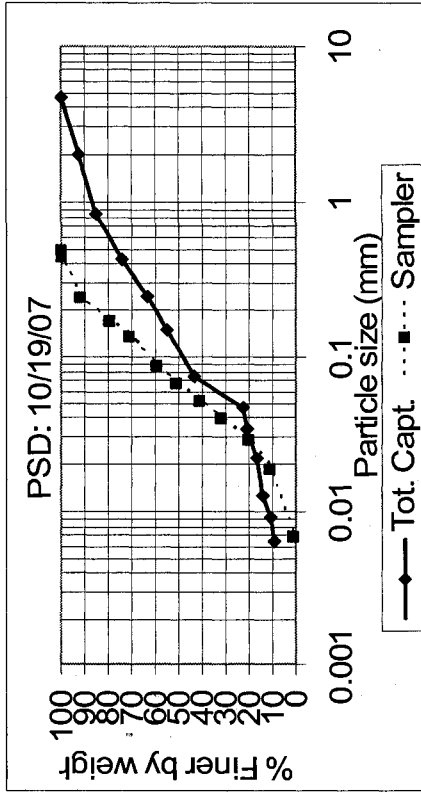


Figure D-1j: 11/03/07

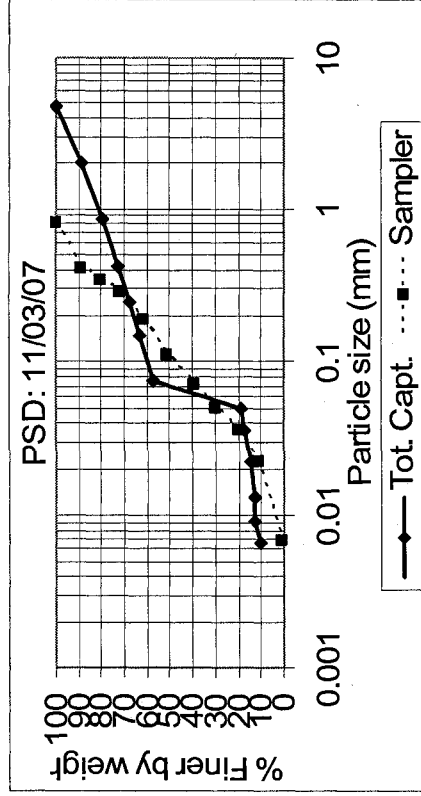


Figure D-1k: 1/11/08

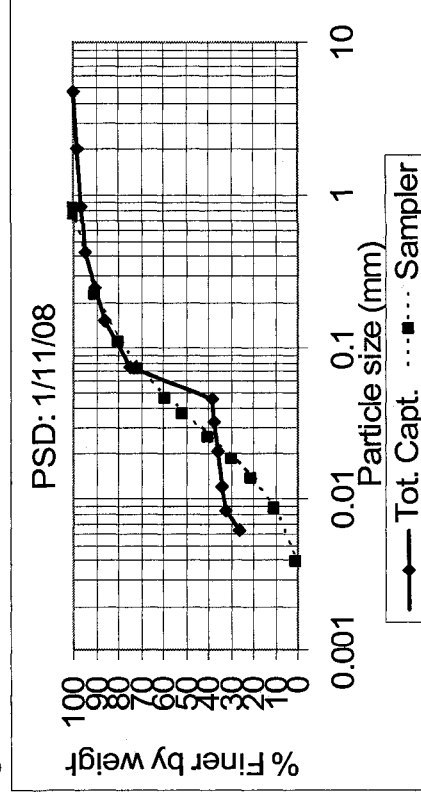


Figure D-1l: 3/04/08

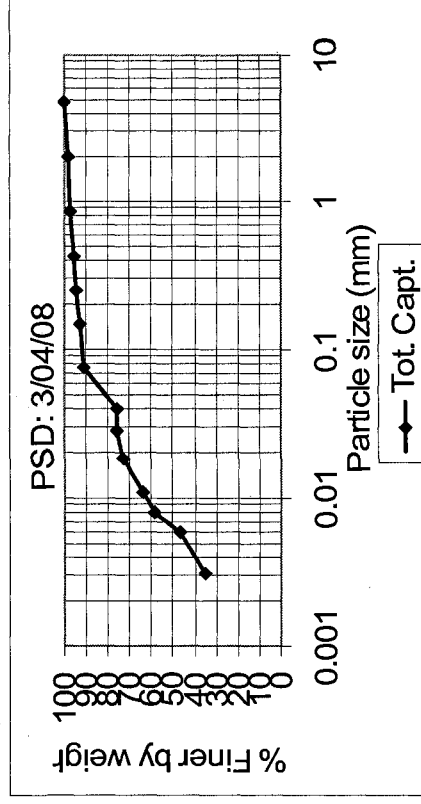


Figure D-1m: 4/28/08

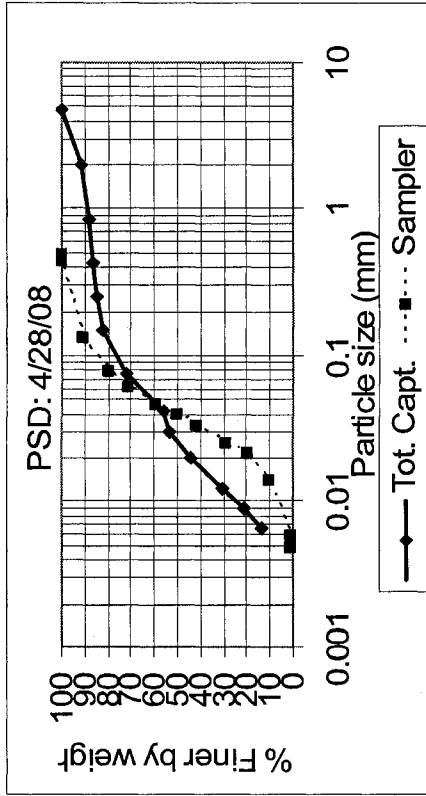


Figure D-2: Particle Size Influence on SSC & TSS EMC Differences

Figure D-2a: D<sub>70</sub>

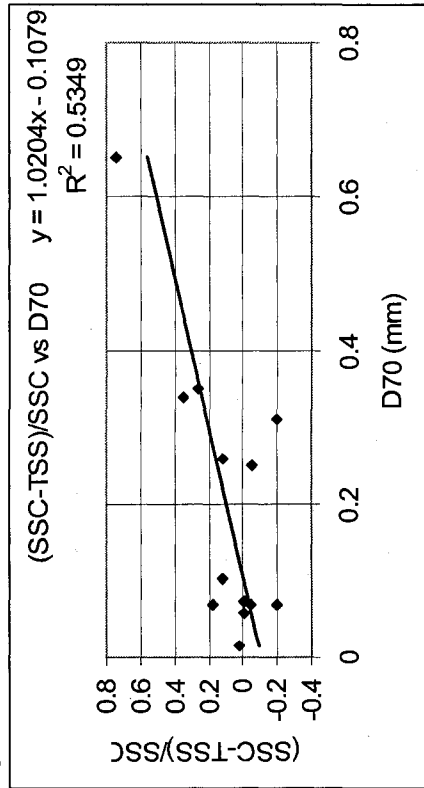


Figure D-2b: D<sub>50</sub>

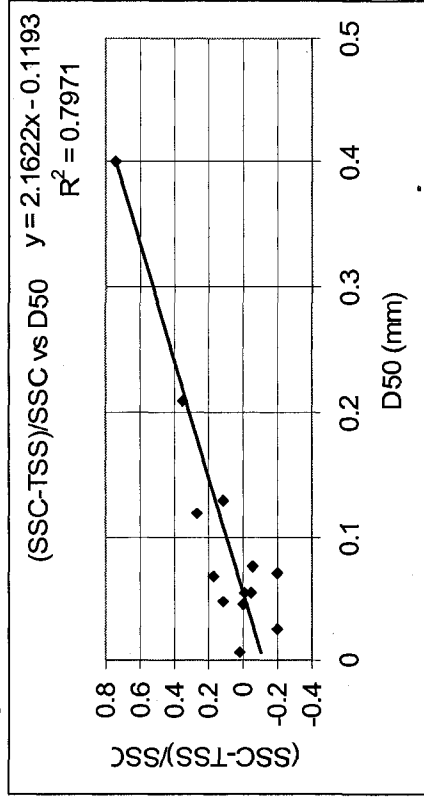


Figure D-2c: D<sub>30</sub>

