Exfiltration Trenches for Post Construction Storm Water Management for Linear
Transportation Projects: Field Study of Suspended Materials

A thesis presented to
the faculty of
the Russ College of Engineering and Technology of Ohio University

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Master of Science

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This thesis titled
Exfiltration Trenches for Post Construction Storm Water Management for Linear
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by

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ABSTRACT

HUSAM A. ABU HAJAR, M.S., March 2012, Civil Engineering

Exfiltration Trenches for Post Construction Storm Water Management for Linear Transportation Projects: Field Study of Suspended Materials

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Highway storm water runoff contributes to the degradation of surface water quality in the United States. The most important pollutant in highway runoff is the total suspended solids (TSS). The United States Environmental Protection Agency (U.S.EPA) requires the runoff to be treated before it is conveyed to surface water. The exfiltration trench is one of the best management practices (BMP’s) utilized by the Ohio Department of Transportation (ODOT) to treat highway runoff in-situ and consists of three layers: pervious concrete, type 3 backfill material (aggregate) and type 2 backfill material (sand). In this study, the exfiltration trench located on SR7, OH, is evaluated based on the pollutants’ removal efficiency, particularly, TSS. TSS was removed at an efficiency of 41% in the originally constructed trench while the reconstructed trench achieved 69% TSS removal. Other water quality parameters investigated in this study include particle size analysis, turbidity and pH which were performed on both influent (highway runoff) and effluent (treated influent) samples.

Approved: _____________________________________________________________

Gayle F. Mitchell

Neil D. Thomas Professor of Civil Engineering
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CHAPTER 1: INTRODUCTION

1.1. Urbanization Impact on Highway Storm Water Runoff

Highway storm water runoff is the flow produced from rainfall or snowmelt events over impervious surfaces such as the paved streets. As a result of urbanization, the quality and quantity of highway storm water runoff have been adversely affected. The quality impact is observed by the elevated amounts of pollutants transported within the runoff; because as the runoff flows over an impervious surface (e.g., paved streets, parking lots, and building rooftops), it accumulates debris, chemicals, sediments or other pollutants that impose negative impacts on the receiving water quality if the runoff is discharged untreated. The sources of pollution vary, but the main source is the vehicular activities which directly and indirectly contribute to highway runoff pollution. Another important source is the construction activities byproducts that are transported within the runoff such as highway maintenance and the construction in areas adjacent to highways which contribute to more suspended solids transported within the runoff.

These two major sources (vehicular and construction activities) are directly related to urbanization; therefore, the impacts of highway runoff in urban areas are more obvious than rural areas. Other sources of pollution include atmospheric depositions and dustfall.

On the other side, the quantity (hydrological) impact results from the increased peak flow because new impervious surfaces for flow are created as a result of urbanization; therefore, reducing the amount of infiltration through the ground. Increased
flow discharges might also contribute to the erosion of stream banks; thus, generating more solids and pollutants introduced to the runoff.

1.2. Major Pollutants in the Highway Runoff

As mentioned previously, highway storm water runoff washes a variety of pollutants from the surface of the road. The major pollutants transported within the runoff include total suspended solids (TSS); nutrients; heavy metals; organic compounds; oil and grease and pathogenic and nonpathogenic microorganisms. Many studies have demonstrated the importance of TSS as a water quality parameter, because TSS is responsible for the transport of other pollutants such as metals and nutrients which are adsorbed to the surface of suspended solids (USEPA, 2004). TSS also affects the organisms of the receiving aquatic systems by reducing photosynthesis and direct impact on organisms’ bodies (Barrett et al., 1995). Therefore; most of the research conducted on this topic focused on TSS and set the target for treatment based on the TSS removal efficiencies.

1.3. Receiving Water Systems

The majority of storm water produces highway runoff. Some portions of the highway runoff infiltrates through the ground. Other portion is removed via evaporation, while most of the runoff is transported and discharged to the receiving water bodies such as streams, rivers, lakes and wetlands. Environmental impacts of highway runoff are determined based on the characteristics of the receiving water body such as the size and the biological diversity, size of the drainage area and the pollutants potential for dispersion. However, no acute toxicity has been reported in the receiving water bodies;
yet, higher concentrations of metals were detected in organisms living near the highways (Barrett et al., 1995). Metals were also found to be bioaccumulating in the streams and lakes’ sediments (Barrett et al., 1995). Highway runoff also affects the groundwater. It has been reported that elevated concentrations of metals, nitrogen and organics have been detected in groundwater in areas of highway runoff control structures (Barrett et al., 1995).

1.4. Mitigation of Highway Runoff Impacts

Urban highway storm water runoff has been addressed by the U.S. Environmental Protection Agency (EPA) as nonpoint source pollution. Therefore; many regulations have been enacted to mitigate the negative impacts of this pollution such as the Clean Water Act (CWA) and the National Pollutant Discharge Elimination System (NPDES) (USEPA, 2004).

Controlling the highway storm water runoff pollution can be achieved by source and treatment controls. Particulate matter and the adsorbed pollutants are the majority of pollution in the highway runoff; therefore, removing the particulate matter from the runoff by settling or filtration is the most efficient way for treating the runoff.

Treatment control can be achieved by effective transportation and land use planning to reduce the amount of pollutants emitted to the surface of the highway. For example, minimizing pesticides and fertilizers use will reduce the amount of organic compounds introduced to the runoff. Street sweeping proved efficient in removing the large particles (Barrett et al., 1995).
Treatment control can be achieved via the use of Best Management Practices (BMP’s). Storm water best management practices were introduced in the 1960’s. In the beginning, the BMP’s aimed at controlling the quantity of highway runoff. Recently, BMPs were further employed to control the quality of the runoff by removing the contaminants.

BMP’s can remove pollutants from the runoff via settling, sorption, filtration, and phytoremediation. The most popular BMP’s utilized are (ODOT, 2011c; USEPA, 2004):

- Bioretention Cells
- Vegetative Filters
- Constructed Wetlands
- Ponds
- Infiltration Systems
- Filters

1.5. Exfiltration Trench as a Best Management Practice

Exfiltration Trench (ExT) is a BMP utilized by the Ohio Department of Transportation (ODOT). It captures and treats highway runoff via the use of permeable concrete and filter media (ODOT, 2011c). ExT consists of three 6-inch thickness layers: the first layer is pervious concrete as per ODOT Construction and Material Specifications item 306 CT; the second layer is type 3 structural backfill material (aggregate) as per ODOT Construction and Material Specifications item 703.11 A, and the third layer is type 2 structural backfill material (sand) as per ODOT Construction and Material Specifications item 703.11 B. A geotextile fabric layer is placed under the sand layer to
retain the filter media. Underlying the trench layers, a 4-inch perforated pipe receives the filtrated water and connects to a 4-inch nonperforated pipe as per ODOT Construction and Material Specifications item 707.31, which might discharge into a drainage structure or onto the slope using a reinforced concrete outlet (ODOT, 2011c). Figure 1.1 illustrates the components of ExT. According to ODOT specifications, the typical width of the ExT is 8 in and the typical depth is 18 in while the length varies depending on the drainage area (ODOT, 2008b).

Figure 1.1: ExT Components (Adapted from Wawszkiewicz, 2011)
1.6. Scope of Work

1.6.1. Site Description

This research is a field study conducted on the ExT located on State Route 7, OH which is considered as an urban highway. The trench is 9.75 in wide, 18 in deep, and 16 ft long. The drainage area is 0.83 acre and the 4-lane asphaltic highway average daily traffic (ADT) is 16,460 with truck traffic 8% (ODOT, 2010). The adjacent land on the trench side is a wooded area while on the opposite side across the street; the Smith Concrete plant is located. Figure 1.2 shows the exfiltration trench site.

Figure 1.2: Exfiltration Trench Location in Reno, OH
1.6.2. Analytical Approach

Among highway runoff water quality parameters, TSS, turbidity, particle size analysis and pH are investigated in this study. Samples were obtained for influent and effluent from the site with the aid of two ISCO 6712 automatic samplers. Influent sampler was collecting samples from the gutter area of the pavement prior to the trench surface, while effluent sampler probe was placed underneath the geotextile layer, so that the collected water represented the treated influent. Based on the influent and effluent water quality parameters, ExT performance can be evaluated by computing the removal efficiencies.

1.7. Research Objectives

- Monitor and determine the concentrations of water quality constituents in highway storm water runoff and ExT effluent at the research site. These constituents include: TSS; turbidity; pH and particle size analysis.
- Speculate on the origin of solids found in the highway runoff; whether they are pavement surface abrasion, vehicle tires, corrosion of vehicle body, de-icing products, oil and grease and fluid leakage or soil deposits and placements.
- Statistically analyze the water quality constituents’ data.
- Validate the performance of the exfiltration trench based on performance efficiency as percentage reduction of water quality constituents between influent and effluent concentrations.
- Study the relationship between highway runoff constituents and in-situ conditions such as antecedent dry weather days.
- Evaluate the maintenance of the ExT.
- Compare the field study with the lab study conducted previously on ODOT pervious concrete, aggregate and sand samples in terms of media characteristics, maintenance and performance.
- Compare performance of the ExT before and after maintenance.
- Compare performance of the ExT as originally constructed and after reconstruction.
- Evaluate the impact of the winter season and winter maintenance practices on highway runoff quality.
- Investigate the existence of the first flush phenomenon based on the time-wise TSS variations.
- Assess the ability of the ExT to treat high pH water based on lab tests conducted on trench media samples (aggregate and sand) using concrete sawing water influent.

1.8. Thesis Outline

Chapter one is an introduction to the research subject. Chapter two is a summary of literature review conducted on the topic. Chapter three includes analytical and experimental approaches that were followed in this research. Chapter four is the results and findings of this research, and chapter five discusses the results and conclusions of this study and recommendations for future research.
2.1 Highway Runoff Characterization

2.1.1 Event Mean Concentration

Event mean concentration (EMC) is a mathematical approach used to quantify pollutants’ concentration in the runoff as an average representative value for a single event. The need for EMC is basically for the comparison purposes between influent and effluent in order to assess the performance of a BMP facility. However, EMC does not provide a time-wise variation of the concentrations which might be an important parameter in the design of a BMP facility, especially for large storms which inversely affect EMC due to the dilution effects (huge rainfall amounts) or the exhaustion of pollutant masses in long duration events (Kim et al., 2005; Sansalone et al., 1998).

The most common way to express the EMC is the flow weighted average (Kim et al., 2005; Lee et al., 2002; Sansalone et al., 1998; Sansalone & Cristina, 2004; Wu et al., 1998). The formula used to estimate the flow weighted EMC is:

\[
EMC = \frac{M}{V} = \frac{\int_0^{t_r} C(t)Q(t)dt}{\int_0^{t_r} Q(t)dt} = \frac{\sum C(t)Q(t)}{\sum Q(t)}
\]

Equation 2-1

Where:

- \( M \) = Total mass of pollutant delivered in an event.
- \( V \) = Total volume of runoff delivered in an event.
- \( C(t) \) = Concentration of a specific water quality parameter at time \( t \).
- \( Q(t) \) = Runoff flow rate at time \( t \).
- \( t_r \) = Time of runoff.
The arithmetic average for all events’ EMCs is used to obtain an average site specific value, which can be a useful tool to characterize the highway runoff for a specific site (Wu et al., 1998).

Total Mass Emission (TME) is used to express the total amount of pollutants (kg) washed from the catchment area and can be computed by two ways as shown in Equations 2-2 and 2-3 (Kim et al., 2005):

\[
\text{TME} = \text{Rainfall} \times \text{catchment area} \times \text{runoff coefficient} \times \text{EMC} \quad \text{Equation 2-2}
\]

\[
\text{TME} = \text{Total runoff} \times \text{EMC} \quad \text{Equation 2-3}
\]

Another approach is to express pollutants’ loading resulting from land-based activities as mass/area/runoff duration (kg/ha-year). The site mean loading (SML) can be estimated as shown in Equation 2-4 (Wu et al., 1998):

\[
\text{SML} = \frac{\text{(arithmetic avg. EMC’s} \times \text{avg. flow} \times \text{avg. storm duration)}}{\text{avg. No. antecedent dry days} \times \text{drainage area}} \quad \text{Equation 2-4}
\]

Barrett et al. (1998) did not use the flow weighted average approach to estimate the EMC; instead, a simple arithmetic average for the concentrations in each single event was used to express EMC. However, for all events, the results were expressed as median and co-variation.

Some researchers did not use the EMC approach. Legret and Pagotto (1999) computed the pollutant loading (Ls) by multiplying the average pollutant concentration by the volume of flow for each event for 1 km length of the motorway section studied (kg/km). The results then were expressed as annual pollutant load (APL) in Kg/km by the following formula:
\[ APL = P \times \frac{V_m}{P_m} \times \frac{L_s}{V_s} \]  

Equation 2-5

Where:

\( P \) = Annual precipitation including the unsampled events (mm).

\( V_m \) = Total runoff volume during the monitored period (m\(^3\)).

\( P_m \) = Total precipitation depth during the monitored period (mm).

\( L_s \) = Pollutant load (kg/km).

\( V_s \) = Sampled runoff volume (m\(^3\)).

2.1.2 Highway Runoff Contaminants

Storm water runoff or nonpoint source pollution (NPS) discharge forms around 30% of the surface water quality degradation causes in the U.S. Around 90% of NPS are agricultural, urban runoff and mine drainage (Wu et al., 1998). Highway runoff is a major source of water pollution due to the imperviousness of highway surfaces (Kim et al., 2005). Highway runoff is also considered as the main reason for the degradation of the water quality in the U.S. (Barrett et al., 1998). The most dangerous environmental impact is in places of environmental sensitivity such as groundwater recharge, wetlands and drinking water supply watersheds (Wu et al., 1998).

Mitchell et al. (2002) and Sansalone and Teng (2004) summarized the major contaminants found in highway runoff as follows:

- Sediments and suspended solids.
- Nutrients and organic compounds.
- Heavy metals.
- Oil and grease.
• Pathogenic and nonpathogenic bacteria.

The suspended and dissolved solids are of main concern, because they can transport metals attached to their surfaces, which can produce a chemical oxygen demand in the receiving aquatic environments (Sansalone & Teng, 2004).

2.1.3 Sources of Pollution

Sources of highway runoff pollution can be divided into the following categories (Kim et al., 2005; Legret & Pagotto, 1999; Mitchell et al., 2002; Sansalone and Teng, 2004; Wu et al., 1998):

• Chronic sources, which include two main sources of pollution:
  1. Vehicular activities which introduce pollution to the highway surface, such as metals produced by brake pad wear, combustion byproducts, tires wear, corrosion products, the abrasion of metallic parts of vehicles, and fluid drippings.
  2. Wet and dry atmospheric depositions which is referred to as the bulk precipitation and happens in dry and wet weather conditions. It may contribute up to 48% of the TSS in the highway runoff. It is affected by the surrounding land use; i.e., for urban areas, it results in higher atmospheric depositions and vice versa in rural areas.

• Gross pollutants, such as litter, vegetation and construction debris.

• Seasonal sources, such as the pollution resulting from the introduction of deicing agents.
- Temporary sources, such as temporarily road works and construction. It was reported in a study conducted by Barton (1977) in southern Ontario that the TSS levels in a small stream increased up to 1390 mg/l during highway construction. However; after construction, TSS levels decreased to the normal levels (<5 mg/l) (Barton, 1977).

- Accidental sources, such as the accidental introduction of hazardous chemicals.

2.1.4 Factors Affecting Highway Runoff Quality Parameters

Kayhanian et al. (2007); Lee et al. (2011) and Mitchell et al. (2002) summarized the factors affecting highway runoff quality as follows:

- Number of antecedent dry weather days, which was found in some studies to be directly affecting the water quality parameters except for pH. However; Barrett et al. (1995) reported that weak correlations have been found in literature between the number of antecedent dry weather days and the water quality parameters.

- Rainfall intensity, which indicates a combination between the total rainfall and the duration of an event. If the intensity increases, the concentration of various pollutants decreases due to the dilution effect.

- Average daily traffic (ADT) or Average Annual Daily Traffic (ADDT). Theoretically, it should directly affect the concentrations, especially metals concentrations. However, Barrett et al. (1995) reported that no clear relationship has been defined in the literature, which can be explained by the fact that some removal mechanisms such as air turbulence might interfere with the results by removing the pollutants from the surface; thus, obscuring the relationship.
• Drainage area, which inversely affects the concentration of pollutants in the runoff.

• Land use: agricultural and industrial areas exhibit higher concentrations for most of the constituents in the highway runoff, while residential and open land uses runoff is expected to have lower concentrations than the average. This is because the air depositions (aerial application of fertilizers and pesticides) and industrial activities contribute to additional pollution in the highway runoff.

Despite the above mentioned factors, no definitive relationships between those variables and the concentrations of pollutants in the runoff have been reported; since other site specific conditions, seasonal variations and highway maintenance actions might affect the concentrations and the loading of pollutants (Barrett et al., 1995).

2.1.5 Highway Runoff Total Suspended Solids

Li and Davis (2008) stated that the sources of TSS in the highway runoff include natural anthropogenic sources such as different types of soil (clay, silt and sand), vegetation residues, vehicular wear, weathering of buildings and structures and even pathogens. As TSS increases, the effect on the streams receiving highway runoff increases, since TSS is related to other pollutants such as metals, COD, Total Kjeldahl Nitrogen (TKN), and NO₃.

Due to the impacts of TSS on the receiving aquatic system, TSS is considered the most important water quality parameter in the highway runoff. Barrett et al. (1995) summarized the environmental effects of TSS as follows:
- TSS transports many other pollutants such as metals and nutrients. These pollutants are adsorbed to the surface of suspended solids and transported within the runoff.

- TSS reduces the light transmission through the aquatic system; thus, minimizing the photosynthesis, which in effect reduces the dissolved oxygen levels and affects the food supply for the aquatic organisms.

- Suspended solids affect the aquatic organisms through coating and abrasion, which will eventually reduce the diversity and density of the fauna in the receiving system.

- Suspended solids depositions may lead to decreased capacity of the receiving aquatic systems.

Table 2.1 presents the average TSS EMC’s and mass loadings (washed-off mass) for a study conducted by Kim et al. (2005) on eight highways in South California region.

| Table 2.1: Highway Runoff TSS Statistical Summary for Southern California Region (Kim et al., 2005) |
|---|---|---|---|---|---|---|---|---|
| No. Events | Min | Max | Median | Mean | S.D | 95% upper | 95% lower |
| EMC (mg/l) | 39 | 5.21 | 874 | 87.5 | 160 | 175 | 216 | 103 |
| Mass Loading (g/m²) | 39 | 0.06 | 17.3 | 0.83 | 2.43 | 3.91 | 3.7 | 1.14 |

In Table 2.2, average influent and effluent TSS values are shown for the partial exfiltration reactor (PER) located in Southbound Inter State 75, OH, and tested by Sansalone and Teng (2004).
Table 2.2:  
Typical PER Influent and Effluent TSS and flow Volumes in an Experimental Site in Cincinnati, OH (Sansalone & Teng, 2004)

<table>
<thead>
<tr>
<th>Event Date</th>
<th>Influent</th>
<th>Effluent</th>
<th>Reduction %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Flow volume (L)</td>
<td>TSS (mg/l)</td>
<td>Flow volume (L)</td>
</tr>
<tr>
<td>Nov 25, 1996</td>
<td>215</td>
<td>200</td>
<td>63</td>
</tr>
<tr>
<td>Dec 16, 1996</td>
<td>268</td>
<td>141</td>
<td>121</td>
</tr>
<tr>
<td>Jun 12, 1997</td>
<td>464</td>
<td>72</td>
<td>181</td>
</tr>
</tbody>
</table>

A study conducted by Wu et al. (1998) in Charlotte, NC, aimed at characterizing the highway runoff pollution for different types of surfaces (varying in the imperviousness) with different settings (urban, semi-urban and rural). The results obtained were considered as representative for the south eastern part of the US. Table 2.3 presents the TSS findings for the three types of highways tested by Wu et al. (1998) along with the average daily traffic for each.

Table 2.3:  
TSS EMC's, Annual Loadings and Average Daily Traffic for Three Sites in Charlotte, NC (Wu et al., 1998)

<table>
<thead>
<tr>
<th>Site</th>
<th>Type</th>
<th>Average Daily Traffic (Veh/day)</th>
<th>TSS (mg/l)</th>
<th>Annual loading (kg/ha-year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Urban</td>
<td>25,000</td>
<td>283</td>
<td>2678</td>
</tr>
<tr>
<td>II</td>
<td>Semi-Urban</td>
<td>21,500</td>
<td>93</td>
<td>528</td>
</tr>
<tr>
<td>III</td>
<td>Rural</td>
<td>15,500</td>
<td>30</td>
<td>612</td>
</tr>
</tbody>
</table>

Legret and Pagotto (1999) conducted their study on a 12,000 vehicle/day rural highway, in Loire-Atlantique, France. It was found that pH was almost stable and neutral for the monitored period (49 events). TSS mean was 71 mg/l with a range of 16-247 mg/l and a standard deviation of 61 mg/l, knowing that the highest TSS concentrations were
recorded in winter due to the increase in the insoluble matter in the deicing salt. Samples were collected in two ways: regular samples collected by automatic sampler and sediment samples collected from the flow channel. Sediments’ analysis showed that 79% of the sediments were sand (>200 μm), approximately 95% of which were inorganic matter, while the sediments in the samples collected by the automatic sampler were finer (82.4% fines) (Legret & Pagotto, 1999).

Legret and Pagotto (1999) proposed a detailed break-down of the TSS annual loading which shows the contribution of each source of pollution to the highway runoff TSS. Table 2.4 shows the contribution of each pollution source to the annual TSS loading. From Table 2.4, it can be concluded that tire wear contributes the most to TSS annual loadings in the site mentioned above (almost half of TSS is from tire wear).

Table 2.4:
Contribution of Each Pollution Source to TSS Annual Loadings, Loire-Atlantique Site, France (Legret and Pagotto, 1999)

<table>
<thead>
<tr>
<th></th>
<th>Kg/km/year</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tire wear</td>
<td>314</td>
<td>49.8</td>
</tr>
<tr>
<td>Brake linings</td>
<td>100</td>
<td>15.9</td>
</tr>
<tr>
<td>Deicing agents</td>
<td>130</td>
<td>20.6</td>
</tr>
<tr>
<td>Air depositions</td>
<td>86</td>
<td>13.7</td>
</tr>
<tr>
<td>Total</td>
<td>630</td>
<td>100</td>
</tr>
</tbody>
</table>

Another study was conducted by Barrett et al. (1998) in Austin, Texas. The research was carried out at three sites:

- Site I (West 35 Street), residential and commercial, 100% asphalt paved with an average daily traffic of 58,150 veh/day.
- Site II (Convict Hill road), residential and undeveloped, 100% asphalt paved with an average daily traffic of 8,780 veh/day.

- Site III (Walnut Creek road), commercial and high density residential, paved highway and grassy shoulders, with an average daily traffic of 47,240 veh/day.

TSS results for the three sites are presented in Table 2.5:

<table>
<thead>
<tr>
<th></th>
<th>Site I</th>
<th>Site II</th>
<th>Site III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Median (mg/l)</td>
<td>129</td>
<td>91</td>
<td>19</td>
</tr>
<tr>
<td>Covariance (mg/l)</td>
<td>0.9</td>
<td>0.9</td>
<td>0.8</td>
</tr>
<tr>
<td>Mean EMCs (mg/l)</td>
<td>212</td>
<td>221</td>
<td>-</td>
</tr>
<tr>
<td>Annual (kg/ha)</td>
<td>1306</td>
<td>977</td>
<td>101</td>
</tr>
</tbody>
</table>

It can be observed that the TSS concentrations detected in site III are the lowest which can be explained by the fact that the runoff from this site was collected after passing over a vegetative swale unlike the other two sites from which the runoff was sampled directly from the pavement surface (Barrett et al., 1998).

Deletic and Orr (2005) conducted a study on an urban road in Aberdeen, Scotland. The main purpose of the study was to characterize the sediments on the surface and the spatial variation of sediments’ masses across the section of the highway. The spatial distribution of sediments across the highway indicated that approximately two thirds of the total sediments exist in the first 0.5 m strip next to the curb.

TSS can be related to other parameters. Deletic (1998) calibrated the turbidity meter in order to estimate the TSS based on turbidity values. The correlation was made
Based on previous TSS and turbidity data which gave a cross correlation coefficient $R = 0.98$.

From a study conducted on the 7th highway in Gangwon-do Province, South Korea (2007-2009), TSS results for four rainfall events are shown in Table 2.6 (Lee et al., 2011). The results are expressed as TSS range and TSS mass for the initial 20 minutes of the storm. The catchment area is 2,500 m$^2$ with a residential and commercial surrounding land use and an ADT of 6000 veh/day.

Table 2.6: *TSS Ranges and Cumulative Loadings in Gangwon-do Province, South Korea (Lee et al., 2011)*

<table>
<thead>
<tr>
<th>Event</th>
<th>TSS ranges (mg/l)</th>
<th>TSS cumulative loading (g/20 min)</th>
<th>Percent of total mass loading</th>
</tr>
</thead>
<tbody>
<tr>
<td>09/14/2007</td>
<td>30-250</td>
<td>1265</td>
<td>14%</td>
</tr>
<tr>
<td>04/09/2008</td>
<td>30-300</td>
<td>2776</td>
<td>53%</td>
</tr>
<tr>
<td>03/13/2009</td>
<td>25-370</td>
<td>1151</td>
<td>21%</td>
</tr>
<tr>
<td>05/16/2009</td>
<td>15-250</td>
<td>570</td>
<td>20%</td>
</tr>
</tbody>
</table>

Lee et al. (2011) came up with model that expresses the TSS event mean concentration in terms of runoff volume. The data for 50 events were used to come up with the following:

$$\text{EMC TSS (mg/l)} = 0.0002 Q^3 - 0.0576 Q^2 + 4.6376 Q + 56.116 \quad \text{Equation 2-6}$$

Where $Q = \text{runoff volume (m}^3/\text{event)}$.

From Equation 2-6, the peak TSS concentration exists at $Q = 70 \text{ m}^3/\text{event}$ and starts decreasing afterwards.
According to a comprehensive study conducted in California by Kayhanian et al. (2007), which aimed at the characterization of highway runoff for 34 sites, it was found that metals might exist in particulate form (Pb: 83%; Arsenic, Cadmium, Chromium and Zinc: 60-65%; Copper: 50% and Nickel: 55%). Thus, by removing the particulate matter from the runoff, these metals can be removed at an efficiency of 50% (Kayhanian et al., 2007). The TSS results for this study are shown in Table 2.7.

Table 2.7: Summary of TSS Data in California (Kayhanian et al., 2007)

<table>
<thead>
<tr>
<th>Land use</th>
<th>AADT (veh/day)</th>
<th>Range</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>-</td>
<td>1-2988</td>
<td>112.7</td>
<td>59.1</td>
<td>188.8</td>
</tr>
<tr>
<td>Urban (high AADT)</td>
<td>&gt; 100,000</td>
<td>-</td>
<td>158.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Urban (low AADT)</td>
<td>30,000-100,000</td>
<td>-</td>
<td>76.3</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Non Urban</td>
<td>&lt; 30,000</td>
<td>-</td>
<td>69.9</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

Another predictive equation was developed by Kayhanian et al. (2007) using multiple regression methods for predicting EMCs (mg/l) for various pollutants based on multiple parameters.

\[
\ln (\text{TSS EMC}) = 4.28 - 0.124\beta_1 + 0.102 \beta_2 - 0.099 \beta_3 + 4.934 \beta_4
\]

\text{Equation 2-7}

Where:

\[\beta_1 = \ln (\text{Total event rainfall-mm})\].

\[\beta_2 = \ln (\text{Number of antecedent dry weather days-days})\].

\[\beta_3 = \ln (\text{Seasonal cumulative rainfall-mm})^{1/3}\].

\[\beta_4 = \text{AADT} \times 10^{-5}\]

TSS is in mg/l.
Barrett et al. (1995) summarized the literature values and ranges for highway storm water runoff water quality parameters as shown in Table 2.8.

Table 2.8:  
*Highway Runoff Water Quality Parameters in Literature (Adapted from Barrett et al., 1995)*

<table>
<thead>
<tr>
<th>Water Quality Parameter</th>
<th>Concentration (mg/L unless indicated)</th>
<th>Load (kg/ha/year)</th>
<th>Load (kg/ha/event)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Solids</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>437 - 1147</td>
<td>-</td>
<td>58.2</td>
</tr>
<tr>
<td>Dissolved</td>
<td>356</td>
<td>148</td>
<td>-</td>
</tr>
<tr>
<td>Suspended</td>
<td>45 - 798</td>
<td>314 - 11,862</td>
<td>1.84 - 107.6</td>
</tr>
<tr>
<td>Volatile, dissolved</td>
<td>131</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Volatile, suspended</td>
<td>4.3 - 79</td>
<td>45 - 961</td>
<td>0.89 - 28.4</td>
</tr>
<tr>
<td>Volatile, total</td>
<td>57 - 242</td>
<td>179 - 2518</td>
<td>10.5</td>
</tr>
<tr>
<td>pH (SU)</td>
<td>7.1 - 7.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity (JTU)</td>
<td>84 - 127</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>19</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

The following table presents a summary of 24 sites data prepared by the Federal Highway Administration (1990) from 10 different states. The data in the table include average daily traffic, surface type, land use, imperviousness, number of lanes, annual rain and the median TSS.
### Table 2.9:
**Total Suspended Solids Data for 24 Study Sites (Adapted from FHWA, 1990)**

<table>
<thead>
<tr>
<th>Site No.</th>
<th>State code</th>
<th>SITE</th>
<th>Avg daily traffic 1000 VPD</th>
<th>Number of traffic lanes</th>
<th>Sect type</th>
<th>Surface type</th>
<th>Curb</th>
<th>Land use</th>
<th>Area (Acres)</th>
<th>% IMP</th>
<th>Annual rain inch</th>
<th>TSS mg/l</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>AR-1</td>
<td>LITTLE ROCK I-30</td>
<td>42</td>
<td>42</td>
<td>4</td>
<td>4</td>
<td>BF</td>
<td>ASP</td>
<td>NO</td>
<td>U-3</td>
<td>1.5</td>
<td>90</td>
</tr>
<tr>
<td>2</td>
<td>CA-1</td>
<td>LOS ANGELES I-405</td>
<td>200</td>
<td>200</td>
<td>8</td>
<td>8</td>
<td>F</td>
<td>CON</td>
<td>YES</td>
<td>U-2</td>
<td>3.2</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>CA-2</td>
<td>SACRAMENTO HWY 50</td>
<td>86</td>
<td>43</td>
<td>8</td>
<td>4</td>
<td>G</td>
<td>CON</td>
<td>YES</td>
<td>U-4</td>
<td>2.45</td>
<td>82</td>
</tr>
<tr>
<td>4</td>
<td>CA-3</td>
<td>WALNUT CREEK I-680</td>
<td>70</td>
<td>70</td>
<td>6</td>
<td>6</td>
<td>-</td>
<td>CON</td>
<td>YES</td>
<td>U-3</td>
<td>2.1</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>CO-1</td>
<td>DENVER I-25</td>
<td>149</td>
<td>149</td>
<td>10</td>
<td>10</td>
<td>G</td>
<td>ASP</td>
<td>YES</td>
<td>U-4</td>
<td>35.3</td>
<td>37</td>
</tr>
<tr>
<td>6</td>
<td>FL-1</td>
<td>BROWARD CO HWY 834</td>
<td>20</td>
<td>20</td>
<td>6</td>
<td>6</td>
<td>G</td>
<td>ASP</td>
<td>BOTH</td>
<td>U-2</td>
<td>58.3</td>
<td>36</td>
</tr>
<tr>
<td>8</td>
<td>FL-2</td>
<td>MIAMI I-95</td>
<td>140</td>
<td>70</td>
<td>6</td>
<td>3</td>
<td>B</td>
<td>ASP</td>
<td>YES</td>
<td>U-1</td>
<td>1.43</td>
<td>100</td>
</tr>
<tr>
<td>11</td>
<td>MN-1</td>
<td>MINNEAPOLIS I-94</td>
<td>80</td>
<td>80</td>
<td>10</td>
<td>10</td>
<td>C</td>
<td>CON</td>
<td>YES</td>
<td>U-2</td>
<td>21</td>
<td>55</td>
</tr>
<tr>
<td>12</td>
<td>MN-2</td>
<td>ST PAUL I-94</td>
<td>65</td>
<td>65</td>
<td>6</td>
<td>6</td>
<td>CF</td>
<td>CON</td>
<td>YES</td>
<td>U-2</td>
<td>16.3</td>
<td>49</td>
</tr>
<tr>
<td>13</td>
<td>NC-1</td>
<td>EFLAND I-85</td>
<td>26</td>
<td>26</td>
<td>4</td>
<td>3</td>
<td>G</td>
<td>ASP</td>
<td>NO</td>
<td>N-1</td>
<td>2.49</td>
<td>51</td>
</tr>
<tr>
<td>14</td>
<td>PA-1</td>
<td>HARRISBURG I-81(Ph.1)</td>
<td>24</td>
<td>24</td>
<td>6</td>
<td>6</td>
<td>G</td>
<td>CON</td>
<td>NO</td>
<td>U-4</td>
<td>18.5</td>
<td>27</td>
</tr>
<tr>
<td>15</td>
<td>PA-2</td>
<td>HARRISBURG I-81(Ph.2)</td>
<td>56</td>
<td>28</td>
<td>4</td>
<td>2</td>
<td>G</td>
<td>CON</td>
<td>NO</td>
<td>U-4</td>
<td>2.81</td>
<td>45</td>
</tr>
<tr>
<td>17</td>
<td>TN-1</td>
<td>NASHVILLE I-40</td>
<td>88</td>
<td>88</td>
<td>6</td>
<td>6</td>
<td>CG</td>
<td>CON</td>
<td>YES</td>
<td>U-1</td>
<td>55.6</td>
<td>37</td>
</tr>
<tr>
<td>18</td>
<td>WA-5</td>
<td>MONTOSANO SR-12 (5)</td>
<td>7.3</td>
<td>7.3</td>
<td>2</td>
<td>2</td>
<td>G</td>
<td>ASP</td>
<td>YES</td>
<td>N-4</td>
<td>0.28</td>
<td>100</td>
</tr>
<tr>
<td>19</td>
<td>WA-6</td>
<td>PASCO SR-12 (6)</td>
<td>4</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>G</td>
<td>ASP</td>
<td>CON</td>
<td>N-5</td>
<td>1.25</td>
<td>100</td>
</tr>
<tr>
<td>21</td>
<td>WA-9</td>
<td>PULLMAN SR-270E (9)</td>
<td>5</td>
<td>2.5</td>
<td>2</td>
<td>1</td>
<td>G</td>
<td>ASP</td>
<td>YES</td>
<td>N-4</td>
<td>0.25</td>
<td>100</td>
</tr>
<tr>
<td>23</td>
<td>WA-1</td>
<td>SEATTLE I-5 (1)</td>
<td>106</td>
<td>53</td>
<td>8</td>
<td>4</td>
<td>G</td>
<td>CON</td>
<td>YES</td>
<td>U-3</td>
<td>1.22</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>WA-2</td>
<td>SEATTLE SR-520 (2)</td>
<td>84</td>
<td>42</td>
<td>4</td>
<td>2</td>
<td>B</td>
<td>CON</td>
<td>YES</td>
<td>U-1</td>
<td>0.099</td>
<td>100</td>
</tr>
<tr>
<td>26</td>
<td>WA-4</td>
<td>SNOQ PASS I-90 (4)</td>
<td>15</td>
<td>7.7</td>
<td>6</td>
<td>3</td>
<td>G</td>
<td>CON</td>
<td>YES</td>
<td>N-2</td>
<td>0.18</td>
<td>100</td>
</tr>
<tr>
<td>27</td>
<td>WA-7</td>
<td>SPOKANE I-90 (7)</td>
<td>35</td>
<td>17</td>
<td>6</td>
<td>3</td>
<td>B</td>
<td>CON</td>
<td>YES</td>
<td>U-1</td>
<td>0.22</td>
<td>100</td>
</tr>
<tr>
<td>28</td>
<td>WA-3</td>
<td>VANCOUVER I-205 (3)</td>
<td>17</td>
<td>8.6</td>
<td>6</td>
<td>3</td>
<td>G</td>
<td>CON</td>
<td>YES</td>
<td>U-4</td>
<td>0.28</td>
<td>100</td>
</tr>
<tr>
<td>29</td>
<td>WI-1</td>
<td>MILWAUKEE HWY 45</td>
<td>85</td>
<td>85</td>
<td>6</td>
<td>6</td>
<td>CG</td>
<td>CON</td>
<td>YES</td>
<td>U-3</td>
<td>106</td>
<td>31</td>
</tr>
<tr>
<td>30</td>
<td>WI-2</td>
<td>MILWAUKEE I-794</td>
<td>53</td>
<td>53</td>
<td>8</td>
<td>8</td>
<td>B</td>
<td>CON</td>
<td>YES</td>
<td>U-1</td>
<td>2.1</td>
<td>100</td>
</tr>
<tr>
<td>31</td>
<td>WI-3</td>
<td>MILWAUKEE I-94</td>
<td>116</td>
<td>116</td>
<td>8</td>
<td>8</td>
<td>-</td>
<td>ASP</td>
<td>YES</td>
<td>U-3</td>
<td>7.6</td>
<td>64</td>
</tr>
</tbody>
</table>

**Notes:**

(A) Land use surrounding area

U = Urban, 1. undefined, 2. commercial/residential, 3. residential, 4. suburban

N = Non-Urban, 1. undefined rural, 2. forest, 3. undeveloped, 4. agricultural, 5. desert

(B) Section type

C = cut, F = fill, G = at grade, B = bridge

(C) Road surface type

CON = concrete, ASP = asphalt

**Mean** 143

**Median** 93

**COV** 1.16

**N** 24
2.1.6 Highway Runoff Particle Size Distribution

The particle size distribution is one of the most important physical characteristics of the solids transported in the highway runoff. It determines the applicability of an in-situ treatment system. Moreover, the mobility, transport and partitioning of metals depend mainly on the solids’ particle size which can function as a reservoir for the pollutants (Deletic & Orr, 2005; Sansalone et al., 1998). Removal of pollutants from the runoff depends on the particle size as well, because larger particles have larger settling velocity (Barrett et al., 1995). First flush phenomenon has also been found to be affected by the particle size of the pollutants; however, first flush can be identified more clearly in case of dissolved rather than particulate solids (Barrett et al., 1995). Solids in highway runoff range from smaller than 1μm to larger than 10,000 μm (Sansalone et al., 1998). Particles of smaller sizes (fines) have higher concentrations of pollutants because they are more bioavailable and mobile than the larger settleable particles. The relatively large surface area and the presence of clay minerals and organics ease the adsorption of metals (Cristina & Sansalone, 2003; Deletic & Orr, 2005), hence; Cristina and Sansalone (2003) investigated the first flush in terms of suspended solids having particle size of (2-75) μm, typically, < 50 μm.

Particle size analysis is usually conducted by several methods (Legret & Pagotto, 1999; Sansalone et al., 1998):

- Sieve analysis after oven drying: for particles ranging in size from 9.5 mm (#3/8) through 25 μm (# 500).
- Laser sizer: for particles smaller than 500 μm.
• Hydrometer analysis: for particles smaller than 75 μm.

Sansalone et al. (1998) reported that based on the particle size analysis, it is possible to predict the origin of the solids as follows:

• Particles retained on sieve # 200 (>75 μm): inorganic coated with asphalt or other organic materials.

• Particles passing through sieve # 200: mostly organics or clay particles.

Sansalone et al. (1998) conducted a study in Cincinnati, Ohio on an asphaltic pavement with a drainage area of 300 m² and an urban (commercial and industrial) surrounding land use. They found that 2-8 μm solids were washed rapidly from the pavement. Table 2.10 shows the particle size, TSS and pH summary for the site studied.

Table 2.10:
**PS, TSS and pH Summary for Cincinnati, OH Site (Sansalone et al., 1998)**

<table>
<thead>
<tr>
<th></th>
<th>Range</th>
<th>Mean</th>
<th>Median</th>
<th>SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d_{60}$ (μm)</td>
<td>480-1200</td>
<td>742</td>
<td>700</td>
<td>184</td>
</tr>
<tr>
<td>$d_{50}$ (μm)</td>
<td>370-785</td>
<td>555</td>
<td>570</td>
<td>120</td>
</tr>
<tr>
<td>$d_{30}$ (μm)</td>
<td>200-450</td>
<td>320</td>
<td>350</td>
<td>85</td>
</tr>
<tr>
<td>$d_{10}$ (μm)</td>
<td>65-180</td>
<td>117</td>
<td>110</td>
<td>41</td>
</tr>
<tr>
<td>TSS (mg/l)</td>
<td>28.6-258.6</td>
<td>130.7</td>
<td>136.7</td>
<td>57.2</td>
</tr>
<tr>
<td>pH</td>
<td>5.9-7.56</td>
<td>6.83</td>
<td>6.8</td>
<td>0.55</td>
</tr>
</tbody>
</table>

As mentioned earlier, particle size analysis can be a helpful tool for the design and selection of a BMP facility; since it can predict the removal mechanism. If (media diameter/particle diameter) is less than 10, it is surface straining removal; if (media diameter/particle diameter) ranges between 10 and 20, significant filtration within the
porous portion of system takes place, which leads to decreasing the infiltration capacity of the system unless it has been recovered by backwashing. And if \((\text{media diameter/particle diameter})\) is greater than 20, particles will be captured by the mechanisms of Brownian motion, sedimentation and interception (Sansalone et al., 1998).

Deletic and Orr (2005) reported in their study in Aberdeen, Scotland, that the median particle size next to the curb was found to be 397 μm while this decreased to 238 μm at a distance of 0.75 m from the curb. In winter, especially the snow season, the median particle size increased next to the curb from 397 μm to 450 μm, while the load of sediments was three times larger than the non-snow season sediments loads (Deletic & Orr, 2005).

2.1.7 Winter Season Environmental Impacts

2.1.7.1 Snow Best Management Practices

Many studies have revealed that snow season and its best management practices lead to elevated concentrations of pollutants, such as TSS and metals. Engelhard et al. (2007) carried out a study in Alpine region, in the city of Innsbruck, Austria. It aimed at evaluating the pollution resulting from the accumulated snow on the roadsides and from the related best management practices. The reasons for the environmental impacts of roadside snow are the porous structure of the snow; large surface area of the snow and ice crystals; freezing and thawing and the relatively long residence time which extends the exposure duration to the pollutants (Sansalone & Glenn, 2002).
Usually, after a snow event, snow piles are plowed against the side of the road away from the pavement surfaces. The accumulated piles are then either left to melt naturally forming runoff or removed and dumped into streams or rivers (Sansalone & Glenn, 2002).

Engelhard et al. (2007) summarized the environmental impacts of snow and its best management practices as follows:

- Atmospheric depositions are higher in the snow flakes than in raindrops due to the larger surface area.
- The roadside snow acts as a sink for further atmospheric depositions.
- In cold weather, the increased chemical pollution might be caused by the low efficiency of motor vehicles.
- Elevated levels of NaCl (most popular deicing agent) leads to an increase in the highly mobile chloride ion and the corresponding washout of heavy metals; thus, creating further pollution in the receiving water.
- The sudden melting of snow piles induces a high flow which might affect the whole sewerage system, wastewater treatment plant and the receiving water.
- If part of the runoff resulting from snow piles melting reaches the wastewater sewerage system, it might slow down or inhibit the biological activity due to the low temperature.
- In case of direct depositions of snow piles into receiving water bodies, elevated salt concentrations were detected up to 1300 mg/l.
2.1.7.2 **Deicing Agents**

In the snow season, significant quantities of deicing agents are discharged to the highways. The most popular deicing agent is NaCl. However, other deicing agents might be used such as sand and CaCl$_2$. More than $1 \times 10^7$ tons of rock salt is applied to the North American highways every year (Sansalone & Glenn, 2002). Cyanide is used in the form of iron cyanide as a coating material for the salt particles applied to the highways for the anti-caking assurance (Sansalone & Glenn, 2002). The dissolution of CN in water under the presence of sunlight and oxygen produces a very toxic runoff (Sansalone & Glenn, 2002). In their study which was conducted in Cincinnati, Ohio, Sansalone and Glenn (2002) stated that the total amount of salt rock coated with cyanide applied along the 27-km section of interstate was estimated to be $2.2 \times 10^5$ kg.

The use of deicing agents led to adverse environmental impacts such as the destruction of roadside surface soil by Na$^+$; degradation of aquatic systems due to the elevated levels of Na$^+$ and Cl$^-$; mobilization of heavy metals from the highway surfaces and infrastructure corrosion damage (Sansalone & Glenn, 2002).

In the city of Innsbruck, Austria, approximately 3,000 tons of salts and 2,500 tons of sand were discharged to the streets in the winter of 2005-2006; thus, increasing TSS concentrations in the molten snow (Engelhard et al., 2007). It was concluded also that the highest concentrations of TSS in the roadside snow corresponded to the highest traffic densities. No correlation between the precipitation rate and the pollution was obtained.

In Englehard et al. (2007) study, representative samples were obtained for each snow event as follows: one sample from a residential (low traffic) area, five samples from
a main street (high traffic area) and two samples from exit lane on highway (2 m and 4 m distances from the curb). Table 2.11 presents the TSS mean concentrations and ranges at the different sampling locations.

Table 2.11:  
*Molten Snow TSS Mean Concentrations and Ranges (Engelhard et al, 2007)*

<table>
<thead>
<tr>
<th>Sampling location</th>
<th>Mean TSS (mg/l)</th>
<th>Range (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low traffic</td>
<td>289</td>
<td>6-683</td>
</tr>
<tr>
<td>High traffic</td>
<td>959</td>
<td>2-3794</td>
</tr>
<tr>
<td>Highway</td>
<td>629</td>
<td>216-1804</td>
</tr>
<tr>
<td>2 m distance from the curb</td>
<td>323</td>
<td>13-991</td>
</tr>
<tr>
<td>4 m distance from the curb</td>
<td>88</td>
<td>11-324</td>
</tr>
</tbody>
</table>

Sansalone and Glenn (2002) in their study in Cincinnati, Ohio, found that the total dissolved solids (TDS) increased rapidly in snow samples from 100 to 10,000 mg/l in less than 10 hours from the beginning of the event. Additionally, TSS increased to 100,000 mg/l at several sites while an average decrease of 1 pH standard unit (1 SU) was observed.

Snowmelt impacts (environmental and hydrological) depend on the type of the surface. The following table describes the effects of snowmelt from different types of surfaces.
Table 2.12: Runoff and Pollutant Characteristics of Snowmelt Stages (Adapted from USEPA 2004)

<table>
<thead>
<tr>
<th>Snowmelt Stage</th>
<th>Duration/ Frequency</th>
<th>Runoff Volume</th>
<th>Pollutant Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pavement Melt</td>
<td>Short, but many times in winter</td>
<td>Low</td>
<td>Acidic, high concentrations of soluble pollutants, chloride, nitrate, lead. Total load is minimal.</td>
</tr>
<tr>
<td>Roadside Melt</td>
<td>Moderate</td>
<td>Moderate</td>
<td>Moderate concentrations of both soluble and particulate pollutants.</td>
</tr>
<tr>
<td>Pervious Area Melt</td>
<td>Gradual, often most at end of season</td>
<td>High</td>
<td>Dilute concentrations of soluble pollutants, moderate to high concentrations of particulate pollutants, depending on flow.</td>
</tr>
<tr>
<td>Rain-on-Snow Melt</td>
<td>Short</td>
<td>Extreme</td>
<td>High concentrations of particulate pollutants, moderate to high concentrations of soluble pollutants. High total load.</td>
</tr>
</tbody>
</table>

2.1.8 Hydrology of Highway

Wu et al. (1998) interpreted some linear relationships from the data obtained in Charlotte, NC, site between the total rainfall in mm (denoted as L) and the flow level in mm (denoted as P) as follows:

For urban areas: $L = -2.032 + 1.007P; R^2 = 0.95$  
Equation 2-8

For semi-urban areas: $L = -1.981 + 0.705P; R^2 = 0.90$  
Equation 2-9

For rural areas: $L = -4.14 + 0.69P; R^2 = 0.91$  
Equation 2-10

Furthermore, it was concluded that as the imperviousness of the watershed increases, the hydrological response to a storm event becomes faster (Wu et al., 1998).
2.2 Highway Storm Water Runoff Impacts

The interaction among the wet weather flow (WWF), the land use, and urbanization byproducts impacts the physical, chemical and biological integrity of the environment. These impacts are summarized as follows (USEPA, 2004):

- Construction creates new surfaces for flow; therefore, the storm water would flow over an impervious surface rather than infiltrate through the ground. As a result of decreased storm water infiltration, the groundwater recharge decreases; which might be detrimental for those regions that depend mainly on the groundwater as a water supply source.
- Storm water runoff affects the streams through erosion by either stream widening or increasing the depth of the channel. This leads to the degradation of aquatic habitat and affects the aquatic populations.
- Increased peak flow rates resulting from urbanization causes overbank floods due to exceeding stream capacity, which damages the downstream structures.
- The increased runoff temperature in summer affects some stream species that are sensitive to temperature.
- The storm water runoff picks up pollutants deposited on the land which will degrade the quality of the receiving water body. These pollutants include sediments, heavy metals, nutrients, hydrocarbons, gasoline additives, pathogens, deicers, herbicides and pesticides.
The following table presents the detailed physical, habitat, biological and chemical impacts resulting from urbanization and development, which are reflected on the highway runoff quality and quantity (USEPA, 2004).

Table 2.13:  
*Categories of Urbanization Impacts -Construction and Development (Adapted from USEPA, 2004)*

<table>
<thead>
<tr>
<th>Impact Type / Metric</th>
<th>Impairment or Change to Beneficial Use</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Physical</strong></td>
<td></td>
</tr>
<tr>
<td>Hydrologic regime</td>
<td></td>
</tr>
<tr>
<td>Runoff volume</td>
<td>Flooding, groundwater recharge, hydrologic balance, etc.</td>
</tr>
<tr>
<td>Peak discharge</td>
<td>Flooding, channel erosion, habitat loss</td>
</tr>
<tr>
<td>Flow duration and frequency</td>
<td>Channel erosion, habitat loss</td>
</tr>
<tr>
<td>Groundwater recharge, water table elevation and baseflows</td>
<td>Water table, local wells, baseflows, habitat loss</td>
</tr>
<tr>
<td><strong>Geomorphic</strong></td>
<td></td>
</tr>
<tr>
<td>Channel geometry</td>
<td>Channel erosion, sediment deposition, habitat loss</td>
</tr>
<tr>
<td>Sediment transport</td>
<td>Aggradations, degradation, channel capacity</td>
</tr>
<tr>
<td><strong>Flooding</strong></td>
<td></td>
</tr>
<tr>
<td>Thermal</td>
<td></td>
</tr>
<tr>
<td><strong>Habitat</strong></td>
<td></td>
</tr>
<tr>
<td>Attachment sites, embeddedness, fish shelter, channel alteration, sediment deposition, stream velocity and depth, channel flow status, bank vegetation protection, bank condition score, and riparian vegetation zone</td>
<td>Impairment or loss of habitat structure results in reduction or losses in biologic conditions and communities.</td>
</tr>
<tr>
<td><strong>Biological</strong></td>
<td></td>
</tr>
<tr>
<td>Total taxa Ephemeroptera, Plecoptera, Tricoptera (EPT) taxa</td>
<td>Biologic conditions and communities can be reduced or eliminated as a result of impairment or loss of habitat structure caused by physical impacts resulting from construction and development activities.</td>
</tr>
<tr>
<td>% taxa</td>
<td></td>
</tr>
<tr>
<td>% EPT</td>
<td></td>
</tr>
<tr>
<td>Family Biotic Index (FBI)</td>
<td></td>
</tr>
<tr>
<td><strong>Chemical (Water Quality)</strong></td>
<td>Water quality degradation or impairment can have many negative consequences: drinking water violations, increased water treatment costs, beach closures, shellfish bed closures, loss of boating use, fishery loss, reduction of reservoir and lake volumes due to sediment volume.</td>
</tr>
<tr>
<td>Sediment, nutrients, metals, herbicides and pesticides, deicers, pathogens, petroleum, hydrocarbons, Methyl Tertiary Butyl Ether (MTBE), grease, and other toxic organic carbons</td>
<td></td>
</tr>
</tbody>
</table>
2.3 First Flush Phenomenon

2.3.1 First Flush Definition

First flush is the elevated concentration/mass of constituents observed in the initial portion of the storm water runoff that is disproportionate to the flow (Sansalone & Cristina, 2004; Sansalone et al., 1998; Su & Mitchell, 2006). It may also be defined as the substantial increase in the pollutants’ concentration in the initial period of storm water runoff which is then decreased for later times in the storm event (Lee et al., 2002). The first flush might be considered as the first 0.5 inch of runoff volume and often taken for the design requirements in order to be treated by the BMP facilities (Barrett et al., 1998). Deletic (1998) used the first flush definition as the first 20% of the runoff volume that contains higher concentrations of pollutants than the remaining period of runoff. A high first flush might be assumed when more than 50% of the total pollutant mass is delivered in the first 30% of the runoff volume, while a medium first flush exists if 30-50% of the total pollutant mass is delivered in the first 30% of the runoff volume (Kim et al., 2005). Another criterion of 0.75 inch of inclusive runoff (entire drainage area) as a first flush definition was introduced by Sansalone and Cristina (2004). Lee et al. (2011) concluded that the peak concentration for both TSS and COD occurs 20 minutes after the beginning of the runoff and starts decreasing after that, which indicates the occurrence of first flush. Barrett et al. (1995) reported that the first flush phenomenon is more common to occur with the dissolved constituents such as nutrients and lead. However, it is more complicated with respect to particulate matter (Barrett et al., 1995).
Deletic (1998) introduced two reasons for the inconsistency in the first flush definitions found in literature:

- The variations in sampling approaches; since some procedures tend to extend the lag time between samples collection. Therefore, an important portion of the runoff might be unsampled and misrepresented, especially in case of summer storms (small duration).
- The absence of triggering settings in the sampling methods which makes it ambiguous; since it might differ with respect to flow or rainfall triggering.

Hence, Deletic suggested the sampling trigger to be set according to the first tip of the rainfall and samples to be collected every 10 seconds along the duration of the event; thus, covering a wide and precise range of flow.

The importance of the first flush phenomenon comes from the fact that it is one of the significant reasons for the degradation of the aquatic receiving systems (Lee et al., 2002). By quantifying the amount of pollutants washed out from the surface of the highway, it can be determined if the treatment of the initial portion of the runoff is enough or the treatment of the whole runoff is desired (Cristina & Sansalone, 2003).

2.3.2 Water Quality Volume

Water quality volume represents the volume of storm water runoff producing the first flush, i.e., containing the majority of pollutants transported during a rainfall event, which should be captured and treated by the BMP (Cristina & Sansalone, 2003; ODOT, 2011a; Sansalone & Cristina, 2004; Sansalone et al., 1998). It can be calculated according to the following equation (ODOT, 2011a): 

\[
V_{\text{water quality}} = \frac{Q_{\text{first flush}}}{\text{flow rate}}
\]
\[ W_{Qv} = \frac{(P \times A \times C_q)}{12} \quad \text{Equation 2-11} \]

Where:

- \( W_{Qv} \) = Water quality volume (Acre-feet)
- \( P \) = Precipitation (0.75 inches)
- \( A \) = Contributing drainage area (acres)
- \( C_q = 0.858i^3 - 0.78i^2 + 0.774i + 0.04 \)
- \( I \) = Impervious area divided by the total area (use 0.9 within existing roadway for calculation purposes)

\( C_q = 0.9 \) when all drainage area is impervious.