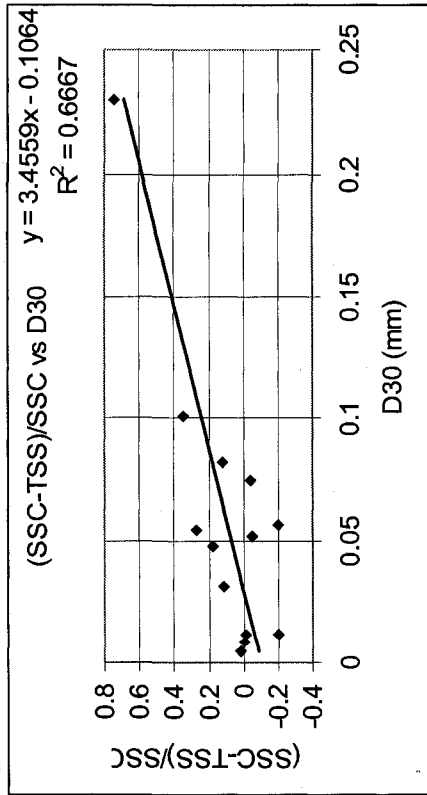


Table D-1: Actual and Monitored Volume and Mass for All Events

Date	AS Volume L	TC Volume L	TC Load kg	SSC-AS Kg	TSS-AS kg	SSC-TC kg	TSS-TC kg
6/20/2006	1433	2700	0.110	0.075	0.061	0.141	0.114
6/23/2006	6938	11300	1.797	1.287	0.989	2.096	1.611
7/21/2006	6424	11700	1.880	0.828	0.424	1.508	0.772
7/28/2006	5626	13380	1.980	0.666	0.307	1.583	0.731
8/15/2006	3754	8117	0.230	0.078	0.058	0.170	0.124
12/2/2006	4513	8285	0.509	0.333	0.217	0.611	0.398
1/6/2007	5702	6382	0.235	0.221	0.196	0.247	0.219
3/2/2007	3001	7031	1.148	0.485	0.486	1.136	1.138
4/12/2007	4842	6714	0.508	0.339	0.342	0.470	0.474
4/27/2007	6224	8443	0.417	0.195	0.205	0.264	0.278
5/11/2007	5912	9901	3.912	2.186	1.927	3.661	3.228
9/11/2007	3265	6836	0.383	0.040	0.033	0.084	0.069
9/27/2007	4163	8444	3.655	1.969	0.505	3.993	1.023
10/19/2007	3795	9481	0.214	0.078	0.057	0.195	0.143
11/3/2007	13146	9373	0.196	0.112	0.134	0.080	0.095
1/11/2008	6520	7404	0.876	0.816	0.853	0.926	0.969
3/4/2008	9151	8918	0.573	0.642	0.631	0.626	0.615
4/28/2008	8149	10770	0.337	0.281	0.337	0.372	0.446