The water quality volume corresponds to the first flush definition used widely in the literature. From OEPA and as used in ODOT permit, it is assumed that 0.75 inches of rainfall produces the water quality volume (ODOT, 2011a).

2.3.3 First Flush Parameters

There are several parameters controlling the occurrence and the features of the first flush such as runoff volume, rainfall intensity, traffic intensity, antecedent dry weather days, surrounding land use, and other site specific conditions which might control the first flush phenomenon including soil saturation, streets’ sweeping and wind direction (Kim et al., 2005).

The first flush definitions presented widely in literature are site specific; since they depend on the hydrology, site conditions and loadings (Sansalone & Cristina, 2004). Lee et al. (2002) stated that the area of watershed, rainfall intensity, impervious area and number of antecedent dry weather days control the first flush phenomenon. The
anthropogenic activities such as the variability of the traffic during the runoff might complicate the first flush definition (Sansalone & Cristina, 2004).

Deletic (1998) assumed that FF$_{20}$ (assuming the first 20% of the runoff volume represents the first flush) depends on the following parameters:

- Climatic characteristics: Number of antecedent dry weather days, total precipitation and water temperature.
- Rainfall characteristics: Rainfall intensity, maximum rainfall intensity and the time required to reach the maximum intensity.
- Runoff quantity characteristics: Volume and maximum flow rate.
- Runoff quality characteristics: Total, mean, range and maximum loading rate of each quality parameter.

Despite the above controlling parameters, Lee et al. (2002) found a low correlation between the percentage of impervious area and the occurrence of first flush. No correlation between the number of antecedent dry weather days and the first flush was noticed, while the rainfall intensity was found to inversely affect the trend of first flush due to the dilution effect (Lee et al., 2002).

The water quality parameters used to assess the existence and features of the first flush include heavy metals, oil and grease, nitrate, particulate matter, TSS, COD, orthophosphorus, TKN, conductivity, pH and temperature (Deletic, 1998; Kim et al., 2005; Lee et al. 2002; Sansalone & Cristina, 2004).

The first flush phenomenon was found more likely to occur in smaller watersheds than larger watersheds, especially, when the imperviousness increases, because in large
watersheds, the early runoff from areas far from the sampling location arrives and mixes with later runoff from early adjacent areas (longer travel time); thus, no pronounced peak in the pollutants’ concentrations can be noticed (Kim et al., 2005; Sansalone & Cristina, 2004).

2.3.4 Modeling Approaches and Results

Kim et al. (2005) used several regression, stochastic, and deterministic simulation models. For these models, the principal parameter is mass emission rate and its relation to the time. They investigated the first flush phenomenon with respect to site specific conditions on a small watershed and estimated the washed-off pollutants by assuming an initial pollutants’ mass existing on the surface of the highway, remaining mass after the runoff ends and added mass due to the atmospheric or vehicular depositions during the runoff. By applying a mass balance on these parameters, the washed-off mass can be determined. Based on the analysis conducted, the two parameters that showed a trend for a first flush are TSS and COD; 30% and 45% of the events showed medium and high first flush respectively.

Cristina and Sansalone (2003); Sansalone and Cristina (2004); Sansalone et al, (1998) investigated the existence of the first flush based on comparing the normalized total mass of pollutants delivered (M) and the normalized total volume of runoff delivered (V). Whenever M is greater than V, this indicates the occurrence of mass based first flush (MBFF).

They also used the water quality volume term to represent the first flush. Based on their findings in two urban highways in Cincinnati, OH, and Baton Rouge, LA, sites, it was
found that the criterion of 0.75 inch of inclusive runoff (entire drainage area) is an appropriate first flush definition (Cristina & Sansalone, 2003; Sansalone & Cristina, 2004; Sansalone et al., 1998). They also checked another definition of the first flush which is the transportation of 80% of the pollutants mass within the first 20% of the runoff volume, but the data from both sites did not meet this criterion.

Lee et al. (2002) conducted a study in Chongju, South Korea, to evaluate the first flush for residential and industrial runoff and compare it with results from the literature. Several approaches were proposed for defining the first flush. The graphical approach was used by plotting the partial normalized mass delivered at any time \( m \) versus the partial normalized total flow delivered at the same time \( q \). If the plot is located above the 45° line, a first flush exists.

Lee et al. (2002) proposed another approach by assuming an exponential relationship between \( m \) and \( q \), i.e., \( m = q^b \). When \( b \) is less than one, this implies the occurrence of first flush and when it decreases, the strength of the first flush increases (inversely proportional). Furthermore, a first flush can be judged by finding the difference between \( m \) and \( q \); \( \Delta = m - q \). If the maximum difference is greater than 0.2, first flush exists. The last approach is by computing the cumulative area ratio which can be determined by plotting both normalized cumulative mass and volume against the cumulative rainfall and finding the ratio between the areas under the cumulative normalized mass to volume curves. The data showed a strong first flush when using the difference method, i.e., for residential areas, TSS showed the strongest trend while for industrial, the orthophosphorus showed the strongest first flush trend. If using the
exponential relationship, the strongest trend was found for TKN and the weakest for TSS. Cumulative area ratio method showed that the strongest trend in the residential areas was recorded for COD while for the industrial, TKN showed the strongest trend (Lee et al., 2002).

Su and Mitchell (2006) investigated the existence of the first flush using a first order model which predicts the concentration of water quality parameters with respect to the initial concentration and the normalized cumulative runoff volume. The results indicated that there is a first flush with respect to TSS at the inlet of the studied wetland.

Deletic (1998) conducted a study on urban drainage systems in Belgrade, Yugoslavia, and Lund, Sweden. The quality parameters monitored included: TSS, conductivity, pH and temperature. The normalized cumulative mass and volume delivered were plotted for these quality parameters and the computed normalized cumulative pollutant masses delivered up to the time that 20% of the runoff was delivered was denoted as FF20. If FF20 is obviously higher than 20%, FF20 exists. No remarkable first flush was observed (FF20 : 25-30 %) (Deletic, 1998).

2.4 Experimental Approaches

2.4.1 Monitored Site Parameters and Apparatus

There are several in-situ parameters to be monitored that help characterizing and modeling the results. These parameters and the corresponding apparatus include:

- Runoff flow rate: can be measured by the following options:

  1. Flow meter (Kim et al., 2005).
2. Measuring the velocity and the depth of the flow by inserting a flow-velocity sensor in an opened manhole located in the storm water sewer system (Lee et al., 2002).

3. A channel having a V-notch weir and ultrasonic flow meter (Legret & Pagotto, 1999; Wu et al., 1998) or bubbler flow meter (Barrett et al., 1998) for measuring the flow levels in the channel.

- Rainfall intensity: Tipping bucket rain gauge (Barrett et al., 1998; Kayhanian et al., 2007; Kim et al., 2005; Lee et al., 2011; Legret & Pagotto, 1999; Wu et al., 1998).
- Traffic counting: Using a video camera (Deletic & Orr, 2005).

2.4.2 Sampling Methods

Sampling procedure is a vital point since it describes the best way to obtain representative samples. Several procedures were followed by researchers in order to obtain highway runoff samples, which were varied by the sampling method and apparatus used. The most common concept for sampling was the intensive sampling in the beginning of runoff and then the lag between samples is increased for the rest of runoff period. Kim et al. (2005) used a flow proportional automatic sampler for collecting composite samples. Five samples were obtained in the first hour of the event. Additional samples were obtained for the remaining time of the event. Sansalone and Teng (2004) used the same apparatus (automatic sampler) in which samples are poured into polypropylene bottles. However, the sampling lag was more intense; i.e., for the first 50 minutes of the event, samples were collected every two minutes, while for the remaining
of the PER discharge, a sample every (10-30) minutes was obtained. Barrett et al. (1998); Kayhanian et al. (2007); Lee et al. (2011); Legret and Pagotto (1999); Mitchell et al. (2002); Su and Mitchell (2006); Wu et al. (1998) utilized automated samplers (ISCO or American Sigma Automatic Sampler) for discrete and composite sampling. It also provides the flow rate values at different stages by converting the flow levels in the channel to flow rates. Composite sampling was achieved via collecting a fixed volume at intervals of equal flow.

Samples can be obtained manually. Sansalone and Cristina (2004) obtained the samples manually every (1-2) minutes. Lee et al. (2002) followed the manual sampling method by collecting samples at a frequency of (3-5) minutes until reaching the peak flow, and then the interval of sampling became (15-30) minutes. Snow samples are the best example of manual sampling, by which samples are taken at different distances from the curb (Engelhard et al., 2007).

Sediments, especially those retained in the flow channel, are collected manually (Legret & Pagotto, 1999; Mitchell et al., 2002). Other traditional sediments’ sampling methods include dry vacuuming and sweeping (Deletic & Orr, 2005). However, these dry methods are not capable of detecting sediments of smaller sizes; thus, Deletic and Orr (2005) introduced a new wet sampling method for dust/sediments sampling which was capable of collecting smaller particle sizes that the dry methods are not able to detect (smaller than 500 μm, particularly, smaller than 63 μm). Wet method is the simultaneous washing and vacuuming by having an enclosed area, sealed thoroughly to ensure that all
particles are restricted inside. Pressure deionized water washing is applied and then vacuumed (Deletic & Orr, 2005).

2.5 Best Management Practices for Storm Water Treatment

2.5.1 Best Management Practices (BMP’s) Definition and Objectives

BMP’s are in-situ engineering tools that manage the quality and quantity of storm water runoff, to reduce the physical, chemical and biological impacts on the receiving stream. The quality management is achieved by the removal of pollutants from the runoff (nonpoint source pollution) while the quantity management is the control of runoff volume and peak flow discharge (Kim et al. 2005; ODOT, 2011b).

Since the Clean Water Act (CWA) was enacted, the treatment of polluted water has focused mainly on the domestic and industrial wastewater. Consequently, the surface water quality has improved in the United States to meet the standards for water quality; thus, decreasing the water borne diseases (USEPA, 2004). However; the challenge remaining in the water quality is the storm water runoff pollution.

Storm water BMP’s were introduced in the 1960’s. Initially, the purpose of the BMP’s was to manage the quantity of the runoff, such as peak flow capturing (USEPA, 2004). However, the main objective of the BMP’s has recently become to restrict water constituents (in particulate or mobile form) from further movement within the runoff to avoid the negative impact on the receiving aquatic, terrestrial, animal or human life systems (Sansalone and Teng, 2004). It was discovered that the runoff contains high concentrations of constituents such as organics, herbicides, metals, nutrients and pesticides. Thus, US Environmental Protection Agency (EPA) requires regional urban
planning in order to reduce the amount of pollutants in the runoff (Kim et al., 2005). The general objectives for the BMP’s are summarized as follows (UESPA, 2004):

- Flood and peak discharge control.
- Water quality control.
- Groundwater recharge and channel protection
- Habitat protection and ecological sustainability strategies.

These objectives can be reordered and combined depending on the situation. For instance, in the water quality control, TSS is the most important parameter to be removed, and in general, the required percent removal is 80%. However, some states require removal of other water quality parameters such as metals (USEPA, 2004).

2.5.2 Projects Thresholds for Post-Construction BMP’s

According to Ohio EPA’s National Pollutant Discharge Elimination System (NPDES) general permit for storm water discharges, each project is classified based on its earth disturbing activities (EDA), which may be defined as any activity that exposes the bare ground to the runoff which will allow the runoff to pick up erodible materials from the surface of the ground. For instance, road construction and maintenance including the removal of pavement to the sub-grade is an EDA. Furthermore, areas where various seeding activities are applied are also included in the EDA. In general, for areas having an EDA larger than 1 acre, BMP will be required (ODOT, 2011a).
2.5.3 Treatment Requirements for New Construction Projects

According to ODOT (2011a), the BMP is required to treat 100% of the new impervious area and 20% of the existing impervious area; thus, the treatment percent weighted average can be estimated for a drainage area using the following equation:

\[ T = \frac{[A_{ix} \times 0.20] + (A_{in} \times 1.00)}{(A_{ix} + A_{in})} \]

Equation 2-12

Where:

\( T \) = Treatment percent (decimal)

\( A_{ix} \) = Existing impervious area (acres)

\( A_{in} \) = New impervious area (acres)

2.5.4 BMPs Types and Performance

BMP’s can be divided into two categories based on the functional performance (Kim et al., 2005; ODOT, 2011b; USEPA, 2004) as follows:

- Source control: This includes preventive actions to control the pollutant from reaching the runoff (e.g. covering storage area, drifting the runoff away from pollution sources, streets’ sweeping, spills’ prevention and household hazardous waste recycling programs and other educational ways).

- Treatment control: The removal of pollutants from a contaminated runoff (e.g. vegetated biofilters, ponds, infiltration, detention basins, wetlands and filters).

Most of the BMP’s are designed to treat the initial runoff delivering the elevated concentrations of pollutants, while the remaining flow bypasses without receiving any treatment (Sansalone & Cristina, 2004; Sansalone & Teng, 2004) such as partial
exfiltration reactor (PER), wet lands, hydrodynamic separators and filters and vegetated swales. TSS is often set as a target for BMP’s performance (Li & Davis, 2008).

The next section includes brief descriptions of each BMP type.

2.5.5 Most Popular Utilized BMP’s

2.5.5.1 Bioretention Cell

Bioretention cell is an example of a BMP capable of capturing suspended and dissolved solids in the water quality volume using a combination of soil, sand, and mulch as an adsorption-filtration media. The removal through bioretention is achieved by evapotranspiration and filtration through the soil during the ponding stage (Li & Davis, 2008; ODOT, 2011c). It has been concluded that finer grain size media results in better TSS removal and lower penetration depths through the media. Once the influent water filtrates through the soil, it will be captured and drained to an outlet through a perforated pipe. Bioretention proved efficient in the removal of TSS (55- > 99%), where highway runoff influent TSS to the facility ranged from 22 to 9025 mg/l, while the treated effluent TSS ranged from 10-225 mg/l (Li & Davis, 2008). Based on the lab tests conducted by Li and Davis (2008), the results underestimated the life time of the facility; since it was found that the decreased permeability can be recovered in-situ to a certain extent by biological factors such as earth-worms which loosen the structure of the soil.

2.5.5.2 Vegetative Filters

Vegetative filters (Grassy swales) are roadside vegetated graded shoulders and ditches sloped gently by which the pollutants in the highway runoff are removed via
sorption, precipitation, filtration, co-precipitation and biological uptake processes (Barrett et al. 1998; ODOT, 2011c; Wu et al. 1998).

There are several factors controlling the removal efficiency of the grassy swales such as grass type, grass density, blade size and shape, flexibility and texture of the grass cover and the area of vegetated zone (Barrett et al. 1998).

In a study conducted by Barrett et al. (1998) located in Walnut Creek road in Austin, Texas, they observed that the TSS concentrations of the runoff which has already infiltrated through a grassy ditch were significantly low (median 19 mg/l); thus, they decided to study the concentrations before the runoff reaches the ditch. The influent and effluent TSS concentrations were monitored for selected events. It was found that the TSS influent EMC was 77 mg/l while the effluent EMC was 35 mg/l with a reduction of 54% in the EMC and 82% in the TSS loads.

More than 16 studies have reported the effectiveness of biofilters in the removal of suspended solids. Peak flow discharge is also controlled with such facilities and groundwater recharge is provided (particularly for small storm events) (USEPA, 2004).

Despite the advantages of the grassy swales in the removal of pollutants from the runoff, some environmental risks might be generated (Barrett et al., 1998):

- Higher concentrations of fecal coliform and streptococcus from human origin imposing human health risk.
- Grassy swales may become a trap for hazardous materials such as gasoline spills.
2.5.5.3 Constructed Wetlands

Wetlands are heavily planted areas which contribute to the removal of aquatic pollutants from runoff through a set of processes (Mitchell et al., 2002; ODOT, 2011c) including:

- Biological processes: Uptake and transformation.
- Physical processes: Evaporation, sedimentation, emulsification, adsorption and filtration.
- Chemical processes: Chelating, precipitation, decomposition and chemical adsorption.

Wetlands are designed to maintain 0.5-2 feet of runoff during the dry weather period; therefore, a large surface area is required due to the limited allowable depth.

More than 11 studies on the wetland pond system and 5 studies on the extended detention wetlands have reported the effectiveness of this category of BMP’s on the removal of suspended solids. However, they do not provide groundwater recharge as well as not protecting the streams from erosion due to peak runoff (USEPA, 2004).

2.5.5.4 Ponds

This includes extended detention and retention basins. In case of extended detention, the runoff is captured and released over 48 hours; thus, reducing the peak flow and flooding possibilities. The storage volume is determined based on the water quality volume which has to be increased by 20% if sedimentation is to be considered. There are two types of the extended detention: detention basins and underground detention. The retention basin is a BMP that should contain a minimum level of water during the dry
periods (permanent pool); thus, placing the additional runoff over the existing level. It can accommodate 75% of the water quality volume. The full storage water depth is typically 3-6 feet (0.91-1.83 m) with a volume less than 15 Ac-ft (18,495 m$^3$). This BMP is good for large tributaries. However, it requires large space (ODOT, 2011c).

It has been reported in more than 33 studies that wet (detention) ponds were efficient in TSS removal. However, the physical impacts of ponds were not quite as efficient as the chemical impacts, i.e., ponds do not provide ground water recharge. Although ponds might control the peak discharge, they can cause downstream floods (USEPA, 2004).

2.5.5.5 Infiltration Trenches

Infiltration is the treatment of storm water runoff through the interaction of water constituents with the receiving media such as soil, sand or gravel. The filtered water is then discharged to the groundwater. Infiltration basin and infiltration trench are examples of infiltration systems designed to accommodate the water quality volume. Infiltration basin is an open surface that releases water to the ground through infiltration. This system is usually good for areas 5- 50 Acres. Infiltration trench is an excavated trench lined with filter fabric (geotextile) and filled with gravel (ODOT, 2011c).

In case of infiltration trenches, the soil to be used should generally have a minimum saturated infiltration rate of 0.5 in/hr. However, the problem associated with infiltration facilities such as infiltration trench is the clogging. It was reported that approximately 20% of infiltration trenches did not function properly as was designed to,
and one third of infiltration trenches showed extreme signs of clogging (Barrett et al., 1995).

Little information is available on the effectiveness of infiltration BMP’s on the removal of suspended solids. However; this type of BMP’s showed effective results on controlling the peak flow, reducing the runoff volume and recharging the groundwater (USEPA, 2004).

2.5.5.6 Filters

The most common type of filters is sand filters. According to USEPA (2004), one study has reported that sand filters can remove 87% of suspended solids and another study showed that sand/peat filters can remove 66% of suspended solids. However, sand filters are not designed for water quantity control such as controlling the peak flow (USEPA, 2004).

2.5.5.7 Manufactured Systems

Manufactured systems are usually underground structures located in manholes to allow for maintenance. Most of these systems treat the water quality flow by settling the particulate matter (ODOT, 2011c).

2.5.5.8 Summary of Performance of BMPs

The following table presents a summary of different types of BMP’s along with their efficiency in TSS removal.
Table 2.14: Median of TSS Influent and Effluent Average Concentrations for Different BMP’s Studied (Adapted from Geosyntec Consultants & Wright Water Engineers Inc, 2008)

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Sample Location</th>
<th>Detention Pond (n=25)</th>
<th>Wet Pond (n=46)</th>
<th>Wetland Basin (n=19)</th>
<th>Biofilter (n=57)</th>
<th>Media Filter (n=38)</th>
<th>Hydrodynamic Devices (n=32)</th>
<th>Porous Pavement (n=6)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suspended Solids</td>
<td>Influent</td>
<td>72.65 (41.70-103.59)</td>
<td>34.13 (19.16-49.10)</td>
<td>37.76 (18.10-53.39)</td>
<td>52.15 (41.41-62.88)</td>
<td>43.27 (27.25-59.58)</td>
<td>39.61 (21.95-76.27)</td>
<td>-</td>
</tr>
</tbody>
</table>

n = number of BMP’s reported

2.5.6 Removal Mechanisms

BMP’s can treat highway runoff by different mechanisms. The main removal processes occurring in the BMP’s are summarized as follows (USEPA, 2004):

- **Settling:** This mechanism is mainly used for the removal of soil particles and sediments. Moreover, other pollutants are also removed via this mechanism because metals and other pollutants are often attached to the surface of suspended solids. The most important factor controlling settling is the particle size. As the particle size of the settling solids increases, the settling velocity increases. Other factors might interfere with settling and reduce its rate such as turbulent flow eddies.

- **Filtration:** This mechanism is the removal of pollutants from the runoff by the passage through a filter material (typically sand or peat) which is placed in a trench. Filtration is capable of removing particulates and adsorbed pollutants; i.e., can remove suspended solids, organics and metals.
- Sorption: It is the cation exchange capability of filter particles to remove ionic pollutants from the runoff.

- Phytoremediation: It is the use of plants and trees to degrade and stabilize pollutants in the runoff by metabolism. In some cases, volatilization might be the way to get rid of organic compounds.

The following table combines the different types of BMP’s and the removal process occurring in each BMP type.

<table>
<thead>
<tr>
<th>Pollutant Constituents</th>
<th>Treatment BMP Type and Process Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Ponds</td>
</tr>
<tr>
<td>Heavy Metals</td>
<td>Sorption</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
</tr>
<tr>
<td>Toxic Organics</td>
<td>Sorption</td>
</tr>
<tr>
<td></td>
<td>Biodegradation</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
</tr>
<tr>
<td></td>
<td>Phytovolatilization</td>
</tr>
<tr>
<td>Nutrients</td>
<td>Bioassimilation</td>
</tr>
<tr>
<td></td>
<td>Phytoremediation</td>
</tr>
<tr>
<td></td>
<td>Sorption</td>
</tr>
<tr>
<td></td>
<td>Bioassimilation</td>
</tr>
<tr>
<td></td>
<td>Filtration</td>
</tr>
<tr>
<td>Solids</td>
<td>Settling</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
</tr>
<tr>
<td>Oil and Grease</td>
<td>Sorption</td>
</tr>
<tr>
<td></td>
<td>Settling</td>
</tr>
<tr>
<td>BOD5</td>
<td>Biodegradation</td>
</tr>
<tr>
<td></td>
<td>Biodegradation</td>
</tr>
<tr>
<td>Pathogens</td>
<td>Settling</td>
</tr>
<tr>
<td></td>
<td>Predation</td>
</tr>
<tr>
<td></td>
<td>Filtration</td>
</tr>
</tbody>
</table>

*Table 2.15: Removal Processes Occurring in BMP’s (Adapted from USEPA, 2004)*
2.5.7 BMP’s Clogging and Maintenance

BMP clogging is recognized by the gradual decrease of the BMP permeability until it becomes a relatively impermeable matrix due to the accumulation of suspended solids (Balades et al., 1995). The sand is often caught at the surface of permeable material. Clay particles (or any finer particles) are captured in the pores between sand particles (Balades et al., 1995). The suspended solids were found to be constrained in the effective surface area of the bioretention cell which extends to a depth of 15 to 20 cm from the surface (Li & Davis, 2008). However, Balades et al. (1995) concluded that clogging of the porous pavement is limited to the first two centimeters from the surface.

Researchers have demonstrated several methods for cleaning and unclogging porous pavements BMP facilities. Balades et al. (1995) investigated several cleaning methods such as moistening followed by sweeping, sweeping followed by suction, suction alone and high pressure water jet and suction (15-80 MPa). They found that the first two methods were not efficient since clogging particles tend to move deeper. However, the suction alone and the high pressure water jet and suction proved to be efficient ways for recovery.

Sansalone and Teng (2004) suggested that the trapped solids within the top layer of the tested trench (cementitious porous pavement) can be removed by modified street cleaning techniques such as water spray injections and subsequent vacuuming. For bioretention, the case is different, as the maintenance can be achieved by the periodic (1-2 yrs) removal of the effective surface media (Li & Davis, 2008).
As a preventive measure, some practices have to be followed during the construction of most BMPs, especially those depending on the infiltration of water through natural soil or the exfiltration to the surrounding soil. For instance, no traffic has to be allowed over the land surrounding the BMP so that not to compact the soil. Also, the excavation machine has to be selected carefully so that excavation process will not reduce the voids in the soil particles. Moreover, the runoff has to be diverted away from the facility before the completion of all construction facilities, because this runoff will contain plenty of sediments due to erosion, which leads to an early clogging (Barrett et al., 1995).

2.5.8 BMP Selection Criteria

The BMP should be selected in order to achieve the maximum treatment of runoff without affecting the design features such as road utilities (ODOT, 2011b). The main goal of using BMP’s is to reduce the physical, chemical and biological impacts of highway storm water runoff. However, BMP cost, ease of maintenance, and community acceptance should be taken in consideration for the design. Table 2.16 presents a comparison between different BMP’s with respect to economical, environmental and community factors.
Table 2.16: 
BMP Selection for Community and Environmental Factors (Adapted from USEPA, 2004)

<table>
<thead>
<tr>
<th>BMP</th>
<th>Maintenance Effort</th>
<th>Community Acceptance</th>
<th>Cost</th>
<th>Other Factors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ponds</td>
<td>Dry</td>
<td>Easy</td>
<td>Medium</td>
<td>Low</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>Medium</td>
<td>High</td>
<td>Trash and debris can be a problem</td>
</tr>
<tr>
<td></td>
<td>Wetlands</td>
<td>Medium/High</td>
<td>Medium</td>
<td>Medium/High</td>
</tr>
<tr>
<td></td>
<td>Infiltration</td>
<td>Trench High</td>
<td>High</td>
<td>Avoid large stones, frequent</td>
</tr>
<tr>
<td></td>
<td>Basin</td>
<td>Medium</td>
<td>Low</td>
<td>pooling</td>
</tr>
<tr>
<td></td>
<td>Biofilters</td>
<td>Low/Medium</td>
<td>High</td>
<td>Landscaping</td>
</tr>
<tr>
<td></td>
<td>Filters</td>
<td>High</td>
<td>Mixed</td>
<td>Out of sight, traffic bearing</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>filter media</td>
</tr>
</tbody>
</table>

2.5.9 Exfiltration Trench (ExT) as a BMP

ExT is a BMP installed parallel to the roadway that is a part of the shoulder concrete structure and placed a minimum of 15 feet prior to any drainage inlet, catch basin or curb cut. The main feature of the ExT is the use of permeable concrete and filter media to capture and treat the storm water runoff. Then the filtrated water reaches a 4-in perforated pipe connected to a 4-in nonperforated pipe which might discharge into drainage structure (ODOT, 2011c). The runoff bypassing the trench (untreated runoff) is discharged to the closest inlet; therefore, it is excluded from the next trench calculations (ODOT, 2011c). Figure 2.1 shows an exfiltration trench located in SR7, Marietta, OH. Exfiltration trench consists of three layers: pervious concrete, structural backfill type 3 (aggregate) and structural backfill type 2 (sand filter). Figure 2.2 shows the cross section of the exfiltration trench.
Figure 2.1: Exfiltration Trench Located in SR7, Marietta, OH

*Note:* This is not the trench on which this research was conducted

Figure 2.2: Exfiltration Trench Cross-Section- Drawing: WQ-1.3 (ODOT, 2010)

EXFILTRATION TRENCH
Cross-Section
(NTS)
There are some restrictions that might limit the use of the ExT, such as short sections less than 25 feet, small shoulders (less than 2-feet wide), parking areas, within a driveway return, or on a curved section. If the ExT is to be constructed in a superelevated roadway, it should not be placed on the high side (ODOT, 2011c).

A Partial Exfiltration Trench (PET) was designed and tested by Li et al. (1999). PET is a BMP facility which functions to control the quality and quantity of runoff due to the porous spaces and exfiltration through the soil (Li et al., 1999). The PET is 30 cm wide and consists of the following components:

- Porous pavement on the top (10 cm).
- Sand media extending (40-90 cm) below the pavement.
- 10-cm diameter perforated pipe (2% perforation).
- Surrounding (native) soil contributing to the exfiltration.

Similarly, Sansalone and Teng (2004), investigated the use of Partial Exfiltration Reactor (PER) as a BMP facility which partially treats the highway runoff by considering the initial runoff containing the highest concentrations of constituents. The components of the PER are similar to the previously used PET with minor modifications:

- Cementitious Porous Pavement (CPP) on top of the trench.
- Geosynthetic (GS) nonwoven spun bonded polypropylene layer under the CPP.
- Engineered filtration-adsorption media: oxide coated sand (OCS).
- Perforated pipe (PP) at the bottom surrounded by granular materials for the bottom drainage.
• The PER is surrounded by native clayey soil which allows the exfiltration through.

The performance of the PER was assessed based on quality and quantity measurements as follows (Sansalone & Teng, 2004):

• Quality Assessment
  1. Reduction of total pollutant runoff concentrations: 24-93% for metals, 23-86% for TSS and 37-70% for COD.
  2. Reduction of total mass: 57-98% for metals and 69-96% for TSS.

• Quantity Assessment:
  1. 55-70% reduction in the storm water volume.
  2. 36-85% reduction in the peak flow.

The water quality reductions are achieved via the PER components separately; the removal of TSS is achieved by the CPP layer, while the dissolved metals are removed by the OCS layer and the infiltrated solids are strained on the GS layer. The reduction in the volume of runoff (quantity removal) resulted from water exfiltration through the surrounding native clayey soil having a permeability of $K_{sat} = 1 \times 10^{-6}$ cm/s. The pH increased from 6.5 (influent) to 8.5 (effluent) by the infiltration through the CPP layer (Sansalone & Teng, 2004). The main feature of the PER is the usage of OCS, which enhances the adsorption ability more than the plain sand due to the relatively large surface area.
2.6 Clean Water Regulations

2.6.1 Clean Water Act (CWA)

The Clean Water Act (CWA) is an expansion of the Federal Water Pollution Control Act which was enacted in 1948 and was reorganized in 1972. However, the name CWA corresponds to the amendments in 1977. CWA’s main concern is the quality of navigable waters of the United States for fishing and swimming by regulating the discharge of pollutants by individuals or corporations into water bodies. It also authorized the U.S. EPA to set the standards for water quality such as the maximum contaminant levels in drinking water and standard effluent levels. Moreover, the U.S. EPA is required under this Act to develop and implement the National Pollutant Discharge Elimination System (NPDES) permit program (USEPA, 2004).

Several revisions to the CWA took place afterwards. For example, the 1981 revisions included increasing the capabilities of treatment plants built under the construction grants program which was initiated under the 1977 amendments. However, this program was replaced by the Clean Water State Revolving Fund in 1987. This new funding strategy addressed the EPA-state partnership in order to meet water quality needs. This system varies whether the responsibility of the implementation of NPDES program lies on the state or the U.S. EPA. In 1987 amendments, municipal and industrial storm water was addressed as point source discharges (USEPA, 2004).

2.6.2 National Pollutant Discharge Elimination System (NPDES)

This program was introduced in 1972 under the CWA to control water pollution in the United States by regulating the point source pollution and enforcing effluent
limitations. Point source pollution is any discrete or confined conveyance that causes contamination to the environment. Since the NPDES was issued, the amount of safe water for swimming and fishing in the United States increased from one third to two thirds of the nation’s waters. One of the NPDES areas is storm water runoff. In this section; the storm water runoff is addressed as a point source pollution resulting from the flowing of runoff over impervious paved surfaces and picking up various pollutants such as debris, chemicals and sediments. The main target of this permit is to prevent the discharge of the pollutants washed with the runoff into the water bodies such as streams, rivers, lakes or coastal waters. This permit covers three possible sources of pollution: municipal separate storm sewer systems (MS4s), construction activities (one acre or larger) and industrial activities. The operators of such facilities might be required to obtain a permit under the NPDES program to discharge the runoff (USEPA, 2004).
CHAPTER 3: METHODOLOGY

3.1 Trench Installation

The exfiltration trench was installed on August 6th, 2010, on State Route 7, Marietta, OH. The installation was carried out under a traffic control set by the ODOT in order to ease the work and to ensure the safety of the workers. The frame work of the trench was prepared by the contractor in the concrete shoulder next to the curb in the previous season and was filled with sand. The trench dimensions are 9.75 in wide, 18 in deep, and 16 ft long. A 4-in perforated pipe surrounded by granular material was placed underneath the trench to receive the treated water. Figure 3.1 shows the empty trench prior to materials installation. The trench installation was accomplished according to the following steps:

Figure 3.1: The Empty Trench Prior to Materials Installation
1- After removing the sand from the trench, cleaning and leveling the trench bottom, a ¼” thick polypropylene board that has the same width as that of the trench was placed at the bottom, so that all water flowing to the bottom will be directed toward the effluent collecting probe. This board extended from the beginning of the trench until approximately 2 ft before the end leaving a space to place the effluent collecting probe. See Figure 3.2.

Figure 3.2: Trench Bottom after Installing the Polypropylene Board

2- A 4-in PVC pipe was placed at the end of the trench bottom perpendicular to the curb in which the effluent sampler collecting probe and flow bubbler were laid as shown in Figure 3.3. One quarter of the pipe’s perimeter was cut so that its edge matches the polypropylene board; and therefore, the water passing the
geotextile and flowing over the board will be discharged to the pipe. Two holes were drilled in the back so that when the level of water reaches 3 in, it will drain. This pipe was fixed to the trench walls and connected with another 3-in PVC pipe that extends from the bottom of the trench and connects with another pipe through a hole cored out in the curb that eventually ends in the effluent sampler cabinet as shown in Figure 3.3.

![Figure 3.3: Effluent Collecting Probe Location](image)

3- The geotextile fabric was then placed on top of the board covering the bottom pipe. The geotextile layer extends from the bottom to the top of the concrete shoulder. Figure 3.4 illustrates the installation of the geotextile layer.
4- The three layers (sand, aggregate and concrete) were installed respectively. Each layer was 6 in deep. Figures 3.5 and 3.6 show the installation of the three layers. In Figure 3.6, the left end of the trench was isolated by a polypropylene board so that to place piezometric tubes at the interfaces between layers.
Figure 3.5: Aggregate and Sand Layers Installation

Figure 3.6: Concrete Layer Installation
5- A tipping bucket rain gauge (ISCO 674) was positioned on a stand that is 1.5 m high from the ground and its cable was connected with the influent sampler through 3-in PVC buried pipes. Figure 3.7 shows the rain gauge set-up.

6- The influent sampler collecting probe and flow bubbler were placed in a small groove on top of the concrete shoulder prior to the trench. The collecting tube extends to the influent sampler cabinet through a 3-in PVC buried pipe. Figure 3.8 shows the trench surface and the influent collecting probe groove. The piezometric tubes were located at the interfaces between each layer inside and outside the barrier as shown in Figure 3.8. Figure 3.9 shows the finished trench surface, influent and effluent samplers, rain gauge and the pervious concrete specimens.
Figure 3.8: The Finished Trench Surface and Influent Collecting Probe Groove

Figure 3.9: The Finished Trench Surface, Sampling Apparatus and Pervious Concrete Specimens
3.2 Trench Maintenance

The trench was clogged after event 20 (November 3\textsuperscript{rd}, 2010); which was recognized when the effluent sampler stopped collecting samples for this event and the previous event, which meant that water is not passing through the pervious concrete. Also the trench surface was completely covered with a considerable amount of soil; which clogged the surface pores of the concrete layer as shown in Figure 3.10. After the clogging of the trench; maintenance was performed to the trench on November 16\textsuperscript{th}, 2010. The ODOT staff used a vacuum truck to vacuum the surface. The maintenance process is explained in the following steps.

Figure 3.10: The Clogged Trench Surface
A- Prior to Maintenance

It was raining and the runoff was almost covering the surface of the trench as shown in Figure 3.11.

![Figure 3.11: The Runoff Prior to Maintenance](image)

B- Vacuuming process

This was performed with the aid of the vacuuming truck shown below. The trench surface was vacuumed for about 15 minutes. This was sufficient to remove the solids entrapped within the surface of the trench. Figure 3.12 illustrates the vacuuming process.
C- Pressure washing:

This process was performed in order to remove more solids entrapped at deeper depths. It lasted for almost 15 minutes. Figure 3.13 shows the pressure washing process.
D- Simultaneous pressure washing and vacuuming

In this step, both pressure washing and vacuuming were done at the same time as shown in Figure 3.14; so that the vacuum can pick up the solids washed out from the trench. This process lasted for almost 15 minutes.
After the whole process of vacuuming and pressure washing, the effluent sampler started collecting some samples which were a mix of the runoff and the water jet through the trench. This maintenance process targeted the concrete layer by washing and vacuuming the solids entrapped within the concrete pores; which indicates that the clogging is more likely to occur in the concrete layer (particularly the top surface). Figure 3.15 shows the trench surface after maintenance.
3.3 Tap Water Test

After the maintenance was performed to the trench, a tap water test was carried out on November 24th, 2010, in order to investigate the contribution of the trench materials to the effluent total suspended solids. The weather was cloudy but the pavement was entirely dry so that no runoff interfered with the test. This test was performed by introducing 120 gallons of tap water influent to the trench using a hose as shown in Figure 3.16. As the water reached the effluent collecting probe, the effluent sampler was triggered to start collecting samples based on a 2-cm water level detected by the attached flow bubbler. A total of six effluent samples were collected with a total volume of 5.53 L as shown in Figure 3.17. This implies that the majority of the influent was not directed
toward the effluent outlet, which might be due to saturating the trench materials (porous concrete, aggregate and sand layers) or the water might be leaking out to the sides of the trench without being directed toward the collecting point. Similar test was performed on the reconstructed trench on July 6th, 2011. The results for both tests are presented in Chapter 4.

Figure 3.16: Introducing Tap Water Influent to the Trench
3.4 Exfiltration Trench Demolishing and Reconstruction

The trench monitoring after maintenance continued until the second clogging took place. The last event monitored was on April 11\textsuperscript{th}, 2011 (Event 39-2). Again, the effluent sampler stopped collecting samples which indicated the clogging of the trench. The trench surface accumulated significant amounts of sediments and debris; thus, the water was not filtering through the concrete layer as shown in Figure 3.18. Therefore; the trench materials were removed and the trench was reconstructed again on April 28\textsuperscript{th}, 2011. The same installation protocol as described in Section 3.1 was followed except that the geotextile layer was not raised to the street surface as shown in Figure 3.19; instead, it was raised to the interface between sand and aggregate layers. This change in geotextile layer installation was because the first set-up was thought to create water passages between the trench wall and the geotextile layer; therefore, the water moves down without receiving any treatment through trench materials. The depths of concrete and
sand layers remained unchanged (6”). However, the aggregate layer depth was decreased 
(depth= 4 →) because the trench bottom level was originally raised in order to cover the 
holes at the lower part of the trench wall.

Figure 3.18: The Clogged Surface of the Trench

Figure 3.19: Sand Layer Installation in the Reconstructed Trench
3.5 Site Media Samples

3.5.1 Concrete Specimens

Three concrete specimens from the pervious concrete used in the trench construction (original and reconstructed) were poured in acrylic cores (4-in diameter and 6-in height) according to ASTM C 192/ C 192 M (ASTM, 2006a). Specimens were cured for 7 days by covering them with a moist cover at a temperature range of 68 to 86°F (20 to 30°C). Those specimens were tested by falling head permeability test. Figure 3.20 shows three concrete specimens and the effluent from the first tap water permeability run on the first specimen.

When the original trench was replaced for reconstruction, there was an attempt to obtain concrete cores. However, the samples crumbled and disintegrated.

Figure 3.20: Pervious Concrete Specimens and the 1st Tap Water Permeability Effluent of Specimen #1
3.5.2 Aggregate and Sand

Samples of aggregate and sand were obtained at the time of installation of the original trench, at the end of operation of this trench and when the trench was reconstructed. Samples for permeability test and particle size analysis were then obtained from each bucket. Figure 3.21 shows the crumbled concrete, aggregate and sand samples from the original trench at end of operation.

![Samples from the Demolished Trench](image)

Figure 3.21: Samples from the Demolished Trench

3.6 Site Media Samples Testing

3.6.1 Falling Head Permeability Test

This test was used to measure the hydraulic conductivity of pervious concrete and aggregate. It was performed according to the approach described by Meininger (1998). This test was performed on concrete specimens from the original trench (installation) and
from the reconstructed trench. Aggregate samples from the original trench (installation and after demolishing) and from the reconstructed trench were tested according to this procedure as well.

3.6.1.1 Apparatus

- I-shaped vertical acrylic permeameter, 4-inch diameter, with the sample being fixed between two rubber connectors as shown in Figure 3.22. The permeameter is mounted against the wall by a steel ring that connects the pipe with a steel arm fixed to the wall. The flow of water through the permeameter is controlled via a rubber bladder plug.

- Electronic sensor with two rings placed at a predefined distance on the pipe, which provides accurate reading of the time required for the liquid to drop between the two rings by detecting the fiber optic light between the two opposite points on each ring.

- 15-Liter buckets.

- AND GP-12k digital scale with a maximum mass reading of 12 kg, and an accuracy of 0.1 g.

- Tape Measure.

- Thermometer.

- Source of tap water and hose if needed.
3.6.1.2 Procedure

1. The mass of empty mold and mass of mold and concrete specimen are measured; therefore, the dry mass of concrete specimen can be obtained by subtracting the two weights.

2. The height of the specimen is measured at three different locations on the surface; since it is not expected to be flat. The average of the three height readings is recorded as the average height of the specimen.

3. The concrete specimen is then inserted into the permeameter between the two rubber connectors and the screws are tightened so that to ensure no leakage will
happen. The specimen is inserted leaving the irregular surface on the top and the more leveled surface in the bottom.

4. The distance between the two rings of the sensor is set equal to 18 inches. The distance between the upper ring and the bottom of concrete specimen is measured and recorded as $h_1$ and the distance between the lower ring and the bottom of concrete specimen is measured and recorded as $h_2$.

5. The electronic sensor is plugged in an electricity outlet, and checked if it is in the correct mode to start the test (The 0 and 1 lights should be on). The rubber plug is fixed tightly under the sample and an empty bucket is placed underneath to collect the effluent.

6. 10 L tap water is poured in the permeameter by using a hose connected to tap water faucet. The specimen is then left to get saturated in water for approximately 15 minutes.

7. The rubber plug controller is then released and the time required for the water to travel between the two rings is recorded automatically by the electronic sensor. The effluent water temperature is measured and the effluent bucket is then removed, weighed, covered and kept at 4°C for TSS analysis.

8. Same procedure is repeated twice more with the introduction of another 10 L tap water each time. Thus, the total amount of influent tap water introduced is 30 L. Also, the effluent collected from the second and third run is kept at 4°C for TSS analysis.
9. The tap water permeability for the concrete specimen is the average of the permeability for the three runs.

10. Same procedure was followed for testing the tap water permeability of aggregate.

   The coefficient of permeability, \( k \), is computed according to the following Equation:

\[
k = \frac{L \times \ln(h_1 / h_2)}{t}
\]

Equation 3-1

Where:

\( k \) = Coefficient of permeability (cm/s).

\( L \) = Length of the sample (cm).

\( h_1 \) = Initial height of water in the permeameter (at the upper ring) (cm).

\( h_2 \) = Final height of water in the permeameter (at the lower ring) (cm).

\( h_1 - h_2 = 18 \text{ in.} \)

\( t \) = Time (s).

The coefficient of permeability is then corrected to 20°C by multiplying the permeability obtained at the test temperature with the ratio of water viscosity at test temperature to water viscosity at 20°C.

3. 6.2 Constant Head Permeability Test

This test is used to measure the hydraulic conductivity of fine grain soils, such as sand. It was performed according to ASTM D2434 – 68 (ASTM, 2006b). This test was performed on sand samples from the original trench (after installation and after demolishing) and from the reconstructed trench.
3. 6.2.1 Apparatus

- Constant head permeameter, 3-inch diameter and 6-inch height, with tubing outlets.
- Manometer tubes attached to a metric scale.
- Tubes to connect the permeameter outlets with the manometer and with the collecting bucket.
- Graduated cylinder.
- Stop watch.
- Thermometer.
- 15-L buckets.

Figure 3.23 illustrates the constant head permeability test set-up.
3. 6.2.2 Procedure

1. The sand is placed in the permeameter, and the top surface was leveled so that the height of the sand sample will be the same as the permeameter height. The surface is then covered with a screen and a spring is placed on top and compressed with the permeameter cover.

2. Tubes are connected between the two drainage outlets located on the permeameter wall and the manometer tubes. Another tube connects the bucket that is located at higher elevation which maintains a constant volume of water (5 L water) and the outlet on top of the permeameter. Finally, a tube is connected to the bottom outlet of the permeameter to drain the effluent to a separate bucket.

3. Tap water is introduced to the sample by filling the constant volume bucket with 5L and the feeding 10-L bucket is filled as well. The feeding bucket is located at higher elevation than the constant head bucket. The drainage valve of the 5-L bucket is released so that the water starts flowing through the sand sample. The 5-L bucket is monitored to ensure that the water volume does not go below 5 L; therefore, the drainage valve of the feeding bucket is released to compensate for any volume loss.

4. When a steady state condition is reached, which can be observed by the evacuation of all air bubbles from the sand voids, and the manometer readings become more stable, the permeability readings can be taken. This is achieved by collecting a volume of water from the effluent drainage tube into a graduated
cylinder for certain duration (60 seconds). The head values are recorded from the
two manometer tubes.

5. Repeat step 4 until the volume of water in the feeding bucket is entirely
consumed. Record all data and find the average permeability. The effluent water
temperature is measured and the effluent bucket is then removed, weighed,
covered and kept at 4°C for TSS analysis.

6. This procedure is repeated with the introduction of another 10-L tap water to the
feeding tank twice; thus, following the same protocol testing for all site materials
by introducing a total of 30 L tap water at three consecutive runs for each sample.
The coefficient of permeability, $k$, is computed according to the following
Equation:

$$k = \frac{Q L}{At \Delta h}$$

Equation 3-2

Where:

$k$ = Coefficient of permeability (cm/s).

$Q$ = Water discharge (ml).

$L$ = Distance between the two manometer outlets on the permeameter wall (cm).

$A$ = Cross-sectional area of specimen ($cm^2$).

$t$ = Total time of discharge (s).

$\Delta h$ = Difference in head on manometer (cm).

The coefficient of permeability is then corrected to 20°C by multiplying the
permeability obtained at the test temperature with the ratio of water viscosity at test
temperature to water viscosity at 20°C.
Two other sand samples were tested following the same procedure, so that the average coefficient of permeability of the site sand is the average of the three samples.

3.6.3 Particle Size Analysis

Particle size distribution test was performed on the aggregate and sand samples according to ASTM D422 – 63 (ASTM, 2007). Aggregate and sand samples were obtained and passed through a set of standard sieves in order to obtain the weight retained on each sieve.

3.6.4 Porosity Test

The porosity of concrete and aggregate was determined according to ASTM-SEDL (Montes et al., 2005).

3.7 Runoff Sampling Procedure

3.7.1 Samplers Programming and Triggering

Two ISCO 6712 automatic samplers were used to collect influent and effluent runoff samples. Each sampler is equipped with a 12-Volt battery as an electricity source. Attached with each sampler is an ISCO 730 bubbler flow module, which records the level of flow time-wise. The influent sampler is also connected to an ISCO 674 rain gauge which records the instantaneous precipitation. Each sampler can collect up to 24 samples filled in bottles or bags. The samples’ liquid volume is to be determined which can be up to 1 L. Samples were collected in low density polyethylene (LDPE) disposable plastic bags caged in reusable polypropylene plastic holders.

The influent sampler was programmed to start collecting samples after a 0.02-m flow level is detected by the flow bubbler. This program caused the sampler to start
sampling regardless of rainfall events; i.e., a side flow that is 0.02-m deep will cause the influent sampler to start collecting samples. Therefore, the program was modified after event 6 (Sep 3rd, 2010) to start collecting influent samples based on a trigger of 0.01-in precipitation detected by the rain gauge and a minimum flow level of 0.02-m measured by the flow bubbler. This modification in the program solved the problem of fake events. However, the problem of low volume influent samples existed even with this modification. As a result, the program was modified after event 12 (Sep 27th, 2010) to trigger the influent sampler according to a 0.035-m flow level only and collect samples every five minutes so that covering a wide range of event duration is assured. This means that the rain gauge was not involved in the triggering process. Instead, the rain gauge data were useful to record the instantaneous rainfall during the event which can be used then to compute the cumulative rainfall at sampling times. The raise in the flow level (0.02m to 0.035m) was to ensure that there is enough flow at the moment of sampling so that the sample volume will be approximately 1 L without having the program stopped due to insufficient flow. Another advantage of this modification is that coupling the rain gauge and flow bubbler trigger will eliminate sampling at later parts of the event; since the rainfall stops while the runoff keeps flowing.

The effluent sampler was triggered to start collecting samples at 0.02-m flow level detected by the flow bubbler attached to it. The effluent sampler was not connected to the rain gauge; therefore, the sampling process does not depend on the rainfall data. The problem of low volume samples also existed in the effluent samples; therefore, the program was modified after event 12 by raising the level of flow to 0.03 m, which
resulted in almost 1-L effluent samples. The program was modified again to trigger the effluent sampler according to 0.02-m flow level after event R2 (May 15th, 2011) because effluent samples were low in volume (the majority of samples were 50-200 ml volume) in an attempt to get more volume samples.

3.7.2 Preservation of Samples

After each rainfall/snow event, samples were retrieved from the site and brought back to Stocker labs at Ohio University. Samples were either distributed immediately or stored at 4°C for 1-2 days.

3.7.3 Distribution of Samples

The ideal case is to have full set of 1-L samples (24 influent and 24 effluent samples). However, the number and volume of the samples depend on the event characteristics such as rainfall duration and the total precipitation. Assuming the ideal condition, the samples obtained from each 1-L sample bottle were distributed for analysis according to the following division:

- Two 200-ml TSS samples for the first 12 bottles and one 200-ml TSS sample afterwards. However, TSS sample volume was prone to change depending on the liquid availability.

- Two 14-ml samples for total metals (TM), two 14-ml samples for dissolved metals (DM) and two 2-ml samples for COD for the 1st, 5th, 9th, 13th, 17th and 21st bottles. Otherwise, only one sample was obtained for each water quality parameter from each bottle.
- Particle size samples were obtained from the odd numbered samples until bottle #12. The volume of particle size samples was not fixed; since it depends on the concentration of SS (if the sample is heavily polluted, less volume was needed and vice versa).
- One 200-ml oil and grease sample was obtained from the even numbered samples until bottle #12.
- 25-ml turbidity samples were obtained from all samples.
  This procedure was followed even when the number of bottles was less than 24. If the original sample volume was not enough to obtain all above samples, the priority was given to the TSS and metals respectively.

3. 8 Samples Analyses Procedures

3. 8.1 Total Suspended Solids

TSS was performed on runoff samples according to APHA Standard Method #2540. Samples are filtered on 0.45 μm fiber glass filters and oven dried at 103-105 °C. The residue is then weighed and the TSS concentration is given by dividing the mass of the residue (mg) by the sample volume (ml) (Clesceri et al., 1998). Figure 3.24 shows the TSS apparatus.
3. 8.2 Turbidity

Turbidity is a measure of water cloudiness which can be caused by suspended solids such as sand and silt. Also turbidity reflects the amount of microorganisms in water such as bacteria. Turbidity was measured using DRT-15CE Portable Turbidimeter which has a resolution of 0.01 NTU and can measure up to 1,000 NTU.

3. 8.3 pH

The pH is a measure of water acidity or basicity. It was measured for runoff samples prior to samples’ distribution (after samples refrigeration) by pH standard probe. However, after event 24, pH and temperature were obtained after samples were retrieved in the site. The HI 98280 Multiparameter Water Quality Meter was used to measure the pH of runoff samples.
3.8.4 Particle Size Analysis

The particle size analysis was performed using Beckman Coulter LS 230. This instrument finds the particle size distribution based on laser diffraction. The scattered lights reflected from the particles are collected and analyzed over a range of angles. The intensity and scattering angle data are then converted by built-in software to a continuous particle size distribution (by volume). The range of sizes covered is 0.375μm – 2,000μm (Beckman Coulter Inc., 1994). Sample volume varies depending on the amount of solids in the sample; therefore, the volume was not fixed for all samples (range: 50-300 ml). When the sample is loaded, the load obscuration should be monitored until the ―Ok‖ sign appears on the software, which means that the sample load is enough for analysis. If the ―Low volume‖ sign appears, more volume of the sample is to be added. The cycle options are determined from the software and then the sample is run three times. The Beckman Coulter software averages the three runs. The results include the volumetric distribution of the particles over the size range with upper and lower limits of volume percent at each size. The data can be converted to spreadsheets (Beckman Coulter Inc., 1994). Figure 3.25 shows the particle size analysis apparatus.
3.9 Runoff from Concrete Sawing

This test was performed to evaluate the trench materials performance on treating high pH water. The influent was prepared by sawing concrete cores and mixing the resulting concrete particles with tap water until the pH exceeded 11.00. The treatment efficiency is assessed based on the ability to reduce the pH to its natural values (7-8). Figure 3.26 shows the mixing of high pH influent.
3. 9.1 Tested Samples

Sand and aggregate samples obtained from the materials installed in the original trench were used for this test.

3. 9.2 Testing Trials

3. 9.2.1 Test # 1 (04-11-2011)

A sand sample from the original trench sand was placed in the constant head permeameter (3-inch diameter and 6-inch height), and an influent of concrete sawing water was introduced (pH= 11.62). Same constant head permeability test methodology used before was followed. No effluent was obtained since the sample was completely clogged.

3. 9.2.2 Test # 2 (04-11-2011)

The same constant head permeability test methodology was followed, but this time a combination of aggregate and sand was placed in the constant head permeameter.
The upper half was filled with aggregate from the original trench aggregate (the upper 3 inches of the permeameter) while the lower half contained sand similar to what was used in test #1 (the lower 3 inches of the permeameter). The permeability could not be measured since the flow was very slow. However, the sample was left to drain to the next day (almost 24 hours) collecting approximately 700 ml effluent. Figure 3.27 shows the tested sample before and after the test.

On the same day of effluent retrieval, the aggregate layer was removed completely from the permeameter using a spoon, leaving the sand layer which seemed to be unclogged or even the concrete sawn particles have not penetrated through. To check if the sand was clogged or not, distilled water was poured over the sand directly on top (not following the standard constant head procedure) and it was observed that it drained normally without being delayed.

Figure 3.27: Test #2 Sample before and after the Test
3. 9.2.3 Test # 3 (04-14-2011)

In this test, 10 L of the concrete sawing water was fed through the falling head permeameter, in which an aggregate sample was fixed (4-inch diameter and 6-inch height). The permeability of the concrete sawing water through the aggregate was calculated based on the time required for water level in the permeameter to drop a predefined distance of 18 inches. The effluent from the falling head permeability test was then used as an influent for the constant head permeability test on a new sand sample. Note also that approximately an additional 7 L influent (high pH influent) was fed through the falling head permeameter in order to get additional effluent falling head volume to enable the constant head permeability testing, since the constant head test setup requires two containers: the first one which should be kept at a constant level (5 L) and the second one (feeding tank: 10 L liquid volume) draining water to the constant head container to compensate for the level decrease due to the water flow through the sand sample. The constant head test proceeds until the feeding tank gets empty; thus, the total amount of influent that is assumed to pass through the sand sample is 10 L. Two approaches were followed for the constant head permeability test by preparing two sand samples: The first sample was placed in the sampler without receiving any washing (as brought from the site); while the other sample was subjected initially to 10 L tap water to pass through for the purpose of washing, but not following the standard constant head permeability test. The falling head permeability of concrete sawing water through the aggregate (k@20°C) was estimated to be 1.77 cm/s. Again, the water drainage through the sand was very slow, and the head difference between the two permeameter outlets
could not be estimated (no reading could be obtained from the attached manometers); therefore, the permeability could not be estimated. Figure 3.28 shows the unwashed sand sample surface after the test.