Figure D-3a: Regression Models for Maximum Discharge and D<sub>70</sub>

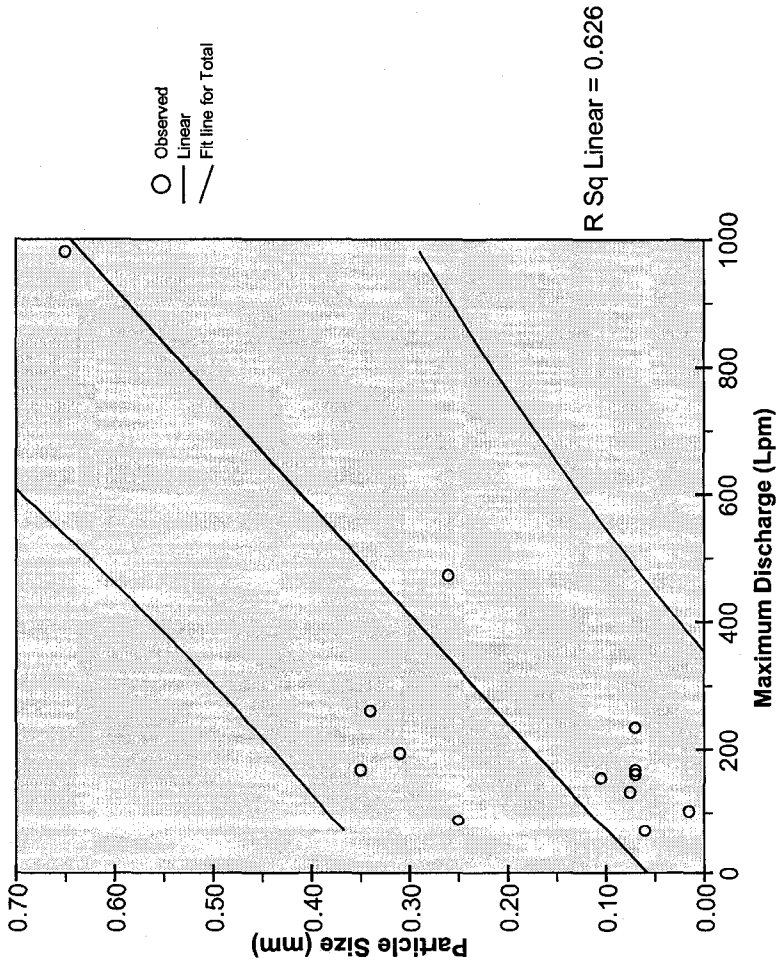


Figure D-3b: Regression Models for Maximum Discharge and  $D_{50}$

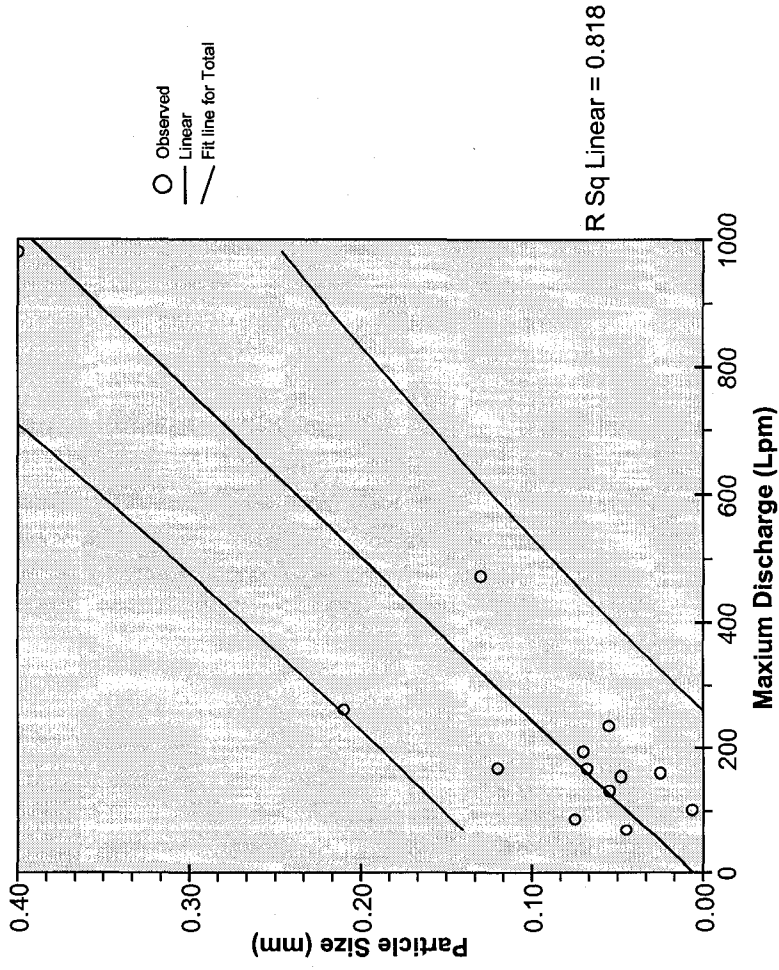


Figure D-4: Adjusted TC PSDs with Decanted Sediments

Figure D-4a: 12/01.06

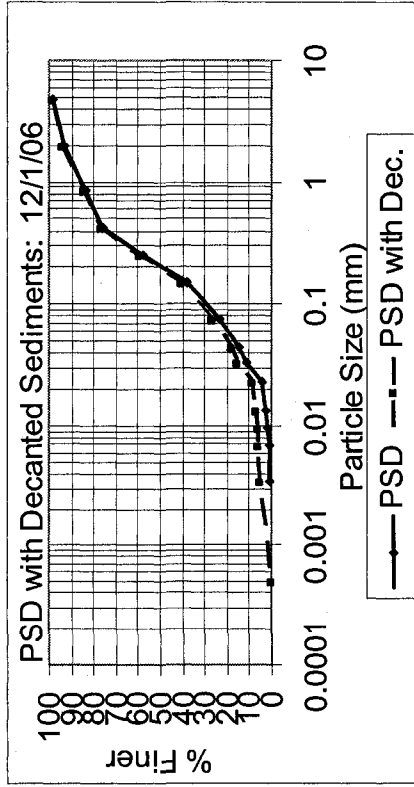


Figure D-4b: 1/6/07

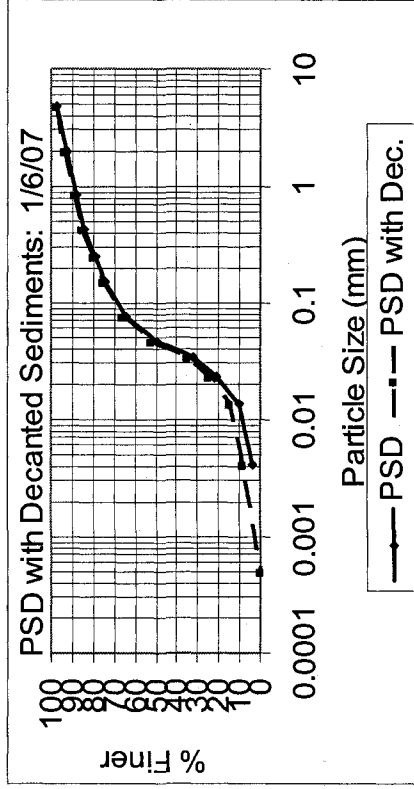


Figure D-4c: 4/12/07

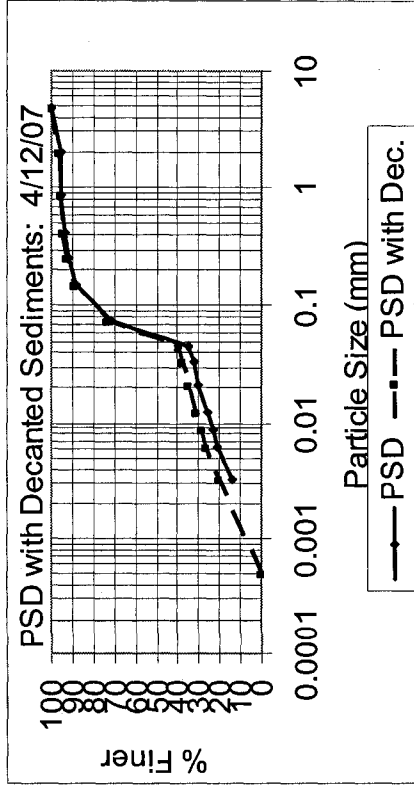


Figure D-4d: 4/27/07