Figure 3.28: Sand Sample Surface after Test #3 (Unwashed)
CHAPTER 4: RESULTS AND DISCUSSION

4.1 Exfiltration Trench Materials Testing

4.1.1 Pervious Concrete Specimens

Concrete specimens were obtained and tested from the original trench and the reconstructed trench. Three concrete specimens were obtained at the time of construction. There was an attempt to obtain concrete cores from the original trench prior to demolishing; however, concrete specimens crumbled.

Pervious concrete specimens were tested for tap water permeability and porosity according to the procedures described in Chapter 3. In the falling head test, the permeability is calculated according to Darcy’s law assuming that the flow is laminar (Mahboob, 2011). However, Mahboob (2011) indicated that the flow regime in the same permeameter used was transient; and hence, the relationship between the velocity (v) and the hydraulic gradient (i) is not linear. Mahboob investigated the relationship between i and v assuming a turbulent flow condition and obtained the following relationship:

\[ i = -0.0398v^2 + 2.25v - 27.759 \]  
Equation 4-1

The permeability of a pervious concrete specimen was computed based on both Darcy’s law and the turbulent flow formula obtained. The percent difference between the two approaches was 6%, so he used Darcy’s law to calculate the pervious concrete specimens’ permeability. Moreover, the field conditions are not similar to lab conditions; since the elevation and velocity heads in the lab are significantly higher than the field (Mahboob, 2011).
4.1.1.1 Original Trench Concrete Specimens

Tap water permeability, porosity and TSS results for the pervious concrete specimens from the original trench are presented in Table 4.1.

**Table 4.1:**
*Summary of Tap Water Permeability, Porosity and TSS Results for Concrete Specimens from the Original Trench*

| Specimen No. | Specimen Volume | Test No. | 
|--------------|----------------|---------|----------------|
|              | cm³             | cm/s    | cm/s           | %   | mg | mg | mg/cm³ | mg/L |
| 1            | 1235.56         | 1       | 3.243          | 3.233 | 41.4 | 219.43 | 291.71 | 0.2361 | 9.724 |
|              |                 | 2       | 3.216          | 3.221 | 39.4 | 182.02 | 211.63 | 0.1667 | 7.054 |
|              |                 | 3       | 3.241          | 3.281 | 32.8 |               |         |          |        |
| 2            | 1269.88         | 1       | 3.132          | 3.149 | 38.4 | 182.02 | 211.63 | 0.1667 | 7.054 |
|              |                 | 2       | 3.134          | 3.134 | 39.4 | 19.52  | 211.63 | 0.1667 | 7.054 |
|              |                 | 3       | 3.182          | 3.182 | 32.8 | 10.09  | 211.63 | 0.1667 | 7.054 |
| 3            | 1235.56         | 1       | 3.805          | 3.799 | 40.8 | 120.11 | 146.52 | 0.1186 | 4.884 |
|              |                 | 2       | 3.786          | 3.786 | 40.8 | 22.24  | 146.52 | 0.1186 | 4.884 |
|              |                 | 3       | 3.805          | 3.805 | 40.8 | 4.17   | 146.52 | 0.1186 | 4.884 |
| Average      |                 |         | 3.394          | 40.2  |      | 216.62 | 0.1740 | 7.221  |        |

Based on the data presented in Table 4.1, the average tap water permeability of the original trench pervious concrete specimens is 3.39 cm/s and the average porosity is 40.2%. The average TSS mass recovered from each specimen is 216.6 mg. TSS is also expressed as the average TSS recovered per specimen volume; thus, estimating the amount of TSS in the concrete layer in the field according to the following equations:

\[
TSS \text{(Concrete Layer)} = TSS \text{ (mg/cm}^3 \text{ sample)} \times \text{Volume of the concrete layer}
\]

Equation 4-2
Field concrete layer volume = 6.5 ft³.

Estimated TSS from the concrete layer = 0.174 mg/cm³ × 6.5 ft³ × 28316.8 cm³/ft³ = 32.03 g

4.1.1.2 Reconstructed Trench Concrete Specimens

Tap water permeability, porosity and TSS results for the pervious concrete specimens from the reconstructed trench are presented in Table 4.2.

Table 4.2:
Summary of Tap Water Permeability, Porosity and TSS Results for Concrete Specimens from the Reconstructed Trench

<table>
<thead>
<tr>
<th>Specimen No.</th>
<th>Specimen Volume (cm³)</th>
<th>Test No.</th>
<th>k_{@20°C} (cm/s)</th>
<th>Average k_{@20°C} (cm/s)</th>
<th>Porosity (%)</th>
<th>TSS Recovered (mg)</th>
<th>Total TSS Recovered (mg)</th>
<th>TSS/Specimen Volume (mg/cm³)</th>
<th>TSS/Influent Volume (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1235.56</td>
<td>1</td>
<td>1.975</td>
<td>2.192</td>
<td>31.4</td>
<td>280.26</td>
<td>423.8547</td>
<td>0.3430</td>
<td>14.128</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.282</td>
<td></td>
<td></td>
<td>94.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.320</td>
<td></td>
<td></td>
<td>48.81</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1235.56</td>
<td>1</td>
<td>3.078</td>
<td>3.116</td>
<td>35.6</td>
<td>117.34</td>
<td>251.8012</td>
<td>0.2038</td>
<td>8.393</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>3.127</td>
<td></td>
<td></td>
<td>105.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>3.143</td>
<td></td>
<td></td>
<td>29.42</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1235.56</td>
<td>1</td>
<td>2.497</td>
<td>2.558</td>
<td>32.9</td>
<td>68.99</td>
<td>121.5235</td>
<td>0.0984</td>
<td>4.051</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.534</td>
<td></td>
<td></td>
<td>37.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.643</td>
<td></td>
<td></td>
<td>15.50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the data presented in Table 4.2, the average tap water permeability of the reconstructed trench pervious concrete specimens is 2.62 cm/s and the average porosity is 33.3%. The average TSS mass recovered from each specimen is 265.7 mg.
The approximate TSS amount that could wash from the concrete layer in the field is estimated according to Equation 4-2 as follows:

Estimated TSS from the concrete layer = 0.215 mg/cm$^3$ \times 6.5 ft$^3$ \times 28316.8 cm$^3$/ft$^3$

= 39.57 g

4.1.1.3 Comparison between Trench and Laboratory Specimens

Table 4.3 and Figure 4.1 show a comparison between the tap water permeability results for the trench specimens (original and reconstructed) and the previously tested laboratory specimens (ODOT pervious concrete specimens).

Table 4.3: Comparison of Tap Water Permeability among ODOT Lab Specimens, Original Trench and Reconstructed Trench Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>k_{@20^\circ C} (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab Specimens (ODOT Mix)</td>
</tr>
<tr>
<td>1</td>
<td>4.581</td>
</tr>
<tr>
<td>2</td>
<td>3.824</td>
</tr>
<tr>
<td>3</td>
<td>4.211</td>
</tr>
<tr>
<td>4</td>
<td>3.195</td>
</tr>
<tr>
<td>5</td>
<td>3.268</td>
</tr>
<tr>
<td>6</td>
<td>3.466</td>
</tr>
<tr>
<td>7</td>
<td>3.294</td>
</tr>
<tr>
<td>8</td>
<td>3.859</td>
</tr>
<tr>
<td>9</td>
<td>3.379</td>
</tr>
<tr>
<td>Average</td>
<td>3.675</td>
</tr>
</tbody>
</table>

As shown in the above table, the permeability of the reconstructed trench concrete specimens, which is almost 71% of the lab specimens’ permeability, is less than the
permeability of the original trench concrete specimens, which is almost 92% of the lab specimens’ permeability. This in turn increases the possibility of an early clogging of the reconstructed trench when compared to the original trench. The difference in the permeability between the two types of specimens can be related to the difference in the porosity; since the porosity of the original trench specimens is 40.2% while the porosity of the reconstructed trench specimens is 33.3%.

![Tap Water Permeability Comparison (cm/s)](image)

Figure 4.1: Comparison of Tap Water Permeability among ODOT Lab Specimens, Original Trench and Reconstructed Trench Specimens

A comparison of TSS results between the reconstructed and original trench concrete specimens is presented in Table 4.4 and Figure 4.2.
Table 4.4: 
Comparison of the Recovered TSS between the Original Trench and the Reconstructed Trench Concrete Specimens

<table>
<thead>
<tr>
<th>Specimen</th>
<th>Total TSS recovered (mg)</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Trench Specimens</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>291.71</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>211.63</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>146.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>216.62</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Reconstructed Trench Specimens</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>423.85</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>251.80</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>121.52</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>265.73</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

According to the values in Table 4.4, the contribution of the concrete layer to the effluent TSS levels is higher in the reconstructed trench than the original trench. However, this does not suggest that the contribution of the trench media including all three layers to the effluent TSS levels is higher in the reconstructed trench; because this is also governed by the other trench layers (sand and aggregate).

Figure 4.2: Comparison of the Recovered TSS between the Original Trench and the Reconstructed Trench Concrete Specimens
4.1.2 Aggregate Samples

Aggregate samples were tested for tap water permeability in a similar way to pervious concrete specimens. Additional sample was tested for the porosity as discussed in Chapter 3.

4.1.2.1 Original Trench Aggregate Samples

Tap water permeability and TSS results for the aggregate samples from the original trench are presented in Table 4.5.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Volume</th>
<th>Test</th>
<th>( k_{@20,^\circ C} )</th>
<th>Average ( k_{@20,^\circ C} )</th>
<th>TSS Recovered</th>
<th>Total TSS Recovered</th>
<th>TSS/Sample volume</th>
<th>TSS/Influent Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>cm(^3)</td>
<td>No.</td>
<td>cm/s</td>
<td>cm/s</td>
<td>mg</td>
<td>mg</td>
<td>mg/cm(^3)</td>
<td>mg/L</td>
</tr>
<tr>
<td>1</td>
<td>1235.56</td>
<td>1</td>
<td>2.073</td>
<td>2.086</td>
<td>4456.11</td>
<td>4912.18</td>
<td>3.976</td>
<td>163.739</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.064</td>
<td></td>
<td>344.94</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.121</td>
<td></td>
<td></td>
<td>111.13</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1236.56</td>
<td>1</td>
<td>2.120</td>
<td>2.132</td>
<td>4711.24</td>
<td>5137.25</td>
<td>4.154</td>
<td>171.242</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.178</td>
<td></td>
<td>314.85</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.098</td>
<td></td>
<td></td>
<td>111.16</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1237.56</td>
<td>1</td>
<td>2.302</td>
<td>2.206</td>
<td>10632.31</td>
<td>12011.00</td>
<td>9.705</td>
<td>400.367</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>2.167</td>
<td></td>
<td>1052.87</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>2.150</td>
<td></td>
<td>325.82</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>2.141</td>
<td></td>
<td>7353.477</td>
<td>5.945</td>
<td>245.116</td>
<td></td>
</tr>
</tbody>
</table>

The average unit weight of the original trench aggregate samples is 1.31 g/cm\(^3\).

From Table 4.5, the average tap water permeability of the original trench aggregate samples is 2.14 cm/s and the average porosity is 46.6%. The average TSS mass recovered
from each sample is 7353.5 mg. The approximate TSS amount that could wash from the aggregate layer in the field is estimated according to Equation 4-2 as follows:

\[
\text{Estimated TSS from the aggregate layer} = 5.945 \text{ mg/cm}^3 \times 6.5 \text{ ft}^3 \times 28316.8 \text{ cm}^3/\text{ft}^3
\]

\[
= 1094.23 \text{ g}
\]

The estimated amount of TSS from the aggregate layer (1094.23 g) is much higher than that from the concrete layer (32.03 g); which indicates that the major contribution to the effluent TSS concentrations is from the aggregate layer (especially in the early stages of monitoring).

### 4.1.2.2 Demolished Trench Aggregate Samples

Tap water permeability and TSS results for the aggregate samples from the demolished trench are presented in Table 4.6.

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Volume</th>
<th>Test No.</th>
<th>( k_{@20°C} ) cm/s</th>
<th>Average ( k_{@20°C} ) cm/s</th>
<th>TSS Recovered mg</th>
<th>Total TSS Recovered mg</th>
<th>TSS/Sample volume mg/cm³</th>
<th>TSS/Influent Volume mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1235.56</td>
<td>1</td>
<td>1.436</td>
<td>1.485</td>
<td>1277.86</td>
<td>3416.12</td>
<td>2.765</td>
<td>113.871</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.538</td>
<td></td>
<td>1304.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.480</td>
<td></td>
<td>834.13</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1236.56</td>
<td>1</td>
<td>1.421</td>
<td>1.556</td>
<td>3026.96</td>
<td>4300.52</td>
<td>3.478</td>
<td>143.351</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.578</td>
<td></td>
<td>728.44</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.668</td>
<td></td>
<td>545.11</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1237.56</td>
<td>1</td>
<td>1.353</td>
<td>1.529</td>
<td>3682.72</td>
<td>5285.34</td>
<td>4.271</td>
<td>176.178</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.596</td>
<td></td>
<td>1070.90</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.639</td>
<td></td>
<td>531.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td>1236.56</td>
<td></td>
<td>1.523</td>
<td>-</td>
<td>4333.991</td>
<td></td>
<td>3.504</td>
<td>144.466</td>
</tr>
</tbody>
</table>
The average unit weight of the demolished trench aggregate is 1.29 g/cm³. From Table 4.6, the average tap water permeability of the demolished trench aggregate samples is 1.52 cm/s. The average TSS mass recovered from each sample is 4334 mg. It was expected that the TSS recovered from the demolished trench aggregate should be higher than that from the original trench aggregate; however, the original trench aggregate TSS was almost 70% higher than the demolished trench aggregate, which might be caused by the elevated concentration of TSS existing initially in the aggregate before installation; and hence, during the trench monitoring period, the aggregate layer was washed gradually until the trench was demolished resulting in a 41% TSS reduction in the aggregate layer. It can be concluded also from the results that additional washing of the aggregate samples is desired to recover more of the TSS retained, because even after the third falling head permeability run, TSS concentrations are still relatively high.

Table 4.7 shows a comparison between the aggregate permeability (after installation and after demolishing) along with the percent reduction.

<table>
<thead>
<tr>
<th></th>
<th>Initial permeability (cm/s)</th>
<th>Permeability after Demolishing (cm/s)</th>
<th>Percent Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial permeability (cm/s)</td>
<td>2.141</td>
<td>1.523</td>
<td>28.9</td>
</tr>
</tbody>
</table>

4.1.2.3 Reconstructed Trench Aggregate Samples

Tap water permeability and TSS results for the aggregate samples from the reconstructed trench are presented in Table 4.8.
Table 4.8:
Summary of Tap Water Permeability and TSS Results for Aggregate Samples from the Reconstructed Trench

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample Volume</th>
<th>Test</th>
<th>Average $k_{@20\degree C}$</th>
<th>TSS Recovered</th>
<th>Total TSS Recovered</th>
<th>TSS/Sample volume</th>
<th>TSS/Influent Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>No.</td>
<td>cm$^3$</td>
<td>No.</td>
<td>cm/s</td>
<td>mg</td>
<td>mg</td>
<td>mg/cm$^3$</td>
<td>mg/L</td>
</tr>
<tr>
<td>1</td>
<td>1235.56</td>
<td>1</td>
<td>1.840</td>
<td>4469.88</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.667</td>
<td>406.60</td>
<td>5038.45</td>
<td>4.078</td>
<td>167.948</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.579</td>
<td>161.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1236.56</td>
<td>1</td>
<td>1.751</td>
<td>2968.83</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.724</td>
<td>116.48</td>
<td>3176.47</td>
<td>2.569</td>
<td>105.882</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.738</td>
<td>91.16</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1237.56</td>
<td>1</td>
<td>1.633</td>
<td>3107.43</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>1.686</td>
<td>158.27</td>
<td>3391.35</td>
<td>2.740</td>
<td>113.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>1.846</td>
<td>125.65</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>1.718</td>
<td>-</td>
<td>3868.755</td>
<td>3.129</td>
<td>128.959</td>
</tr>
</tbody>
</table>

The average unit weight of the reconstructed trench aggregate samples is 1.33 g/cm$^3$. From Table 4.8, the average tap water permeability of the reconstructed trench aggregate samples is 1.72 cm/s and the average porosity is 39.8%. The average TSS mass recovered from each specimen is 3868.8 mg. The approximate TSS amount that could wash from the aggregate layer in the field is estimated according to Equation 4-2 as follows:

Estimated TSS from the aggregate layer = $3.129 \text{ mg/cm}^3 \times 6.5 \text{ ft}^3 \times 28316.8 \text{ cm}^3/\text{ft}^3$

$= 575.92 \text{ g}$
4.1.2.4 Comparison between Trench Samples and Laboratory Samples

Table 4.9 and Figure 4.3 show a comparison between the tap water permeability results for the trench samples (original, demolished and reconstructed) and the previously tested laboratory samples (washed and unwashed).

Table 4.9:
Comparison of Tap Water Permeability among Aggregate Lab Samples (Washed and Unwashed), Original, Demolished and Reconstructed Trench Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lab Samples (Unwashed)</th>
<th>Lab Samples (Washed)</th>
<th>Original Trench Samples</th>
<th>Demolished Trench Samples</th>
<th>Reconstructed Trench Samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3.600</td>
<td>4.230</td>
<td>2.086</td>
<td>1.485</td>
<td>1.695</td>
</tr>
<tr>
<td>2</td>
<td>4.037</td>
<td>4.392</td>
<td>2.132</td>
<td>1.556</td>
<td>1.738</td>
</tr>
<tr>
<td>3</td>
<td>4.323</td>
<td>4.557</td>
<td>2.206</td>
<td>1.529</td>
<td>1.722</td>
</tr>
<tr>
<td>Average</td>
<td>3.987</td>
<td>4.393</td>
<td>2.141</td>
<td>1.523</td>
<td>1.718</td>
</tr>
</tbody>
</table>

Figure 4.3: Comparison of Tap Water Permeability among Aggregate Lab Samples (Washed and Unwashed), Original, Demolished and Reconstructed Trench Samples
According to Table 4.9 and Figure 4.3, the permeability of the reconstructed trench aggregate is almost 80% of the original trench aggregate permeability. However, both aggregate types have relatively low permeability when compared to the washed and unwashed lab samples.

Table 4.10 and Figure 4.4 show a comparison between the TSS results for the trench samples (original, demolished and reconstructed) and the previously tested laboratory samples (washed and unwashed).

Table 4.10:
Comparison of the Recovered TSS among Aggregate Lab Samples (Washed and Unwashed), Original, Demolished and Reconstructed Trench Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total TSS recovered (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab Samples (unwashed)</td>
</tr>
<tr>
<td>1</td>
<td>5240.40</td>
</tr>
<tr>
<td>2</td>
<td>6460.40</td>
</tr>
<tr>
<td>3</td>
<td>5003.40</td>
</tr>
<tr>
<td>Average</td>
<td>5568.07</td>
</tr>
</tbody>
</table>
Figure 4.4: Comparison of the Recovered TSS among Aggregate Lab Samples (Washed And Unwashed), Original, Demolished and Reconstructed Trench Samples

From Figure 4.4, it can be concluded that the aggregate used in the original trench contained the highest amount of TSS compared to other aggregate types shown in the figure. It also can be observed that washing the aggregate lab samples resulted in a 74% decrease in the TSS.

4.1.2.5 Original Trench Aggregate Particle Size Distribution

Sieve analysis was performed on a 1000-g aggregate sample. The results are presented in Table 4.11 and Figure 4.5.
Table 4.11: Original Trench Aggregate Particle Size Distribution

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Mass Retained (g)</th>
<th>Cumulative Retained</th>
<th>Percent Retained%</th>
<th>Percent Passing%</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.50</td>
<td>2.0</td>
<td>2.0</td>
<td>0.2</td>
<td>99.8</td>
</tr>
<tr>
<td>9.50</td>
<td>110.4</td>
<td>112.4</td>
<td>11.2</td>
<td>88.8</td>
</tr>
<tr>
<td>6.30</td>
<td>392.8</td>
<td>505.2</td>
<td>50.5</td>
<td>49.5</td>
</tr>
<tr>
<td>4.75</td>
<td>310.4</td>
<td>815.6</td>
<td>81.6</td>
<td>18.4</td>
</tr>
<tr>
<td>2.00</td>
<td>179.3</td>
<td>994.9</td>
<td>99.5</td>
<td>0.5</td>
</tr>
<tr>
<td>0.85</td>
<td>1.4</td>
<td>996.3</td>
<td>99.6</td>
<td>0.4</td>
</tr>
<tr>
<td>Pan</td>
<td>3.7</td>
<td>1000</td>
<td>100.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4.5: Original Trench Aggregate Particle Size Distribution

From the graph, $D_{60} = 7.2$ mm; $D_{50} = 6.3$ mm; $D_{30} = 5$ mm and $D_{10} = 3$ mm. Thus, $C_C = 2.07$ and $C_U = 13.7$. 
Figure 4.5 shows the particle size distribution of the original trench aggregate along with No. 8, No. 57 and No 67 aggregate distributions as per ODOT 2008 Construction and Material Specifications requirements for type 3 backfill materials (ODOT, 2008a). It can be concluded that the trench aggregate meets the requirements of No. 8 gradation. However, the aggregate does not meet the requirements for structural backfill for bedding and backfill, since the ODOT Construction and Material Specifications requires that it should meet the gradation of No. 57 or No.67. This might be the reason for the low permeability of aggregate site samples when compared to lab samples.

4.1.2.6 Reconstructed Trench Aggregate Particle Size Distribution

Particle size distribution results for the reconstructed trench aggregate are presented in Table 4.12 and Figure 4.6.

Table 4.12: 
Reconstructed Trench Aggregate Particle Size Distribution

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Mass Retained (g)</th>
<th>Cumulative Retained</th>
<th>Percent Retained%</th>
<th>Percent Passing%</th>
</tr>
</thead>
<tbody>
<tr>
<td>12.50</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>9.50</td>
<td>67.0</td>
<td>67.0</td>
<td>6.7</td>
<td>93.3</td>
</tr>
<tr>
<td>6.30</td>
<td>482.0</td>
<td>549.0</td>
<td>54.9</td>
<td>45.1</td>
</tr>
<tr>
<td>4.75</td>
<td>308.5</td>
<td>857.5</td>
<td>85.8</td>
<td>14.3</td>
</tr>
<tr>
<td>2.00</td>
<td>141.5</td>
<td>999.0</td>
<td>99.9</td>
<td>0.1</td>
</tr>
<tr>
<td>0.85</td>
<td>0.5</td>
<td>999.5</td>
<td>100.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Pan</td>
<td>0.5</td>
<td>1000</td>
<td>100.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>
Figure 4.6: Reconstructed Trench Aggregate Particle Size Distribution

From the graph, $D_{60} = 7.3$ mm; $D_{50} = 6.6$ mm; $D_{30} = 5.5$ mm and $D_{10} = 3.9$ mm. Thus, $C_C = 1.86$ and $C_U = 16.53$.

This type of aggregate also meets the requirements for No. 8 aggregate gradation which does not satisfy the requirements for structural backfill for bedding and backfill as per ODOT Construction and Material Specifications 2008.

4.1.3 Sand Samples

Sand samples were tested for tap water permeability using the constant head permeability apparatus as discussed in Chapter 3.
4.1.3.1 Original Trench Sand Samples

Tap water permeability and TSS results for sand samples from the original trench are presented in Table 4.13.

Table 4.13: Summary of Tap Water Permeability and TSS Results for Sand Samples from the Original Trench (after Installation)

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Volume</th>
<th>Test No.</th>
<th>$k_{@20°C}$</th>
<th>Average $k_{@20°C}$</th>
<th>TSS Recovered</th>
<th>Total TSS Recovered</th>
<th>TSS/Sample Volume</th>
<th>TSS/Influent Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>695.00</td>
<td>1</td>
<td>0.0545</td>
<td>0.0515</td>
<td>218.42</td>
<td>281.35</td>
<td>0.405</td>
<td>9.378</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0530</td>
<td></td>
<td>35.89</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0471</td>
<td></td>
<td>27.04</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>695.00</td>
<td>1</td>
<td>0.0705</td>
<td>0.0697</td>
<td>266.47</td>
<td>361.28</td>
<td>0.520</td>
<td>12.043</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0731</td>
<td></td>
<td>55.08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0657</td>
<td></td>
<td>39.73</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>695.00</td>
<td>1</td>
<td>0.0616</td>
<td></td>
<td>682.09</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0595</td>
<td>0.0574</td>
<td>81.35</td>
<td>814.04</td>
<td>1.171</td>
<td>27.135</td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0512</td>
<td></td>
<td>50.60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.0596</td>
<td></td>
<td>-</td>
<td>485.557</td>
<td>0.699</td>
<td>16.185</td>
</tr>
</tbody>
</table>

The average unit weight of the original trench sand is 1.65 g/cm$^3$. From Table 4.13, the average tap water permeability of the original trench sand samples is 0.0596 cm/s. The average TSS mass recovered from each sample is 485.6 mg. The approximate TSS amount that could wash from the sand layer in the field is estimated according to Equation 4-2 as follows:

Estimated TSS from the sand layer = 0.699 mg/cm$^3$×6.5 ft$^3$×28316.8 cm$^3$/ft$^3$

= 128.66 g
4.1.3.2 Demolished Trench Sand Samples

Tap water permeability and TSS results for the sand samples from the demolished trench are presented in Table 4.14.

Table 4.14: Summary of Tap Water Permeability and TSS Results for Sand Samples from the Demolished Trench

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Volume (cm³)</th>
<th>Test No.</th>
<th>$k_{@20°C}$ (cm/s)</th>
<th>Average $k_{@20°C}$ (cm/s)</th>
<th>TSS Recovered (mg)</th>
<th>Total TSS Recovered (mg)</th>
<th>TSS/Sample Volume (mg/cm³)</th>
<th>TSS/Influent Volume (mg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>695.00</td>
<td>1</td>
<td>0.0712</td>
<td>0.0738</td>
<td>116.00</td>
<td>235.76</td>
<td>0.339</td>
<td>7.859</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0720</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0781</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>695.00</td>
<td>1</td>
<td>0.0691</td>
<td>0.0704</td>
<td>153.31</td>
<td>267.00</td>
<td>0.384</td>
<td>8.900</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0681</td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0740</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>695.00</td>
<td>1</td>
<td>0.0833</td>
<td>0.0783</td>
<td>631.29</td>
<td>697.11</td>
<td>1.003</td>
<td>23.237</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0770</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0746</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.074</td>
<td></td>
<td></td>
<td>399.956</td>
<td>0.575</td>
<td>13.332</td>
</tr>
</tbody>
</table>

The average unit weight of the demolished trench sand is 1.62 g/cm³. From Table 4.14, the average tap water permeability of the demolished trench sand samples is 0.074 cm/s. The average TSS mass recovered from each sample is 400 mg.

Table 4.15 shows a comparison between sand permeability (after installation and after demolishing) along with the percent reduction.

Table 4.15: Tap Water Permeability Comparison between Original and Demolished Trench Sand

<table>
<thead>
<tr>
<th>Permeability</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Permeability after Installation (cm/s)</td>
<td>0.0596</td>
</tr>
<tr>
<td>Permeability after Demolishing (cm/s)</td>
<td>0.0741</td>
</tr>
<tr>
<td>Percent Reduction (%)</td>
<td>-24.5</td>
</tr>
</tbody>
</table>
The measured permeability of the demolished trench sand is higher than the original trench sand. However, when the sand from the demolished trench was brought to the lab, it was solidified, and in order to obtain samples, the sand was disturbed and dug with a spoon; i.e., if the sand was to be obtained in its original shape, it will not fit into the constant head permeameter. Therefore, these results might not represent the actual demolished sand permeability.