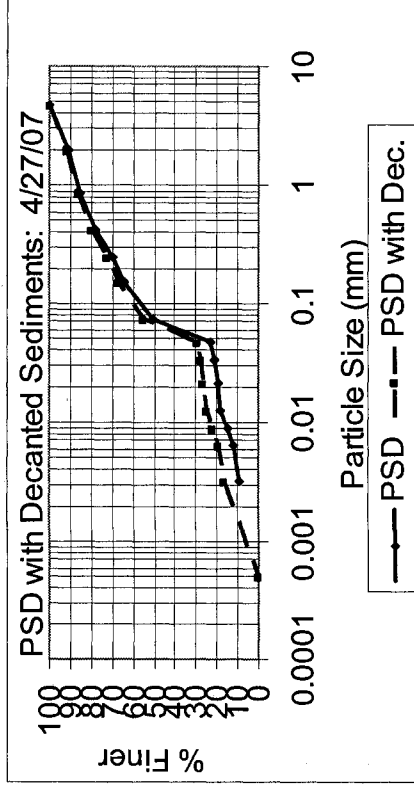




Figure D-4e: 5/11/07

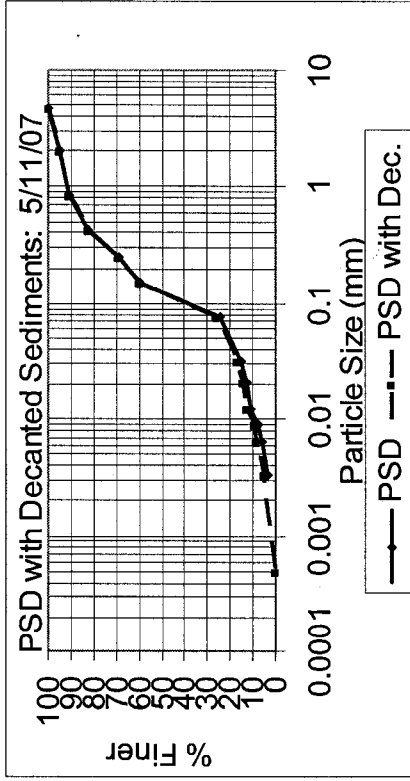


Figure D-4f: 9/11/07

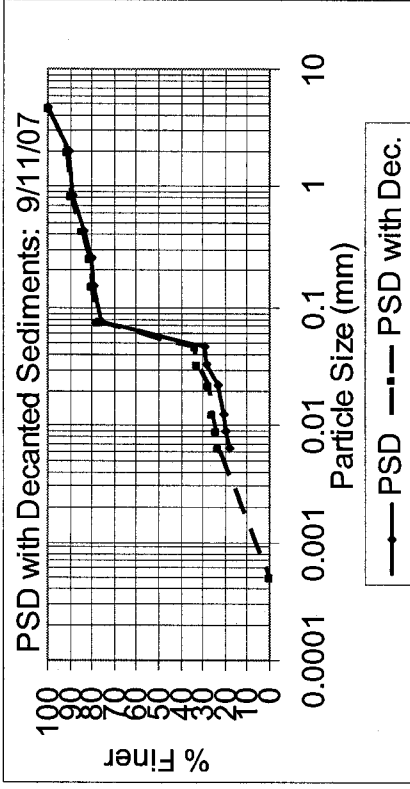


Figure D-4g: 9/27/07

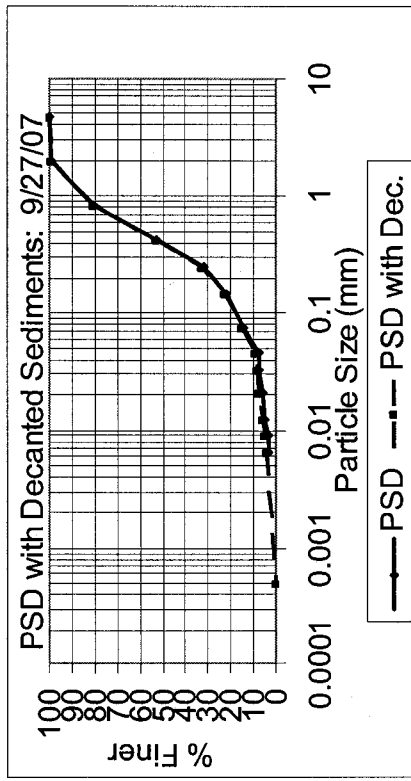


Figure D-4h: 10/19/07

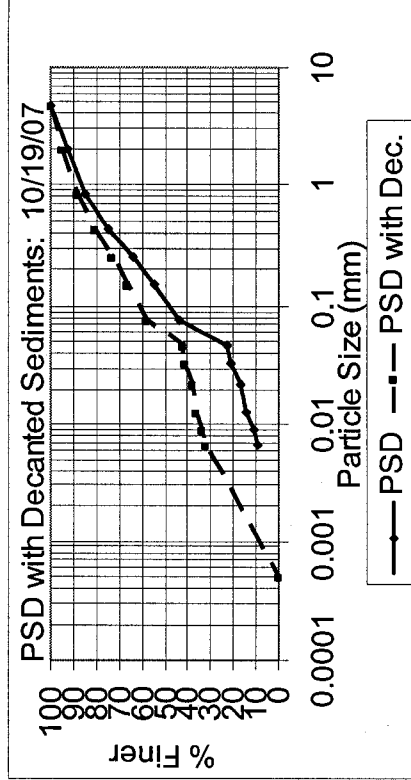


Figure D-4i: 11/03/07

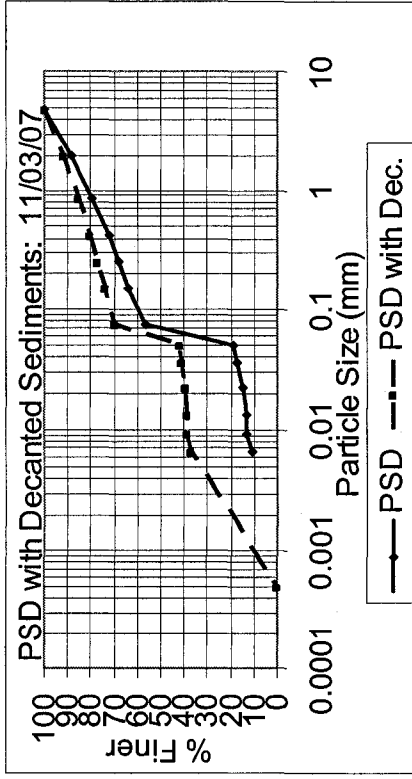


Figure D-4j: 1/11/08

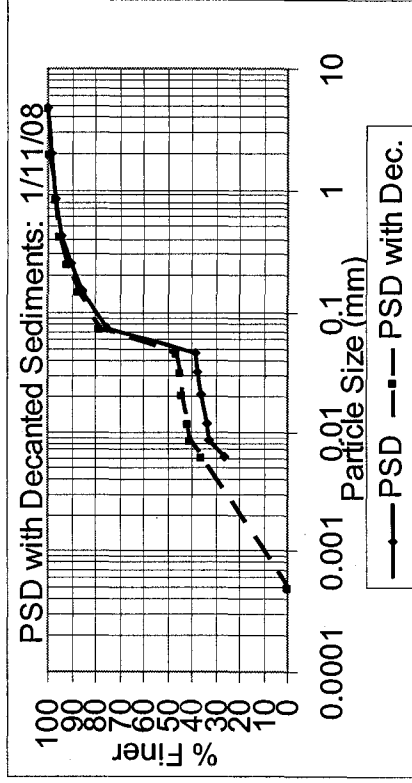
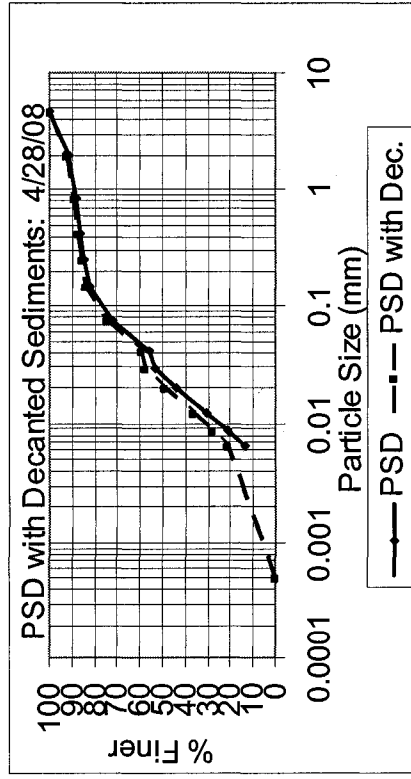