4.1.3.3 Reconstructed Trench Sand Samples

Tap water permeability and TSS results for the sand samples from the reconstructed trench are presented in Table 4.16.

Table 4.16:
Summary of Tap Water Permeability and TSS Results for Sand Samples from the Reconstructed Trench

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>Sample Volume cm³</th>
<th>Test No.</th>
<th>$k_{@20°C}$ cm/s</th>
<th>Average $k_{@20°C}$ cm/s</th>
<th>TSS Recovered mg</th>
<th>Total TSS Recovered mg</th>
<th>TSS/Sample volume mg/cm³</th>
<th>TSS/Influent Volume mg/L</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>695.00</td>
<td>1</td>
<td>0.0822</td>
<td>0.0751</td>
<td>59.18</td>
<td>128.81</td>
<td>0.185</td>
<td>4.294</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0721</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0709</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>695.00</td>
<td>1</td>
<td>0.0823</td>
<td>0.0915</td>
<td>161.11</td>
<td>219.94</td>
<td>0.316</td>
<td>7.331</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0917</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.1005</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>695.00</td>
<td>1</td>
<td>0.1086</td>
<td>0.0928</td>
<td>179.77</td>
<td>361.35</td>
<td>0.520</td>
<td>12.045</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2</td>
<td>0.0831</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>3</td>
<td>0.0867</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>0.0865</td>
<td>-</td>
<td>236.698</td>
<td>0.341</td>
<td>7.890</td>
<td></td>
</tr>
</tbody>
</table>
The average unit weight of the reconstructed trench sand is 1.69 g/cm$^3$. From Table 4.16, the average tap water permeability of the reconstructed trench sand samples is 0.0865 cm/s. The average TSS mass recovered from each sample is 236.7 mg. The approximate TSS amount that could wash from the sand layer in the field is estimated according to Equation 4-2 as follows:

Estimated TSS from the sand layer = \(0.341 \text{ mg/cm}^3 \times 6.5 \text{ ft}^3 \times 28316.8 \text{ cm}^3/\text{ft}^3\)

\[= 62.76 \text{ g}\]

**4.1.3.4 Comparison between Trench Samples and Laboratory Samples**

Table 4.17 and Figure 4.7 show a comparison between tap water permeability results for the trench sand samples (original, demolished and reconstructed) and the previously tested laboratory washed sand samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>(k@20^\circ\text{C} \text{ (cm/s)})</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Lab Samples (Washed)</td>
</tr>
<tr>
<td>1</td>
<td>0.0522</td>
</tr>
<tr>
<td>2</td>
<td>0.0641</td>
</tr>
<tr>
<td>3</td>
<td>-</td>
</tr>
<tr>
<td>Average</td>
<td>0.0581</td>
</tr>
</tbody>
</table>

Table 4.17: *Comparison of Tap Water Permeability among Sand Lab Samples (Washed), Original, Demolished and Reconstructed Trench Samples*
Figure 4.7: Comparison of Tap Water Permeability among Sand Lab Samples (Washed), Original, Demolished and Reconstructed Trench Samples

According to Table 4.17, the permeability of the original trench sand is almost equal to the lab tested washed sand. However, the permeability of the reconstructed trench sand is 45% higher than the original trench sand.

Table 4.18 and Figure 4.8 show a comparison between the TSS results for the trench samples (original, demolished and reconstructed) and the previously tested laboratory washed sand samples.
Table 4.18: 
Comparison of the Recovered TSS among Original, Demolished and Reconstructed Trench Sand Samples

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total TSS recovered (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Original Trench Samples</td>
</tr>
<tr>
<td>1</td>
<td>281.35</td>
</tr>
<tr>
<td>2</td>
<td>361.28</td>
</tr>
<tr>
<td>3</td>
<td>814.04</td>
</tr>
<tr>
<td>Average</td>
<td>485.56</td>
</tr>
</tbody>
</table>

The results shown in Table 4.18 and Figure 4.8 show that the sand used in the reconstructed trench has 51% less TSS than the sand used in the original trench. This might result in reduced TSS concentrations in the reconstructed trench effluent, since the
original trench sand layer contained significant TSS quantities when compared to the reconstructed trench sand.

The amount of TSS recovered from the demolished trench sand samples is less than the original trench samples, which is similar to what was found in aggregate samples. This is also because of the elevated TSS levels found originally in the sand samples; therefore, during the monitoring period of the trench, the sand layer was washed gradually until reaching the levels detected after demolishing.

4.1.3.5 Original Trench Sand Particle Size Distribution

Sieve analysis was performed on a 1000-g sand sample. The results are presented in Table 4.19 and Figure 4.9.

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Mass Retained (g)</th>
<th>Cumulative Retained</th>
<th>Percent Retained%</th>
<th>Percent Passing%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>4.75</td>
<td>16.0</td>
<td>16.0</td>
<td>1.6</td>
<td>98.4</td>
</tr>
<tr>
<td>2.36</td>
<td>210.0</td>
<td>226.0</td>
<td>22.6</td>
<td>77.4</td>
</tr>
<tr>
<td>1.18</td>
<td>156.0</td>
<td>382.0</td>
<td>38.2</td>
<td>61.8</td>
</tr>
<tr>
<td>0.425</td>
<td>366.0</td>
<td>748.0</td>
<td>74.8</td>
<td>25.2</td>
</tr>
<tr>
<td>0.297</td>
<td>149.5</td>
<td>897.5</td>
<td>89.8</td>
<td>10.3</td>
</tr>
<tr>
<td>0.075</td>
<td>98.0</td>
<td>995.5</td>
<td>99.6</td>
<td>0.5</td>
</tr>
<tr>
<td>Pan</td>
<td>4.5</td>
<td>1000.0</td>
<td>100.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4.9 shows the particle size distribution of the original trench sand along with two gradations for type 2 backfill material as per ODOT 2008 Construction and
Material Specifications requirements. It can be concluded that the trench sand meets the requirements for gradation 1.

![Figure 4.9: Original Trench Sand Particle Size Distribution](image)

From the graph, $D_{60} = 1.143$ mm; $D_{50} = 0.937$ mm; $D_{30} = 0.524$ mm and $D_{10} = 0.291$ mm. Thus, $C_C = 3.92$ and $C_U = 0.07$.

4.1.3.6 Reconstructed Trench Sand Particle Size Distribution

Sieve analysis was performed on 1000-g sand sample. The results are presented in Table 4.20 and Figure 4.10.
Table 4.20: 
Reconstructed Trench Sand Particle Size Distribution

<table>
<thead>
<tr>
<th>Size (mm)</th>
<th>Mass Retained (g)</th>
<th>Cumulative Retained</th>
<th>Percent Retained%</th>
<th>Percent Passing%</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.30</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>100.0</td>
</tr>
<tr>
<td>4.75</td>
<td>26.5</td>
<td>26.5</td>
<td>2.7</td>
<td>97.4</td>
</tr>
<tr>
<td>2.36</td>
<td>228.5</td>
<td>255.0</td>
<td>25.5</td>
<td>74.5</td>
</tr>
<tr>
<td>1.18</td>
<td>166.0</td>
<td>421.0</td>
<td>42.1</td>
<td>57.9</td>
</tr>
<tr>
<td>0.425</td>
<td>408.0</td>
<td>829.0</td>
<td>82.9</td>
<td>17.1</td>
</tr>
<tr>
<td>0.297</td>
<td>109.0</td>
<td>938.0</td>
<td>93.8</td>
<td>6.2</td>
</tr>
<tr>
<td>0.075</td>
<td>59.5</td>
<td>997.5</td>
<td>99.8</td>
<td>0.3</td>
</tr>
<tr>
<td>Pan</td>
<td>2.5</td>
<td>1000.0</td>
<td>100.0</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Figure 4.10: Reconstructed Trench Sand Particle Size Distribution
From the graph, $D_{60} = 1.219$ mm; $D_{50} = 1.034$ mm; $D_{30} = 0.664$ mm and $D_{10} = 0.439$ mm. Thus, $C_C = 2.78$ and $C_U = 0.16$. It can be concluded that the trench sand meets the requirements for gradation 1.

4.2 Exfiltration Trench Monitoring

After the trench was installed on August 6th, 2010, the trench monitoring period started. Runoff samples from influent and effluent were collected after each rainfall/snow event and analyzed for several water quality parameters. The trench was clogged on November 3rd, 2010. Maintenance was performed to the trench on November 16th, 2010 in order to remove the solids entrapped within the pores of the concrete layer. A total of 20 events, monitored before maintenance, were called pre-maintenance events. Another monitoring period started after the maintenance which resulted in a total of 23 monitored events until the trench was clogged again on April 11th, 2011. Those events were called post-maintenance events.

The trench was demolished and reconstructed again on April 28th, 2011, after which a new monitoring period started and was called the reconstructed trench monitoring phase. A total of 12 events were monitored after reconstruction.

Table 4.21 summarizes all monitored events data. The data in the table include the date, time, duration, total rainfall, rainfall intensity and the number of antecedent dry weather days for each event. Influent and effluent samples’ number and volume are also included in this table. The detention time was calculated by estimating the time difference between the first influent and effluent samples.
## Table 4.21: Total Events Summary

<table>
<thead>
<tr>
<th>Event No</th>
<th>Date of Event</th>
<th>Time</th>
<th>Duration</th>
<th>Total Rainfall</th>
<th>Rainfall Intensity</th>
<th>No. of Samples</th>
<th>Volume of Samples (L)</th>
<th>No. Antecedent Dry Days</th>
<th>Detention Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8/11/2010</td>
<td>6:11 AM - 6:51 AM</td>
<td>40 min</td>
<td>0.12 inch</td>
<td>3.05 mm/hr</td>
<td>0.180 in/hr</td>
<td>4.572 mm/hr</td>
<td>577 L</td>
<td>3 L</td>
</tr>
<tr>
<td>2</td>
<td>8/11/2010</td>
<td>4:38 PM - 5:33 PM</td>
<td>55 min</td>
<td>0.05 inch</td>
<td>1.27 mm/hr</td>
<td>0.055 in/hr</td>
<td>1.385 mm/hr</td>
<td>2 L</td>
<td>7 L</td>
</tr>
<tr>
<td>3</td>
<td>8/14/2010</td>
<td>5:31 PM - 6:51 PM</td>
<td>20 min</td>
<td>0.4 inch</td>
<td>10.16 mm/hr</td>
<td>1.200 in/hr</td>
<td>30.480 mm/hr</td>
<td>2 L</td>
<td>21 L</td>
</tr>
<tr>
<td>4</td>
<td>8/21/2010</td>
<td>3:39 PM - 9:19 PM</td>
<td>340 min</td>
<td>0.33 inch</td>
<td>8.38 mm/hr</td>
<td>0.058 in/hr</td>
<td>1.479 mm/hr</td>
<td>7 L</td>
<td>6 L</td>
</tr>
<tr>
<td>5</td>
<td>8/22/2010</td>
<td>5:31 AM - 5:41 AM</td>
<td>10 min</td>
<td>0.05 inch</td>
<td>1.27 mm/hr</td>
<td>0.300 in/hr</td>
<td>7.620 mm/hr</td>
<td>4 L</td>
<td>16 L</td>
</tr>
<tr>
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<td>8.89 mm/hr</td>
<td>1.050 in/hr</td>
<td>26.670 mm/hr</td>
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<td>2 L</td>
</tr>
<tr>
<td>7</td>
<td>9/11/2010</td>
<td>7:44 PM - 7:47 PM</td>
<td>3 min</td>
<td>0.01 inch</td>
<td>0.25 mm/hr</td>
<td>0.200 in/hr</td>
<td>5.080 mm/hr</td>
<td>2 L</td>
<td>7 L</td>
</tr>
<tr>
<td>8</td>
<td>9/16/2010</td>
<td>8:30 AM - 9:02 AM</td>
<td>32 min</td>
<td>0.21 inch</td>
<td>5.33 mm/hr</td>
<td>0.394 in/hr</td>
<td>10.001 mm/hr</td>
<td>2 L</td>
<td>21 L</td>
</tr>
<tr>
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<td>6:37 PM - 7:00 PM</td>
<td>23 min</td>
<td>1.32 inch</td>
<td>33.53 mm/hr</td>
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<td>87.464 mm/hr</td>
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<td>10 L</td>
</tr>
<tr>
<td>10</td>
<td>9/24/2010</td>
<td>10:08 PM - 10:16 PM</td>
<td>8 min</td>
<td>0.02 inch</td>
<td>0.51 mm/hr</td>
<td>0.150 in/hr</td>
<td>3.810 mm/hr</td>
<td>3 L</td>
<td>23 L</td>
</tr>
<tr>
<td>11</td>
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<td>0.02 inch</td>
<td>0.51 mm/hr</td>
<td>0.240 in/hr</td>
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<td>3 L</td>
</tr>
<tr>
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<td>25 min</td>
<td>0.1 inch</td>
<td>2.54 mm/hr</td>
<td>0.240 in/hr</td>
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<td>1 L</td>
<td>0(3) L</td>
</tr>
<tr>
<td>13</td>
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<td>51 min</td>
<td>0.14 inch</td>
<td>3.56 mm/hr</td>
<td>0.165 in/hr</td>
<td>4.184 mm/hr</td>
<td>12 L</td>
<td>12 L</td>
</tr>
<tr>
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<td>1.02 mm/hr</td>
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<td>0(5) L</td>
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<tr>
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</tr>
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<td>- min</td>
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<td>- L</td>
<td>-</td>
<td>-</td>
<td>148 L</td>
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<td>0.042 in/hr</td>
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<td>0 L</td>
</tr>
<tr>
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<td>24 L</td>
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<tr>
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<td>24 L</td>
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<td>- min</td>
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<td>-</td>
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<td>-</td>
<td>12 L</td>
<td>18 L</td>
</tr>
<tr>
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<td>8.64 mm/hr</td>
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<td>0 L</td>
<td>24 L</td>
<td>23.050 L</td>
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<td>13 L</td>
<td>24 L</td>
<td>2.500 L</td>
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</tr>
<tr>
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<td>508 min</td>
<td>0.14 inch</td>
<td>3.56 mm/hr</td>
<td>0.017 in/hr</td>
<td>0.420 mm/hr</td>
<td>3 L</td>
<td>18 L</td>
</tr>
<tr>
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<td>11:09 AM</td>
<td>301</td>
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<td>3.30</td>
<td>0.026</td>
<td>0.658</td>
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</tr>
<tr>
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<td>2/1/2011</td>
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<td>8:35 PM</td>
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<td>5.08</td>
<td>0.035</td>
<td>0.896</td>
</tr>
<tr>
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<td>2/21/2011</td>
<td>2/21/2011</td>
<td>9:33 AM</td>
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<td>23.88</td>
<td>0.070</td>
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<td>4:56 PM</td>
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<td>4.32</td>
<td>0.048</td>
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</tr>
<tr>
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<td>0.027</td>
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<td>0.024</td>
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</tr>
<tr>
<td></td>
<td>5/14/2011</td>
<td>5/14/2011</td>
<td>12:27 AM</td>
<td>12:35 AM</td>
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</tr>
<tr>
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<td>1.52</td>
<td>0.450</td>
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</tr>
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<td>7:55 PM</td>
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<td>28.96</td>
<td>1.800</td>
<td>45.720</td>
<td>10</td>
</tr>
</tbody>
</table>
Remarks:
(1) Influent and effluent samplers started collecting samples at the same time.
(2) The rain gauge did not give any data for the total rainfall nor the beginning of the event. However, wunderground.com was used to estimate the total rainfall and the duration.
(3) No effluent samples from this event because they were already full from event 10.
(4) The increase in the number and volume of samples resulted from the samplers programming change.
(5) No effluent samples were collected due to triggering error.
(6) Neither the rain gauge nor the internet websites gave any useful data regarding the start time of the event and the duration, only the total rainfall could be interpreted.
(7) In this event, the influent sampler started sampling 2 hours and 28 minutes before the effluent sampler.
(8) This event started after the maintenance was performed to the trench.
(9) The effluent sampler started collecting samples 3 minutes before influent.
(10) The effluent sampler started collecting samples 21 minutes before influent.
(11) This is a snowmelt event; hence, the time of the event is estimated based on the time the first influent sample was collected. As a result, neither the event duration nor the total rainfall are applicable for such event.
(12) The influent samples were collected on 12/22/2010, while the effluent samples were collected on 12/25/2010 (Snowmelt).
(13) No influent samples were collected.
(14) Influent samples were collected on Jan 26, 2011, while the effluent samples were collected on Jan 23, 2011.
(15) Effluent sampler started sampling 12 minutes before the influent sampler.
(16) Effluent samples were collected approximately 16 hours after the influent.
(17) Effluent sampler started sampling 12 hours before influent.
(18) Effluent samples were collected 5 days later than influent samples.
(19) Effluent sampler started sampling 46 minutes before the influent.
(20) The dash in the event number (e.g. R2-1) indicates that the samples of more than one event were retrieved on the same day.
4.3 Water Quality Parameters Monitored

4.3.1 Total Suspended Solids (TSS) Results

As stated before, exfiltration trench monitoring was divided into three phases: pre-maintenance, post-maintenance and reconstructed trench. TSS results are presented for each monitoring phase separately. Table 4.22 presents the TSS summary for the pre-maintenance events along with the turbidity results. The influent TSS concentration is expressed either as a flow weighted event mean concentration or simple arithmetic average for all influent samples collected in one event. However, the effluent TSS concentration is only expressed by the simple arithmetic average for all effluent samples in one event; since flow data are not available for effluent samples.

TSS removal efficiency is evaluated in two ways: overall removal which is calculated by finding the percent difference between influent and effluent arithmetic averages and the simultaneous samples removal which represents the percent difference between influent and effluent average of the samples collected in the same time frame (excluding influent samples that do not have corresponding effluent samples and vice versa for effluent). The TSS summaries for the post-maintenance and the reconstructed trench events are presented in Tables 4.23 and 4.24 respectively. The data in the tables include the events’ total rainfall, dates, number of antecedent dry weather days, and the rainfall intensity. Each event TSS is expressed in the tables as influent EMC, influent average and effluent average along with the removal efficiency. The average influent and effluent turbidity for each event is also presented in the tables.
Table 4.25 presents the rainfall parameters (total rainfall and rainfall intensity), influent and effluent TSS and turbidity statistical analysis for the whole trench monitoring period. The data are expressed as mean, median, standard deviation and range for all the parameters.

Figures 4.11, 4.12 and 4.13 show the time-wise variation of TSS concentration for the pre-maintenance, post-maintenance and reconstructed trench phases respectively. Figure 4.14 shows the influent and the corresponding effluent concentrations for the original and the reconstructed trench from which the removal efficiency at each influent concentration can be estimated. The removal efficiency variation with time for the pre-maintenance, post maintenance and the reconstructed trench phases is shown in Figures 4.15, 4.16 and 4.17 respectively.

Based on the data presented in Tables 4.22, 4.23 and 4.24, the pre-maintenance mean influent EMC and arithmetic average were 361.59 and 347.16 mg/l, respectively. The post-maintenance mean influent EMC and arithmetic average were 364.26 and 357.76 mg/l, respectively. In the reconstructed trench phase, both influent and effluent averages were less than the original trench corresponding averages. The influent TSS average was 180.01 mg/l while the effluent TSS average was 44.6 mg/l. The influent TSS average and EMC did not correspond for the reconstructed trench as the influent EMC was 258.62 mg/l which is almost 80 mg/l higher than the arithmetic average. This suggests that the flow was variable along the sampling time; therefore, the flow weighted average was different from the simple arithmetic average.
Table 4.22:  
*TSS Summary for the Pre-maintenance Events.*

<table>
<thead>
<tr>
<th>Event No</th>
<th>Date</th>
<th>No. Antecedent Dry days</th>
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<th>Rainfall Intensity</th>
<th>Influent EMC</th>
<th>Influent Avg.Conc</th>
<th>Effluent Avg.Conc</th>
<th>Overall Removal</th>
<th>Simultaneous Samples Removal</th>
<th>Average Turbidity (NTU)</th>
<th>Remarks</th>
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Mean | 0.17  | 0.43  | 361.59 | 347.16 | 258.81 | 52.07 | 57.31 | 224.03 | 147.74 |
Median | 0.06  | 0.18  | 197.57 | 245.61 | 116.76 | 64.15 | 66.55 | 193.00 | 147.60 |
St. Dev  | 0.29  | 0.80  | 278.46 | 266.22 | 483.54 | 32.47 | 27.59 | 115.81 | 62.60 |
### Table 4.23:

**TSS Summary for the Post-maintenance Events**

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<th>Rainfall Intensity</th>
<th>Influent EMC</th>
<th>Influent Avg.Conc</th>
<th>Effluent Avg.Conc</th>
<th>Overall Removal</th>
<th>Simultaneous Samples Removal</th>
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<th>Remarks</th>
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Table 4.24:
*TSS Summary for the Reconstructed Events*

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<th>Influent Avg.Conc (mg/l)</th>
<th>Effluent Avg.Conc (mg/l)</th>
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<th>Simultaneous Samples Removal (%)</th>
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<td>0.18</td>
<td>0.831</td>
<td>440.72</td>
<td>493.88</td>
<td>-</td>
<td>-</td>
<td>159.50</td>
<td>150.14</td>
<td>-</td>
</tr>
<tr>
<td>R2-4</td>
<td>5/14/2011</td>
<td>0.16</td>
<td>0.03</td>
<td>0.095</td>
<td>64.30</td>
<td>64.70</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>75.80</td>
<td>(4)</td>
</tr>
<tr>
<td>R3</td>
<td>5/19/2011</td>
<td>1.50</td>
<td>0.08</td>
<td>0.021</td>
<td>283.86</td>
<td>75.81</td>
<td>37.49</td>
<td>50.55</td>
<td>62.97</td>
<td>79.46</td>
<td>16.21</td>
</tr>
<tr>
<td>R4</td>
<td>6/4/2011</td>
<td>8.61</td>
<td>0.67</td>
<td>0.146</td>
<td>119.35</td>
<td>119.25</td>
<td>21.96</td>
<td>81.58</td>
<td>88.08</td>
<td>62.04</td>
<td>14.92</td>
</tr>
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<td>R5-1</td>
<td>6/15/2011</td>
<td>4.59</td>
<td>0.09</td>
<td>0.106</td>
<td>73.01</td>
<td>62.17</td>
<td>21.70</td>
<td>65.10</td>
<td>65.10</td>
<td>44.31</td>
<td>16.63</td>
</tr>
<tr>
<td>R5-2</td>
<td>6/16/2011</td>
<td>0.47</td>
<td>0.02</td>
<td>0.036</td>
<td>126.32</td>
<td>108.86</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>106.45</td>
<td>(4)</td>
</tr>
<tr>
<td>R6-1</td>
<td>6/23/2011</td>
<td>1.78</td>
<td>0.09</td>
<td>1.350</td>
<td>349.67</td>
<td>232.89</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>158.43</td>
<td>(4)</td>
</tr>
<tr>
<td>R6-2</td>
<td>6/23/2011</td>
<td>0.07</td>
<td>0.17</td>
<td>0.243</td>
<td>143.03</td>
<td>106.16</td>
<td>36.38</td>
<td>65.73</td>
<td>54.47</td>
<td>72.86</td>
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<td>R7</td>
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<td>6.76</td>
<td>1.14</td>
<td>1.800</td>
<td>276.32</td>
<td>128.23</td>
<td>72.28</td>
<td>43.63</td>
<td>67.88</td>
<td>51.70</td>
<td>37.67</td>
</tr>
<tr>
<td>Mean</td>
<td>0.22</td>
<td>0.49</td>
<td>258.62</td>
<td>180.01</td>
<td>44.60</td>
<td>64.55</td>
<td>68.51</td>
<td>95.09</td>
<td>29.41</td>
<td>-</td>
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</tr>
<tr>
<td>Median</td>
<td>0.09</td>
<td>0.19</td>
<td>209.68</td>
<td>114.06</td>
<td>37.49</td>
<td>65.42</td>
<td>66.49</td>
<td>77.63</td>
<td>16.63</td>
<td>-</td>
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</tr>
<tr>
<td>St. Dev</td>
<td>0.34</td>
<td>0.59</td>
<td>231.78</td>
<td>151.32</td>
<td>22.68</td>
<td>15.41</td>
<td>11.31</td>
<td>46.68</td>
<td>20.34</td>
<td>-</td>
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</tr>
</tbody>
</table>

Remarks:
(1) The removal efficiency of this event was excluded from analysis; since it is beyond the range and only was computed base on a total of 3 samples.
(2) No influent samples were collected.
(3) The influent TSS for this event was excluded; because it is the average of only two samples and it is beyond the range of influent TSS values.
(4) No effluent samples were collected.
(5) Simultaneous samples removal cannot be computed because influent and effluent samples were not collected at the same period of time.
Table 4.25:  
*Statistical Summary of TSS and Rainfall Data for the Whole Monitoring Period (Pre-maintenance, Post-maintenance and Reconstructed Trench)*

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Total Rainfall</th>
<th>Rainfall Intensity</th>
<th>Influent EMC</th>
<th>Influent Avg.Conc</th>
<th>Effluent Avg.Conc</th>
<th>Overall Removal</th>
<th>Simultaneous Samples Removal</th>
<th>Average Turbidity (NTU)</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td>(in/hr)</td>
<td>(mg/l)</td>
<td>(mg/l)</td>
<td>(mg/l)</td>
<td></td>
<td>%</td>
<td>%</td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>0.27</td>
<td>0.29</td>
<td>337.89</td>
<td>312.20</td>
<td>210.28</td>
<td>52.91</td>
<td>56.64</td>
<td>182.98</td>
</tr>
<tr>
<td>Median</td>
<td>0.13</td>
<td>0.08</td>
<td>280.09</td>
<td>230.07</td>
<td>120.75</td>
<td>57.35</td>
<td>62.97</td>
<td>159.50</td>
</tr>
<tr>
<td>St. Dev</td>
<td>0.39</td>
<td>0.58</td>
<td>269.31</td>
<td>253.75</td>
<td>325.70</td>
<td>28.70</td>
<td>23.39</td>
<td>113.88</td>
</tr>
<tr>
<td>Range</td>
<td>0.01-2.12</td>
<td>0.008-3.44</td>
<td>32.02-1097.7</td>
<td>32.44-1043.6</td>
<td>21.7-1982.2</td>
<td>2.89</td>
<td>15.88</td>
<td>27-546</td>
</tr>
</tbody>
</table>
Figure 4.11: Pre-maintenance TSS Variation with Time

Figure 4.12: Post-maintenance TSS Variation with Time
Figure 4.13: Reconstructed Trench TSS Variation with Time
Figure 4.14: Influent Vs Effluent Concentrations

- x=y
- 10% removal
- 20% removal
- 30% removal
- 40% removal
- 50% removal
- 60% removal
- 70% removal
- 80% removal
- 90% removal

- Pre-maintenance
- Post-maintenance
- Reconstruction
Figure 4.15: Pre-maintenance Removal Efficiency Variation with Time

Figure 4.16: Post-maintenance Removal Efficiency Variation with Time
Despite the consistency in influent TSS average concentrations between the pre-maintenance and post-maintenance phases, the effluent average concentration of the pre-maintenance phase was higher than the post-maintenance phase (the pre-maintenance mean effluent average concentration was 258.81 mg/l whereas the post-maintenance effluent average concentration was 226.86 mg/l). The reason for the difference between the two effluent averages is that the first event effluent concentration was extremely high (1982.23 mg/l) because this event was the first rainfall event, and based on the trench materials data, aggregate and sand contained high quantities of TSS; therefore, the trench layers produced significantly high TSS effluent concentration due to the first washing of trench materials.
The effect of snow season and its best management practices is not clear based on the influent TSS concentrations; as it was expected to be significantly higher than other times of the year. The highest influent TSS average concentration recorded was 1043.56 mg/l which was in event 31-1 (02/01/2011).