Figure D-4k: 4/28/08



**Appendix E: Figures & Tables for 4.7.1-4.7.2**

Figure E-1a: Particle Size Distribution Methodology Comparison: 12/01/06

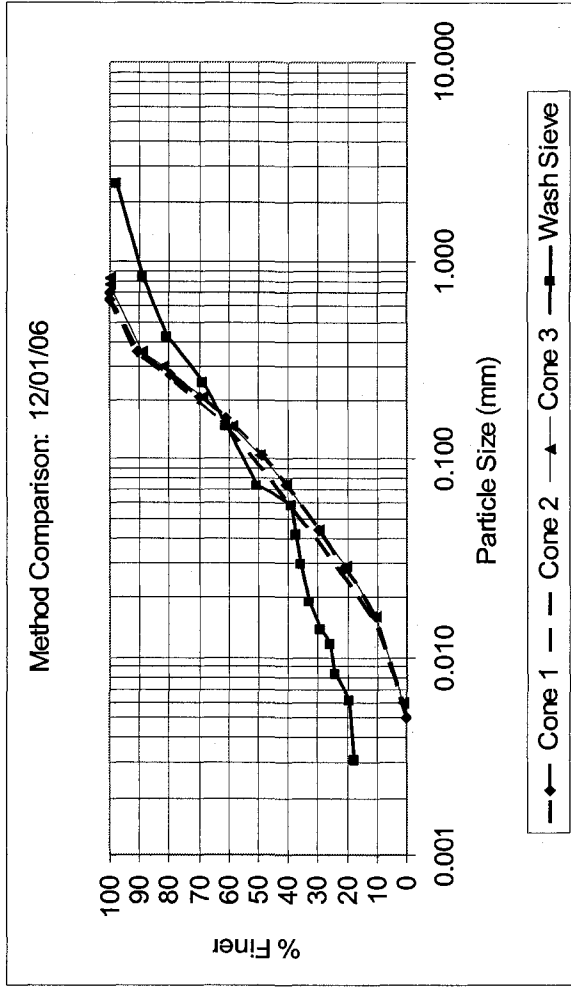


Figure E-1b: Particle Size Distribution Methodology Comparison: 5/11/06

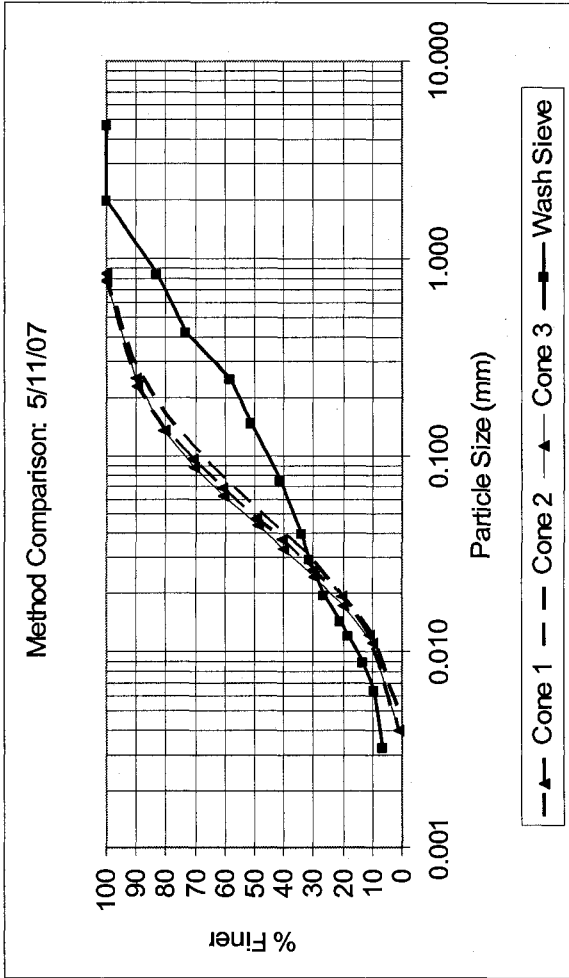


Figure E-1c: Particle Size Distribution Methodology Comparison: 9/27/07