The overall removals for the pre-maintenance, post-maintenance and reconstructed trench phases were 52.07%, 19.85% and 64.55%, respectively, while the simultaneous samples removals were 57.31%, 38.16% and 68.51%. Four events of the post-maintenance events recorded a negative overall removal. This suggests that for these events of the post-maintenance phase, the effluent concentrations were close to or even higher than the influent concentrations. As discussed before in Chapter 3, the geotextile layer set-up was thought to create water passages between the geotextile layer and the trench wall; thus, the runoff flows to the bottom of the trench without receiving any treatment through the trench layers. Therefore; the design was improved in the reconstructed trench so that the geotextile layer was not providing a pathway for untreated flow. The removal efficiencies improved in the reconstructed trench, and the highest effluent TSS concentration was 81.58 mg/l.

The data shown in Table 4.25 is the overall statistical summary data, which included all monitoring phases. Based on this data, the average influent EMC was 337.89 mg/l and the average influent TSS concentration was 312.20 mg/l while the average effluent TSS concentration was 210.28 mg/l. Moreover, the average removal was 52.91% whereas the average simultaneous samples removal was 56.64%

The detailed TSS tables for each event are presented in Appendix A.
4.3.2 Particle Size Distribution

Starting from event 9, particle size samples were obtained from each event for both influent and effluent samples. However, for some events, no particle size samples were obtained due to the lack of liquid volume. Moreover, the required volume for particle size samples depends on the quantity of suspended solids in the sample; i.e., less volume is required for more polluted samples and vice versa.

The sample is loaded into the instrument and if the sample load is enough for analysis, the "ok" sign appears on the software. This is determined based on the load obscuration whether it is in the range of 8%-12%. Therefore, many samples did not meet this range due to the low amount of suspended solids and as a result, "low volume" sign appeared on the software, which indicated that the sample volume was below the detection limit.

Particle size distribution results are expressed in Tables 4.26, 4.27 and 4.28 for pre-maintenance, post-maintenance and reconstructed trench events respectively. Each table contains the influent and effluent mean, median, $d_{90}$ and $d_{10}$ for each event. A summary of the particle size data for each monitoring phase is also provided in each table. Figures 4.18, 4.19 and 4.20 show the time-wise variation of the influent and effluent mean and median particle size for pre-maintenance, post-maintenance and reconstructed trench events respectively. An overall statistical summary for all events (three monitoring phases) is given in Table 4.29, which includes the mean, median, standard deviation and the range of the particle size parameters.
Table 4.26:  
*Particle Size Analysis for the Pre-maintenance Events*

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Event Date</th>
<th>Sample Type</th>
<th>Mean (µm)</th>
<th>Median (µm)</th>
<th>d_{10} (µm)</th>
<th>d_{90} (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>9</td>
<td>9/22/2010</td>
<td>Influent</td>
<td>3.531</td>
<td>4.455</td>
<td>0.878</td>
<td>9.113</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>9/24/2010</td>
<td>Influent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>10.492</td>
<td>10.814</td>
<td>5.155</td>
<td>20.770</td>
</tr>
<tr>
<td>11</td>
<td>9/27/2010</td>
<td>Influent</td>
<td>8.051</td>
<td>8.533</td>
<td>3.769</td>
<td>17.010</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>9.586</td>
<td>10.740</td>
<td>4.301</td>
<td>18.360</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>10.980</td>
<td>11.590</td>
<td>5.154</td>
<td>20.160</td>
</tr>
<tr>
<td>16</td>
<td>10/5/2010</td>
<td>Influent</td>
<td>3.050</td>
<td>3.915</td>
<td>0.805</td>
<td>7.816</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>4.956</td>
<td>6.600</td>
<td>0.959</td>
<td>13.238</td>
</tr>
<tr>
<td>17</td>
<td>10/14/2010</td>
<td>Influent</td>
<td>11.373</td>
<td>14.309</td>
<td>3.244</td>
<td>29.048</td>
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<td>Effluent</td>
<td>17.635</td>
<td>23.195</td>
<td>5.235</td>
<td>43.080</td>
</tr>
<tr>
<td>18</td>
<td>10/18/2010</td>
<td>Influent</td>
<td>1.271</td>
<td>1.310</td>
<td>0.496</td>
<td>3.084</td>
</tr>
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<td>Effluent</td>
<td>2.034</td>
<td>2.590</td>
<td>0.567</td>
<td>4.640</td>
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<tr>
<td>19</td>
<td>10/25/2010</td>
<td>Influent</td>
<td>545.602</td>
<td>690.780</td>
<td>359.224</td>
<td>1427.167</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean</td>
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<td>Influent</td>
<td>103.263</td>
<td>123.793</td>
<td>68.470</td>
<td>217.443</td>
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<tr>
<td>Median</td>
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<td>Influent</td>
<td>9.851</td>
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<td>243.429</td>
<td>133.403</td>
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<td>Effluent</td>
<td>5.394</td>
<td>6.917</td>
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Table 4.27: *Particle Size Analysis for the Post-maintenance Events*

<table>
<thead>
<tr>
<th>Event No.</th>
<th>Event Date</th>
<th>Sample Type</th>
<th>Mean (µm)</th>
<th>Median (µm)</th>
<th>d_{10} (µm)</th>
<th>d_{90} (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>21</td>
<td>11/16/2010</td>
<td>Influent</td>
<td>430.163</td>
<td>453.802</td>
<td>266.479</td>
<td>650.424</td>
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<td>Effluent</td>
<td>2.311</td>
<td>2.775</td>
<td>0.747</td>
<td>6.073</td>
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<td>22</td>
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<td>Influent</td>
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<td>1.987</td>
<td>0.587</td>
<td>270.514</td>
</tr>
<tr>
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<td>Effluent</td>
<td>2.186</td>
<td>0.775</td>
<td>0.475</td>
<td>263.022</td>
</tr>
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<td>23</td>
<td>11/24/2010</td>
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<td>1.306</td>
<td>0.627</td>
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<td>2.038</td>
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<td>Influent</td>
<td>0.694</td>
<td>0.591</td>
<td>0.441</td>
<td>1.978</td>
</tr>
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<tr>
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<td>-</td>
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<tr>
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<td>1261.667</td>
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<td>1904.333</td>
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<tr>
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<td>880.358</td>
<td>478.337</td>
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<td>859.800</td>
<td>1645.167</td>
</tr>
<tr>
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<td>1311.667</td>
<td>1452.333</td>
<td>904.333</td>
<td>1732.000</td>
</tr>
<tr>
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<td></td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
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<td>1.327</td>
<td>0.540</td>
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</tr>
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<td></td>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>33</td>
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<td>Influent</td>
<td>16.458</td>
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<td>4.188</td>
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</tr>
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<td>538.400</td>
<td>207.000</td>
<td>661.400</td>
</tr>
<tr>
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<td>64.524</td>
<td>5.624</td>
<td>190.114</td>
</tr>
<tr>
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<td>-</td>
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</tr>
<tr>
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<td>50.140</td>
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<td>523.300</td>
</tr>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>36</td>
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<td>130.832</td>
<td>25.583</td>
<td>461.350</td>
</tr>
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<td>Effluent</td>
<td>105.184</td>
<td>181.062</td>
<td>21.352</td>
<td>262.928</td>
</tr>
<tr>
<td>37-1</td>
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<td>Influent</td>
<td>2.094</td>
<td>1.178</td>
<td>0.479</td>
<td>39.716</td>
</tr>
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<td>-</td>
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<td>Influent</td>
<td>265.559</td>
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<td>0.777</td>
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</tr>
<tr>
<td>39-1</td>
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<td>Influent</td>
<td>0.942</td>
<td>0.762</td>
<td>0.474</td>
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</tr>
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<td></td>
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<td>-</td>
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<tr>
<td>Mean</td>
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<td>388.605</td>
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<td>566.742</td>
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<td>Effluent</td>
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<td>736.832</td>
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<tr>
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<td>Influent</td>
<td>29.978</td>
<td>57.332</td>
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<td>St. Dev</td>
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<td>365.711</td>
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<td>Effluent</td>
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<td>Event Date</td>
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<td>Median (µm)</td>
<td>d_{10} (µm)</td>
<td>d_{90} (µm)</td>
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<td>0.922</td>
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</tr>
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<td></td>
<td></td>
<td>Effluent</td>
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<td>1.489</td>
<td>0.747</td>
<td>2.173</td>
</tr>
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<td>R2-2</td>
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<td>2.834</td>
<td>0.798</td>
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</tr>
<tr>
<td>R3</td>
<td>5/19/2011</td>
<td>Influent</td>
<td>713.542</td>
<td>778.415</td>
<td>511.133</td>
<td>1024.697</td>
</tr>
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<td>-</td>
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</tr>
<tr>
<td>R5-1</td>
<td>6/15/2011</td>
<td>Influent</td>
<td>7.762</td>
<td>30.926</td>
<td>0.450</td>
<td>113.951</td>
</tr>
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<td>-</td>
<td>-</td>
<td>-</td>
</tr>
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<td>R7</td>
<td>7/18/2011</td>
<td>Influent</td>
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<td>2.374</td>
<td>0.630</td>
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</tr>
<tr>
<td>Mean</td>
<td></td>
<td>Influent</td>
<td>92.567</td>
<td>104.068</td>
<td>64.686</td>
<td>148.517</td>
</tr>
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<td>Effluent</td>
<td>1.369</td>
<td>1.489</td>
<td>0.747</td>
<td>2.173</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td>Influent</td>
<td>3.673</td>
<td>4.432</td>
<td>0.896</td>
<td>9.260</td>
</tr>
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<td></td>
<td></td>
<td>Effluent</td>
<td>1.369</td>
<td>1.489</td>
<td>0.747</td>
<td>2.173</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td>Influent</td>
<td>250.918</td>
<td>272.644</td>
<td>180.392</td>
<td>355.966</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Effluent</td>
<td>-</td>
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</tr>
</tbody>
</table>
Figure 4.18: Particle Size Variation with the Time for the Pre-Maintenance Events

Figure 4.19: Particle Size Variation with the Time for the Post-Maintenance Events
Figure 4.20: Particle Size Variation with the Time for the Reconstructed Trench Events

Table 4.29:
Overall Statistical Summary of Particle Size Distribution for the Whole Monitoring Period.

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Sample Type</th>
<th>Mean (μm)</th>
<th>Median (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>Influent</td>
<td>219.349</td>
<td>247.405</td>
<td>147.041</td>
<td>370.091</td>
</tr>
<tr>
<td></td>
<td>Effluent</td>
<td>307.037</td>
<td>358.477</td>
<td>206.956</td>
<td>457.087</td>
</tr>
<tr>
<td>Median</td>
<td>Influent</td>
<td>8.051</td>
<td>10.570</td>
<td>1.620</td>
<td>29.048</td>
</tr>
<tr>
<td></td>
<td>Effluent</td>
<td>10.039</td>
<td>10.777</td>
<td>4.728</td>
<td>20.465</td>
</tr>
<tr>
<td>St. Dev</td>
<td>Influent</td>
<td>411.501</td>
<td>452.704</td>
<td>285.195</td>
<td>576.606</td>
</tr>
<tr>
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<td>Effluent</td>
<td>525.936</td>
<td>597.238</td>
<td>367.517</td>
<td>719.058</td>
</tr>
<tr>
<td>Range</td>
<td>Influent</td>
<td>0.694-1390</td>
<td>0.591-1510.2</td>
<td>0.441-946.42</td>
<td>1.978-1886.2</td>
</tr>
<tr>
<td></td>
<td>Effluent</td>
<td>0.777-1440.5</td>
<td>0.626-1570.167</td>
<td>0.448-912.6</td>
<td>1.909-1904.333</td>
</tr>
</tbody>
</table>

From Table 4.26, the average influent and effluent mean particle size for the pre-maintenance phase was 103.263 and 9.281 μm, respectively, while the median of influent and effluent mean particle size was 9.851 and 10.039 μm, respectively. It can be
observed that there was no significant difference between influent and effluent mean and median particle size in the pre-maintenance phase. However, the influent mean particle size for events 19 and 20 was 546 and 335 μm, respectively. This might be one of the reasons for the early clogging of the trench, because introducing this type of influent to the trench with relatively large particle size solids will clog the pores in the pervious concrete layer; and thus, water will not filter through the trench layers.

During the post-maintenance phase, the average influent and effluent mean particle size was 348.04 and 497.238 μm, respectively, while the median of influent and effluent mean particle size was 29.978 and 105.184 μm, respectively as shown in Table 4.27. However, the mean particle size was variable. During winter (12/12/2010 to 02/01/2011), the mean particle size for both influent and effluent increased significantly. The highest influent and effluent mean particle size were recorded at event 29 (01/17/2011), in which the influent mean particle size was 1390μm while the effluent mean particle size was 1440.5 μm. This might be due to snow best management practices such as spreading sand on the highway. Another reason is that during the snow season, significant quantities of pollutants are accumulating in the side snow piles. As mentioned previously in Chapter 3, the previous set-up of the geotextile layer might have increased the effluent particle size significantly during the winter season. The mean and median particle size dropped significantly after event 31-2 (02/01/2011).

The reconstructed trench events had relatively low mean particle size except for event R3 in which the mean particle size for influent was 714 μm. The average influent and effluent mean particle size was 92.567and 1.369 μm, respectively, while the median
of influent and effluent mean particle size was 3.673 and 1.369 μm, respectively. Effluent samples’ volume was not enough to obtain particle size samples; therefore, only R2-1 has effluent samples data as shown in the tables in Appendix B.

The particle size results matches the TSS, since the reconstructed trench exhibited the lowest mean and median particle size when compared to the pre-maintenance and post-maintenance. Also, during the winter period, the events that witnessed significant high particle sizes (mean > 1000 μm) had elevated TSS concentrations as well.

From the data presented in Table 4.29, the mean influent and effluent particle size were 219.349 and 307.037 μm, respectively, whereas the median influent and effluent particle size were 8.051 and 10.039 μm. Detailed tables for each event are presented in Appendix B.

4.3.3 pH

The pH was measured for both influent and effluent samples in the lab before the samples were distributed for water quality parameters analyses. However, starting from event 25, samples’ pH was obtained at the site after the samples retrieval, so that to get more accurate and representative pH values. Tables 4.30, 4.31 and 4.31 present the pH results for the pre-maintenance, post-maintenance and reconstructed trench phases respectively. Figures 4.21, 4.22 and 4.23 show the time-wise variation of pH for the pre-maintenance, post-maintenance and reconstructed trench phases respectively.
Table 4.30:  
*pH Summary for the Pre-maintenance Phase*

<table>
<thead>
<tr>
<th>Event No</th>
<th>Date</th>
<th>Influent pH</th>
<th>Effluent pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8/11/2010</td>
<td>8.14</td>
<td>7.75</td>
</tr>
<tr>
<td>2</td>
<td>8/11/2010</td>
<td>-</td>
<td>7.86</td>
</tr>
<tr>
<td>3</td>
<td>8/14/2010</td>
<td>7.06</td>
<td>8.14</td>
</tr>
<tr>
<td>4</td>
<td>8/21/2010</td>
<td>7.17</td>
<td>7.20</td>
</tr>
<tr>
<td>5</td>
<td>8/22/2010</td>
<td>7.32</td>
<td>7.42</td>
</tr>
<tr>
<td>6</td>
<td>9/3/2010</td>
<td>8.10</td>
<td>7.52</td>
</tr>
<tr>
<td>7</td>
<td>9/11/2010</td>
<td>7.31</td>
<td>7.52</td>
</tr>
<tr>
<td>8</td>
<td>9/16/2010</td>
<td>7.80</td>
<td>7.60</td>
</tr>
<tr>
<td>9</td>
<td>9/22/2010</td>
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<td>7.65</td>
</tr>
<tr>
<td>10</td>
<td>9/24/2010</td>
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<td>7.46</td>
</tr>
<tr>
<td>11</td>
<td>9/27/2010</td>
<td>7.60</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>9/27/2010</td>
<td>8.04</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>9/28/2010</td>
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<td>8.25</td>
</tr>
<tr>
<td>14</td>
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<td>8.04</td>
<td>7.94</td>
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<tr>
<td>15</td>
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</tr>
<tr>
<td>16</td>
<td>10/5/2010</td>
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<td>8.07</td>
</tr>
<tr>
<td>17</td>
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<td>7.70</td>
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<tr>
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<tr>
<td>19</td>
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</tr>
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<td>20</td>
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<table>
<thead>
<tr>
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<th>St. Dev</th>
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Table 4.31: pH Summary for the Post-maintenance Phase

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<tbody>
<tr>
<td>21</td>
<td>11/16/2010</td>
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<td>8.14</td>
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<tr>
<td>22</td>
<td>11/23/2010</td>
<td>8.15</td>
<td>8.17</td>
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<td>11/24/2010</td>
<td>8.49</td>
<td>8.25</td>
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<tr>
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</tr>
<tr>
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<td>8.46</td>
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<td>8.46</td>
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<td>39-2</td>
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<td>8.85</td>
<td>-</td>
</tr>
</tbody>
</table>

|          | Mean       | 8.61        | 8.39        |
|          | Median     | 8.60        | 8.29        |
|          | St. Dev    | 0.324       | 0.554       |
Table 4.32: 
*pH Summary for the Reconstructed Trench Phase*

<table>
<thead>
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<th>Influent pH</th>
<th>Effluent pH</th>
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</tr>
<tr>
<td>R2-1</td>
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</tr>
<tr>
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</tr>
<tr>
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<td>6/23/2011</td>
<td>8.13</td>
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</tr>
<tr>
<td>R7</td>
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<td>St. Dev</td>
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<td>0.120</td>
<td>-</td>
</tr>
</tbody>
</table>

Figure 4.21: pH Variation with Time for the Pre-Maintenance Phase
Figure 4.22: pH Variation with Time for the Post-Maintenance Phase

Figure 4.23: pH Variation with Time for the Reconstructed Trench Phase
The pH range was almost the same for influent and effluent in the pre-maintenance phase. The average influent and effluent pH were 7.69 and 7.72, respectively. However, pH levels for influent and effluent increased significantly in the post-maintenance phase starting from event 28 to reach a maximum influent pH of 9.22 and a maximum pH value of 9.46 for effluent. The average influent and effluent pH for the post-maintenance phase were 8.61 and 8.39, respectively. This increase was due to the construction activities and road maintenance that took place during winter in SR7, OH; thus, introducing lime containing byproducts to the highway runoff which will increase the pH due to existence of carbonates. The filtration of water through concrete and aggregate layer might also affect the pH since concrete provides lime particles that might be transported with the filtered water; and thus, increasing the effluent pH.

During the reconstructed trench monitoring phase, the influent pH levels decreased to the normal ranges (below 8.5). The average influent pH for the reconstructed trench phase was 7.93. The pH of the effluent samples from the reconstructed trench was not measured due to the lack of liquid volume.

Table 4.33 presents an inclusive statistical summary for influent and effluent pH for the whole monitoring period. From the table, the overall influent and effluent mean pH were almost the same; the mean influent pH was 8.12 and the mean effluent pH was 8.07.
Table 4.33:  
*pH Overall Summary for the Whole Monitoring Period*

<table>
<thead>
<tr>
<th>Statistical Parameter</th>
<th>Influent pH</th>
<th>Effluent pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean</td>
<td>8.12</td>
<td>8.07</td>
</tr>
<tr>
<td>Median</td>
<td>8.09</td>
<td>7.99</td>
</tr>
<tr>
<td>St. Dev</td>
<td>0.518</td>
<td>0.547</td>
</tr>
<tr>
<td>Range</td>
<td>7.06-9.22</td>
<td>7.20-9.46</td>
</tr>
</tbody>
</table>

4.3.4 Correlation between TSS and other Parameters

4.3.4.1 TSS and Total Rainfall

Influent average TSS concentrations and EMC’s were plotted against the total rainfall for all monitored events that have rainfall data as shown in Figure 4.24.

![Influent TSS Vs Total Rainfall](image-url)
As shown in Figure 4.24, the majority of the data can be found in the rainfall range of 0-0.5 in. However, the data points are scattered and there is no clear correlation between influent TSS concentrations and the total rainfall.

4.3.4.2 TSS and Rainfall Intensity

Another attempt was made to correlate the influent average TSS concentrations and EMC’s with the rainfall intensity as shown in Figure 4.25.

As shown in the above figure, most of the data are located in the 0-0.5 in of rainfall; and therefore, no clear correlation between influent TSS and rainfall intensity could be obtained.
4.3.4.3 TSS and Number of Antecedent Dry Days

Theoretically, the number of antecedent dry days should affect the influent TSS concentrations, because as the number of antecedent dry days increases, more pollutants accumulate on the surface of the highway. Figure 4.26 shows the influent average TSS concentrations and EMC’s and the corresponding numbers of antecedent dry weather day.

![Influent TSS Vs No. Antecedent Dry Days](image)

Figure 4.26: Influent TSS Vs No. Antecedent Dry Days

From Figure 4.26, it can be observed that there is no correlation between the number of antecedent dry weather days and the influent TSS concentration.

4.3.4.4 TSS and Turbidity

As the turbidity reflects the amount of TSS in a water sample, influent and effluent TSS and turbidity values were used to find a correlation between the two water
quality parameters. A total of 554 influent data points and 541 effluent data points were used to find the correlation. Influent and effluent data were plotted separately and based on the results of each data set, the overall correlation is determined. Several regression types were used including linear, polynomial, power and exponential. Also Ln(turbidity) was plotted against Ln(TSS) and the same regression models were used. Among all models used, the power correlation between turbidity and TSS and the linear correlation between Ln(turbidity) and Ln(TSS) exhibited the highest coefficients of determination ($R^2$) with the exact same value of 0.81. However, the data are scattered from the power model in the high range of TSS (>1000 mg/l). Therefore; because the linear correlation between Ln(turbidity) and Ln(TSS) represented the data more closely, it was used to interpret the correlation. Figures 4.27 and 4.28 show the correlation between Ln(turbidity) and Ln(TSS) for influent and effluent respectively. Figure 4.29 shows the overall correlation between Ln(turbidity) and Ln(TSS).
Figure 4.27: Influent Ln (Turbidity) Vs Ln (TSS)

Figure 4.28: Effluent Ln (Turbidity) Vs Ln (TSS)
From Figure 4.29, the final correlation between Turbidity and TSS is:

\[ \ln(\text{Turbidity}) = 0.758 \ln(\text{TSS}) + 1.052; \quad R^2 = 0.81 \]  

Equation 4-3

The scatter in the correlation might be due to the variability in suspended solids nature such as the shape and the particle size. The color of water sample also affects the turbidity measurement.

4.4 In-situ Tap Water Tests

4.4.1 Original Trench In-situ Tap Water Test

This test was conducted on November 24th, 2010, in order to assess the contribution of the trench materials to the effluent TSS levels. The test results are presented in Table 4.34.
Table 4.34:
*TSS Results for the Original Trench Tap Water Test Effluent Samples.*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Volume (ml)</th>
<th>Mass of Filter (g)</th>
<th>Mass of Filter + Residue (g)</th>
<th>TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>970</td>
<td>1.28458</td>
<td>1.39552</td>
<td>114.371</td>
</tr>
<tr>
<td>2</td>
<td>900</td>
<td>1.26712</td>
<td>1.35253</td>
<td>94.900</td>
</tr>
<tr>
<td>3</td>
<td>910</td>
<td>1.26165</td>
<td>1.31024</td>
<td>53.396</td>
</tr>
<tr>
<td>4</td>
<td>960</td>
<td>1.24517</td>
<td>1.27834</td>
<td>34.552</td>
</tr>
<tr>
<td>5</td>
<td>910</td>
<td>1.21808</td>
<td>1.25349</td>
<td>38.912</td>
</tr>
<tr>
<td>6</td>
<td>880</td>
<td>1.26761</td>
<td>1.34764</td>
<td>90.943</td>
</tr>
</tbody>
</table>

Average (mg/l) 71.179

Total TSS recovered (mg) 393.550

In this test, the influent introduced was tap water which is assumed to have no suspended solids. However, the effluent TSS was approximately 71 mg/l; therefore, it can be concluded that the contribution of the trench materials to the effluent TSS is 71 mg/l, which is relatively high, especially for events with low influent TSS concentrations.

4.4.2 Reconstructed Trench In-situ Tap Water Test

This test was conducted on July 6th, 2011, for the same purpose of the original trench tap water test. The test results are presented in Table 4.35.

Table 4.35:
*TSS Results for the Reconstructed Trench Tap Water Test Effluent Samples.*

<table>
<thead>
<tr>
<th>Sample</th>
<th>Volume (ml)</th>
<th>Mass of Filter (g)</th>
<th>Mass of Filter + Residue (g)</th>
<th>TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>635</td>
<td>1.19258</td>
<td>1.23256</td>
<td>39.98</td>
</tr>
<tr>
<td>2</td>
<td>705</td>
<td>1.18954</td>
<td>1.20947</td>
<td>19.93</td>
</tr>
<tr>
<td>3</td>
<td>240</td>
<td>1.121383</td>
<td>1.21561</td>
<td>1.78</td>
</tr>
<tr>
<td>4</td>
<td>325</td>
<td>1.18746</td>
<td>1.19282</td>
<td>5.36</td>
</tr>
<tr>
<td>5</td>
<td>700</td>
<td>1.1873</td>
<td>1.19029</td>
<td>2.99</td>
</tr>
<tr>
<td>6</td>
<td>735</td>
<td>1.18247</td>
<td>1.18766</td>
<td>5.19</td>
</tr>
<tr>
<td>7</td>
<td>720</td>
<td>1.12453</td>
<td>1.21741</td>
<td>2.88</td>
</tr>
<tr>
<td>8</td>
<td>385</td>
<td>1.19417</td>
<td>1.19539</td>
<td>1.22</td>
</tr>
</tbody>
</table>

Average 9.92

Total TSS recovered (mg) 50.06
This test was conducted mainly to wash solids from the surface of the reconstructed trench and to try collecting larger volume effluent samples using the pressure washing. It is hard to predict the amount of influent volume introduced; because part of that influent was used to wash the trench surface and it did not filter through the trench layers. However; 4.45 L effluent samples were collected. The average effluent TSS concentration was 9.92 mg/l and the total TSS recovered was 50.06 mg.

4.4.3 Comparison between the Original and Reconstructed Trench In-situ Tap Water Test

Table 4.36 shows a comparison between the in-situ tap water tests results of the original and reconstructed trench.

<table>
<thead>
<tr>
<th>Trench</th>
<th>Test Date</th>
<th>Avg. TSS (mg/l)</th>
<th>Total volume collected (L)</th>
<th>Total TSS recovered (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original</td>
<td>Nov 22, 2010</td>
<td>71.18</td>
<td>5.53</td>
<td>393.63</td>
</tr>
<tr>
<td>Reconstructed</td>
<td>July 06, 2011</td>
<td>9.92</td>
<td>4.45</td>
<td>50.06</td>
</tr>
</tbody>
</table>

It can be concluded from the table that the materials of the reconstructed trench contained lesser TSS amounts compared to the original trench, and as a result, this leads to less TSS concentrations in the effluent samples. This conforms to what was found in the materials testing (Section 4.1) when the aggregate and sand layers of the original trench were found to contain significantly higher quantities of TSS when compared to the
reconstructed trench sand and aggregate. This also might be one of the reasons behind the lower TSS levels in the effluent for the reconstructed trench.

4.5 First Flush Determination

First flush phenomenon was studied for events that contained 10 or more influent samples. The main water quality parameter studied was TSS. For each event, the parameters included are the time, flow and TSS concentration. The time was normalized at each sample by dividing the relative time at each sample by the relative time at the last influent sample. The normalized time was then expressed as a cumulative normalized time. Flow values were estimated using the modified Manning equation (ODOT, 2011d) as follows:

\[ Q = 0.56 \times \frac{Z}{n} \times S^{1/2} \times d^{8/3} \]  

Equation 4-4

Where:

\( Q = \) Flow (cfs).

\( Z = \) Reciprocal of the pavement cross slope (1/0.05).

\( n = \) Manning’s coefficient of roughness (0.015).

\( s = \) Longitudinal pavement slope (0.002).

\( d = \) Depth of flow in gutter section at curb (feet).

The depths recorded from the flow bubbler probe were used to estimate the flow for each sample according to Equation 4-4. The normalized cumulative flow was calculated by dividing the cumulative flow for each sample by the cumulative flow at the last influent sample. TSS mass (g) was computed according to the following equation:

\[ \text{TSS mass} = \text{TSS}_n \times \text{concentration} \times \text{Flow}_n \times \text{Time}_{n-n-1} \times 1.699 \]  

Equation 4-5
Where:

TSS<sub>n</sub> concentration: TSS concentration at sample n (mg/l).

Flow<sub>n</sub>: Flow at sample n (cfs).

Time<sub>n-n-1</sub>: Relative time difference between sample n and sample n-1 (minute).

1.699 is the conversion factor so that the resulting TSS mass will be in grams.

The difference between the normalized cumulative mass and the normalized cumulative time is denoted as Δ1; while Δ2 represents the difference between the normalized cumulative mass and the normalized cumulative flow. Therefore; if Δ1=0 at any time, this means that the TSS mass delivered is proportionate to the relative time, and if Δ1 > 0; this indicates that the normalized mass delivered exceeds the normalized time.

The same approach was followed by estimating Δ2. If Δ2 > 0; this means that the delivery of TSS exceeds the delivery of water and can be used to assess the strength of the first flush.

ODOT (2011a) uses the first 0.75 in of rainfall to represent the first flush, and based on this, the water quality volume can be estimated according to equation 2-11. The water quality volume for this criterion is 0.0467 acre-feet. The precipitation volume for each event is compared with the water quality volume to determine the existence of the first flush. The normalized time and flow corresponding to 50, 60, 70, 80 and 90% delivered TSS mass are presented in Table 4.37. Detailed first flush parameters for events with 10 or more influent samples are shown in Appendix A.
Table 4.37:
First Flush Summary
Event
No.

Total
Precipitation

Precipitation
Volume

-

inch

Acre-feet

% Time

% Flow

Rainfall

% Time

% Flow

Rainfall

% Time

% Flow

Rainfall

% Time

% Flow

Rainfall

% Time

% Flow

Rainfall

13

0.14
0.04
0.04
0.06
0.04
0.08
0.18
0.04
0.23
0.24
0.53
0.02
0.51
0.2
0.94
0.89
0.13
0.09
0.31
0.04
0.08
0.67
0.09
0.02
0.17
1.14

0.0087
0.0025
0.0025
0.0037
0.0025
0.0050
0.0112
0.0025
0.0143
0.0149
0.0330
0.0012
0.0317
0.0125
0.0585
0.0554
0.0081
0.0056
0.0193
0.0025
0.0050
0.0417
0.0056
0.0012
0.0106
0.0710
Average

22
23
42
61
23
64
81
32
19
56
29
29
25
56
58
22
44
30
43
33
21
19
20
63
57
14
38

16
20
34
50
31
48
82
35
38
47
24
30
29
49
43
49
33
25
59
60
39
17
24
46
38
8
37

0.051
0.033
0.040
0.028
0.020
0.144
0.030
0.106
0.117
0.020
0.010
0.069
0.109
0.276
0.188
0.062
0.176
0.026
0.040
0.120
0.049
0.020
0.087
0.079

29
27
50
73
28
74
83
41
24
59
37
36
36
70
63
30
58
46
52
41
36
21
25
67
58
15
45

25
27
43
51
40
58
83
50
51
52
35
36
39
56
49
55
39
38
64
66
55
21
32
55
42
14
45

0.064
0.037
0.040
0.030
0.023
0.149
0.030
0.133
0.133
0.020
0.010
0.089
0.120
0.321
0.196
0.073
0.188
0.030
0.041
0.134
0.056
0.020
0.106
0.089

38
30
60
83
33
81
85
53
39
61
51
49
50
77
66
44
69
61
62
52
52
24
31
72
60
18
54

38
34
55
56
49
68
86
65
72
56
48
49
51
66
55
65
48
49
69
73
64
28
42
63
46
25
55

0.081
0.040
0.040
0.030
0.030
0.159
0.040
0.163
0.149
0.020
0.020
0.110
0.127
0.366
0.225
0.084
0.201
0.030
0.046
0.162
0.060
0.020
0.125
0.101

52
37
71
88
43
86
87
67
60
65
67
66
69
83
70
56
76
73
73
66
68
29
39
76
61
21
63

55
47
68
67
62
77
89
78
78
63
63
66
65
74
65
76
60
58
77
82
73
38
54
72
50
37
65

0.111
0.040
0.040
0.030
0.030
0.170
0.040
0.177
0.158
0.030
0.020
0.126
0.130
0.414
0.261
0.098
0.220
0.032
0.050
0.224
0.063
0.020
0.144
0.114

64
50
84
93
63
92
91
83
81
73
82
82
82
91
94
79
84
89
91
82
85
59
52
89
63
24
77

70
66
82
81
79
88
93
90
85
75
79
83
80
86
85
91
75
77
91
91
87
68
72
87
57
49
79

0.126
0.040
0.040
0.030
0.030
0.174
0.040
0.192
0.187
0.040
0.020
0.149
0.140
0.505
0.295
0.114
0.250
0.040
0.055
0.270
0.080
0.020
0.161
0.130

14
17
18
19
20
21
22
23
24
25
29
31-2
32
33
34
37-1
38-1
39-2
R1
R3
R4
R5-1
R5-2
R6-2
R7

50% Mass

60% Mass

70% Mass

80% Mass

90% Mass


From Table 4.37, it can be concluded that 50% of the total TSS mass was delivered within the first 38% of the runoff time and 37% of the total flow; 60% of the total TSS mass was delivered in 45% of the runoff time and 45% of the total flow; 70% of the total TSS mass was delivered in 54% of the runoff time and 55% of the total flow; 80% of the total TSS mass was delivered in 63% of the runoff time and 65% of the total flow and 90% of the total TSS mass was delivered in 77% of runoff time and 79% of the total flow. This indicates that the delivery of TSS is disproportionate to time and flow; i.e., the majority of TSS is delivered within the early portions of time and flow, in other words, first flush exists. However, the strength of the first flush depends on the criteria of TSS mass used to define a first flush. Also it can be observed that the total rainfall has only exceeded 0.75 inch in three events. For those events, sampling stopped before reaching the 0.75 inch rainfall; therefore, this first flush criterion cannot be judged. Additionally, the mean rainfall for the monitored events is 0.27 inch which indicates that a 0.75 inch first flush is not appropriate for the studied site. On the other hand, the total precipitation corresponding to 50-90% TSS delivery ranged from 0.01-0.5 inch. The average total rainfall corresponding to 50, 60, 70, 80 and 90% was 0.08, 0.09, 0.1, 0.11 and 0.13 inch, respectively. This might affect the design length of the exfiltration trench, since it should be designed to treat the water quality volume.

As an example, Figure 4.30 shows how the TSS concentrations decreased significantly with the time of runoff for event R4. In Figure 4.31, the normalized cumulative mass is plotted with the normalized time and normalized cumulative flow.
volume for the same event. From this figure, it can be observed that the majority of TSS mass was delivered in the early portions of time and flow.

Figure 4.30: TSS Results- Event R4- 06/04/2011

Figure 4.31: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event R4- 06/04/2011
4.6 Runoff from Concrete Sawing

As mentioned in Chapter 3, this test was conducted on several trials. The first trial did not result in any effluent. Tables 4.38 and 4.39 summarize tests 2 and 3 results.

Table 4.38:
Test # 2 (04-11-2011) Results

<table>
<thead>
<tr>
<th></th>
<th>Volume (L)</th>
<th>pH</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>10</td>
<td>11.64</td>
<td>25.7</td>
</tr>
<tr>
<td>Effluent</td>
<td>0.7</td>
<td>8.03</td>
<td>22.38</td>
</tr>
</tbody>
</table>

Table 4.39:
Test # 3 (04-14-2011) Results

<table>
<thead>
<tr>
<th></th>
<th>Volume (L)</th>
<th>pH</th>
<th>Temperature (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent falling head</td>
<td>10</td>
<td>11.5*</td>
<td>21.7</td>
</tr>
<tr>
<td>Effluent falling head</td>
<td>~ 10**</td>
<td>11.24*</td>
<td>26.9</td>
</tr>
<tr>
<td>Effluent Constant head (unwashed sand)</td>
<td>0.7</td>
<td>9.92</td>
<td>21.78</td>
</tr>
<tr>
<td>Effluent Constant head (washed sand)</td>
<td>1.4</td>
<td>9.41</td>
<td>23.14</td>
</tr>
</tbody>
</table>

* Since the influent was introduced twice to the falling head permeameter (first run with 10 L from which the permeability was estimated and the second run with approximately 7 L for the purpose of providing sufficient volume for the constant head permeability test), the pH and the corresponding temperature values represent the average for the two runs.

** Note that since the first run of test # 3 (unwashed sand) resulted in 700 ml effluent, this meant that the decrease of influent volume was approximately 700 ml; thus, in order to start a new run, this volume loss was compensated to meet the test standards. Therefore, approximately 16 L influent constant head (which is the effluent from the falling head) was needed, keeping in mind that the amount of liquid that is supposed to pass through the sample does not change (10 L).

In all cases, it can be concluded that pH is reduced by the infiltration through the aggregate, sand, or a combination. However, the amount of reduction varies according to the test set-up followed. The highest pH reduction was observed in Test #2, in which the pH dropped 3.61 standard units, while the lowest reduction occurred between the influent and effluent of the falling head (using the aggregate) in which the pH dropped from 11.50
to 11.24. After the aggregate falling head permeability test, the effluent of the falling head was introduced to the constant head permeameter on washed and unwashed sand samples. The overall reduction of Test #3 was 1.32 standard units when using unwashed sand, while it was 1.83 standard units in case of washed sand. Also, the effluent volume collected in the case of washed sand was twice that collected in the case of unwashed sand.

The differences between the set-up in test #2 and test #3 might be the reasons of the pH reduction differences which are summarized as follows:

- The influent was filtered through the aggregate in test #2 for a shorter distance (3 inches) than the aggregate filtration in test #3 (6 inches).
- The type of the permeability test used is different; i.e., in the case of falling head permeability, the influent drops down through the aggregate sample quickly (approximately 4 seconds contact time), while in the constant head permeability test, the influent was in contact with the aggregate sample for longer time (approximately the whole test time); hence, providing sufficient contact time with aggregate might further reduce the pH.
- Another possible reason is that the effluent pH from test #2 was measured after 24 hours of the test time, in order to collect sufficient volume, while it was measured in the same day for test #3.

Washing the sand significantly affected the several parameters related to the experiments conducted on it. Test #3 is considered as a comparable situation between the two cases (washed and unwashed); since it was conducted using the same set-up. The pH
reduction was 1.83 standard units in case of washed sand while it was 1.32 standard units when using the unwashed sand. Furthermore; the effluent volume collected from the washed sand was as twice as that collected from the unwashed sand.
5.1 Summary

In this study, the performance of the exfiltration trench as a best management practice for treating the highway storm water runoff was investigated. The exfiltration trench was constructed on SR7, OH, in an urban highway and consisted of three layers: pervious concrete layer, type 3 backfill material (aggregate) layer and type 2 backfill material (sand) layer. The trench was installed on August 6\textsuperscript{th}, 2010 and was monitored until it was clogged on November 3\textsuperscript{rd}, 2010. The total number of pre-maintenance events monitored before clogging was 20 events. After the clogging of the trench, maintenance was performed on November 16\textsuperscript{th}, 2010, using vacuuming and pressure washing. The post-maintenance monitoring phase started after the maintenance and ended when the trench was clogged again on April 11\textsuperscript{th}, 2011. The total number of post-maintenance events was 23 events. The trench was reconstructed on April 28\textsuperscript{th}, 2010 and the reconstructed trench monitoring phase resulted in a total of 12 monitored events. The difference in the set-up between the original and the reconstructed trench was that the geotextile fabric layer was extended to the top of the original trench, while in the reconstructed trench; the geotextile fabric layer was extended to the interface between the aggregate and the sand layers. The difference in the geotextile layer installation was because it was thought that the former set-up created passages for flow between the geotextile fabric and the trench wall; thus, water was directed toward the effluent collecting point without receiving any treatment though the trench layers.
Samples from the original, demolished and reconstructed trench materials were obtained for tap water permeability and TSS tests except for concrete cores from the demolished trench because the samples crumbled. The average tap water permeability of the three concrete specimens obtained from the original trench was 3.39 cm/s and the average TSS recovered from each specimen was 216.6 mg. The average tap water permeability of the three concrete specimens obtained from the reconstructed trench was 2.62 cm/s and the average TSS recovered from each specimen was 265.7 mg. The porosity of concrete specimens from the original and reconstructed trench was 40.2% and 33.3%, respectively.

Aggregate samples were tested for tap water permeability, porosity and TSS recovered from falling head permeability test. The average tap water permeability of aggregate samples from the original, demolished and reconstructed trench was 2.14, 1.52 and 1.72 cm/s, respectively. The average amount of TSS recovered from each aggregate sample was 7353.5, 4334.0 and 3868.8 mg for original, demolished and reconstructed trench samples respectively. The porosity of original trench aggregate was 46.6% while the reconstructed trench aggregate porosity was 39.8%.

The constant head permeability test was performed to estimate the tap water permeability and the recovered TSS from sand samples. The average tap water permeability for the original, demolished and reconstructed trench sand was 0.0596, 0.0741 and 0.0865 cm/s, respectively and the average amount of TSS recovered from each sand sample was 485.6, 400.0 and 236.7 mg, respectively.
The permeability of the trench concrete specimens was compared to the permeability of the ODOT pervious concrete specimens used for laboratory tests. The original trench concrete permeability was close to the lab specimens’ permeability (92% of the lab specimens’ permeability). However, the reconstructed trench concrete permeability was almost 71% of the lab specimen’s permeability. This difference in the permeability of concrete specimens between the original and the reconstructed trench suggests that the clogging is expected to happen faster in the reconstructed trench. Also, this indicates that the amount of water filtering through the trench might be less than that in the original trench. This corresponds to the reconstructed trench monitoring results, in which the effluent samples’ volume was much less than the influent samples’ volume (effluent samples volume ranged between 50 and 200 ml).

The aggregate samples from the original, demolished and reconstructed trench were compared to the aggregate samples (washed and unwashed) tested previously in the lab. Washing the aggregate in the lab resulted in a 10% increase in the tap water permeability. However, lab samples’ permeability was considerably higher than the trench aggregate permeability. It was found that the original trench and reconstructed trench aggregate permeability was 54 and 43% of the unwashed aggregate lab samples’ permeability respectively. The demolished trench aggregate permeability was 71% of the original trench aggregate permeability. Washing the aggregate in the lab reduced the amount of TSS by 74%. The original trench aggregate produced the highest amount of TSS when compared to reconstructed trench and lab samples. The average TSS recovered from the demolished trench aggregate was 59% of the TSS amount found initially in the
aggregate samples. It is assumed that some of the original suspended materials in the aggregate layer washed out during storm water flow through the system. The amount of TSS recovered from the reconstructed trench aggregate was 53% of what was found in the original trench aggregate. This is an indication that the contribution of the reconstructed trench aggregate layer to the effluent TSS concentration is significantly lower than the original trench aggregate layer. This resulted in a drop in the effluent TSS concentrations in the reconstructed trench monitoring phase compared to effluent TSS concentrations in the original trench monitoring phase.

Sand samples were also compared to the previously tested laboratory washed sand samples. The original trench sand permeability was approximately similar to the washed lab samples. However, the permeability of the demolished trench sand samples was 25% higher than the original trench sand samples’ permeability. This refers to the test conditions; because by the time the demolished trench sand samples were brought from the site, they was solidified, so the sand was loosened with a spoon to obtain a sample that fit into the permeameter. The reconstructed trench sand permeability was 45% higher than the original trench sand permeability. On the other hand, the amount of TSS recovered from the reconstructed trench was 49% of what was found in the original trench, which indicated that the sand layer contribution to effluent TSS concentrations is significantly less than the contribution of the original trench sand, which also conforms to the relatively low effluent TSS concentrations detected in the reconstructed trench phase. The amount of TSS recovered from the demolished trench sand was 82% of the original trench sand’s TSS.
In-situ tap water tests were conducted to estimate the contribution of the trench materials to the effluent TSS concentrations. The first test was conducted on November 24th, 2010, following maintenance. The average TSS concentration of the tap water test effluent was 71.18 mg/l, which suggests that a considerable amount of the runoff effluent TSS concentrations results from the suspended materials washed out from the trench layers. The other tap water test was conducted on the reconstructed trench on July 6th, 2011. The effluent TSS concentration from this test was 9.92 mg/l. These results conformed to what was found in the materials testing, because the amount of TSS recovered from the original trench aggregate and sand samples was much higher than the reconstructed trench materials TSS amounts.

Influent and effluent samples were collected after each rainfall/snow event, preserved at 4°C and analyzed for various water quality parameters. The monitoring period was divided into pre-maintenance, post-maintenance and reconstructed trench phases. The average influent TSS concentrations for the pre-maintenance, post-maintenance and reconstructed trench phases were 347.16, 357.76 and 180.01 mg/l, respectively. The overall average influent TSS concentration was 312.20 mg/l with a median value of 230.07 mg/l, a standard deviation of 253.75 mg/l and a range of 32.44-1043.6 mg/l. As stated earlier in Chapter 4, the influent TSS concentration was expressed either by the arithmetic average or the flow weighted EMC. The average influent TSS EMC’s for the pre-maintenance, post-maintenance and reconstructed trench phases were 361.59, 364.26 and 258.62 mg/l, respectively. The overall average influent TSS EMC was 337.89 mg/l with a median value of 280.09 mg/l, a standard deviation of 269.31 mg/l.
and a range of 32.02-1097.7 mg/l. The effluent average concentration was only estimated by the arithmetic average; since the flow data for effluent samples were not available. The average effluent TSS concentrations for the pre-maintenance, post-maintenance and reconstructed trench phases were 258.81, 226.86 and 44.6 mg/l, respectively. The overall average effluent TSS concentration was 210.28 mg/l with a median value of 210.28 mg/l, a standard deviation of 325.7 mg/l and a range of 21.7-1982.2 mg/l.

The trench efficiency in removing the TSS was expressed as a percent removal which was computed in two ways as discussed in Chapter 4. The average overall removal and the simultaneous samples removal for the pre-maintenance phase were 52.07 and 57.31%, respectively. For the post-maintenance phase, the corresponding average removals were 19.85 and 38.16%, respectively. The average overall and simultaneous samples removals for the reconstructed trench were 64.55 and 68.51%, respectively.

Several correlations were tested between the influent average TSS concentration and other parameters including the total rainfall, rainfall intensity and number of antecedent dry weather days. None of the aforementioned parameters exhibited any correlation with the TSS, since other site specific conditions might interfere. TSS was also correlated with the turbidity, since both reflects the amount of suspended solids in the water sample in a different way. The coefficient of determination ($R^2$) for this correlation was 0.81.

Particle size distribution was also determined for both influent and effluent samples. For the pre-maintenance phase, the influent mean and median particle sizes were 103.26 and 9.85 μm, respectively while the effluent mean and median particle sizes
were 9.28 and 10.04 μm, respectively. During the post-maintenance phase, the influent mean and median particle sizes increased significantly to reach 348.04 and 29.98 μm, respectively. Effluent particle sizes also increased significantly during the post-maintenance phase to reach a mean and a median of 497.24 and 105.18 μm respectively. The mean and median particle sizes decreased in the reconstructed trench phase to a mean of 92.58 μm and a median of 3.67 μm for influent and a mean and median of 1.37 μm for effluent. However, effluent particle size was only estimated for one event due to the lack of liquid volume in the effluent samples. The overall mean particle sizes for influent and effluent were 219.35 and 307.04 μm, respectively while the overall median particle sizes for influent and effluent were 8.05 and 10.04 μm, respectively with an influent and effluent standard deviation of 411.50 and 525.94 μm, respectively.

Based on the visual observation of the runoff samples, the main sources of the suspended solids in the storm water runoff were either tire wear particles or soil (particularly sand). According to Sansalone et al. (1998), particles retained on sieve #200 (>75 μm) are mostly inorganic materials coated with asphaltic or organic materials; otherwise, particles are organics. During the pre-maintenance phase, the range of sizes detected in influent samples suggested that the majority of solids are organics. However, for the last two events, there was a sudden rise in the mean particle size (>300 μm) which is different than what was found before; i.e., different influent was introduced to the trench, which might have contained considerable quantities of sand. During the winter season, the mean particle size increased significantly to over 1000 μm. This sudden rise also suggests that different type of influent was introduced to the trench which might be
due to maintenance activities on the highway, or the spreading of sand on the surface of the highway as a deicing agent. The majority of solids transported in the reconstructed trench phase are thought to be organics; due to the relatively small particle diameters detected.

The relatively large size particles found in this study may also be related to the surrounding conditions. It was observed at the site that considerable amounts of sand were displaced from the adjacent strip in the upstream side of the trench to the concrete shoulder; thus, the runoff transports this sand to the trench which contributed to the clogging of the trench.

The pH was measured for influent and effluent samples. For the pre-maintenance, the average influent and effluent pH were 7.69 and 7.72, respectively. The pH increased during the winter season, which might be due to maintenance activities performed on the highway. The average influent and effluent pH for the post-maintenance phase were 8.61 and 8.39, respectively. The average influent pH for the reconstructed trench phase was 7.93. No effluent pH was recorded for the reconstructed trench phase due to the lack of liquid volume. The overall influent mean and median pH were 8.12 and 8.09, respectively with a standard deviation of 0.518 and a range of 7.06-9.22, while the overall effluent mean and median pH were 8.07 and 7.99, respectively with a standard deviation of 0.547 and a range of 7.20-9.46.

The aggregate and sand from the original trench were tested for high pH influent in order to evaluate the ability of the trench materials to treat high pH influent (>11). A concrete sawing water that has a pH higher than 11 was introduced to the sand and
aggregate. Several set-up’s were tried. A combination of aggregate and sand placed in the constant head permeameter achieved the highest reduction in pH (11.64 – 8.03) although the effluent volume collected was only 7% of the total influent volume; because the sample was clogged due to the large amount of concrete sawing particles accumulated at the interface between aggregate and sand.

First flush phenomenon was investigated in terms of TSS. The ODOT criterion for the first flush was the first 0.75 in of rainfall. However, this criterion does not apply for this site; because the average total rainfall for the monitored events was 0.27 in. Also, three events have only exceeded the 0.75-in rainfall criterion, but the influent samples did not cover the whole rainfall duration. Other approaches were followed to judge the existence of the first flush by estimating the percentage of time and flow required to deliver a certain percentage of mass. In 69% of the events, 50% of the TSS mass was delivered in less than 50% of the flow time; in 77% of the events, 60% of the TSS mass was delivered in less than 60% of the flow time; in 81% of the events, 70% of the TSS mass was delivered in less than 70% of the flow time; in 85% of the events, 80% of the TSS mass was delivered in less than 80% of the flow time and in 77% of the events, 90% of the TSS mass was delivered in less than 90% of the flow time. All the above time and TSS combinations indicate a relatively early delivery of TSS with respect to time. Moreover, in 88% of the events, 50% of the TSS mass was delivered in less than 50% of the total flow volume; in 88% of the events, 60% of the TSS mass was delivered in less than 60% of the total flow volume; in 88% of the events, 70% of the TSS mass was delivered in less than 70% of the total flow volume; in 92% of the events, 80% of the
TSS mass was delivered in less than 80% of the total flow volume and in 81% of the events, 90% of the TSS mass was delivered in less than 90% of the total flow volume. This also confirms that there is a relatively early delivery of TSS with respect to the flow volume. However, there is no strict definition or criteria for the first flush; since it may vary depending on the site specific conditions and other rainfall parameters.

5.2 Conclusions

- The reconstructed trench achieved higher removal efficiencies than the original trench. This can be referred to the change in the set-up explained before.

- The aggregate used in the trench did not satisfy the requirements for structural backfill type 3 materials; since the required aggregate according to ODOT Construction and Material Specifications should meet No. 57 or No. 67 gradations. This is the reason for the difference in the permeability between the trench aggregate and the previously lab tested aggregate samples.

- Based on the lab tests conducted on aggregate and sand samples from the original and the reconstructed trench, the contribution of the reconstructed trench materials to the effluent TSS concentrations was much lower than the contribution of the original trench materials. This also confirms what was found in the in-situ tap water test conducted on both the original and the reconstructed trench. Also, the big difference in the effluent concentrations
found in the original trench and the reconstructed trench matches the findings of these tests.

- The permeability of the concrete specimens from the original trench was higher than the reconstructed trench. This might be the reason for the lack of effluent volume collected due to the low infiltration, and will eventually clog the trench earlier than the original trench.

- The maintenance which was performed on the trench on November 24\textsuperscript{th}, 2010 resulted in a recovery of the trench performance. However, this maintenance targeted the concrete layer by applying surface vacuuming and pressure washing, which suggests that the clogging happened most likely in the concrete layer.

- The maintenance was performed to the trench after 20 monitored events and the trench was demolished after 23 monitored events. This suggests that trench maintenance (vacuuming and pressure washing) is needed 3-4 times annually, in order to recover the decreased permeability of the trench layers, particularly concrete layer.

- The influent particle size increased significantly for the two events prior to the first clogging, which might be the reason for the early clogging. Also, during the winter season, both influent and effluent particle size increased which also affected the performance of the trench.
• The existence of the concrete plant across the road from the trench might have negative impacts on the water quality parameters detected in the runoff samples such as TSS and particle size distribution.

• The first flush criterion set by the ODOT does not satisfy this site. On the other hand, the delivery of TSS mass was investigated with respect to the time and flow volume delivered, and it indicated the early delivery of TSS mass with respect to time and flow volume, in other words, a first flush exists but the strength varies.

• The aggregate and sand reduced the pH of the high pH water influent. However, the effluent volume collected was too low due to the clogging of the sand sample by the high amount of concrete particles.

• There was a correlation between TSS and turbidity; however, the correlation is not strong ($R^2 = 0.81$), since the data was scattered especially in the high TSS concentrations. No correlation was found between TSS and other parameters including the total rainfall, rainfall intensity and the number of antecedent dry weather days.

• Based on the overall averages for pH, the exfiltration trench does not affect the pH of the storm water runoff; i.e., influent and effluent pH are approximately equal.

5.3 Recommendations

Based on the differences between the original and the reconstructed trench, the aggregate and the sand should be washed before installation, because this will reduce the
amount of effluent TSS from the trench materials. This can be seen clearly by the previously tested lab samples in which washing the aggregate resulted in 74% TSS reduction.

A better way for sampling the effluent should be followed. In this study, the effluent collecting probe was placed in an open pipe located below the geotextile fabric layer which was connected to other pipes which eventually end in the effluent sampler cabinet. However, in this set-up, the flow is restricted so that when it exceeds a certain level, it starts draining from the back holes. For more accurate results, the effluent should be directed toward a pipe from which, the flow can be determined.

The geotextile fabric layer should be installed in a way that it extends from the bottom of the trench and covers the outside of the trench walls; therefore, ensuring the water flowing to the trench will pass through all layers.

The trench set-up should allow constructing a built-in permeameter tube or box. This can be achieved by isolating a part of the trench through the installation of an open PVC box that has the same width of the trench. Trench layers are poured inside the box. This box should extend 1 cm above the concrete layer level. When an in-situ permeability test is to be conducted, a similar box with the same dimensions can be placed above the existing one, so that to assure both boxes match.

The in-situ tap water test should be conducted on a regular basis, which helps estimating the time-wise variation of the trench material contribution to the effluent TSS.
REFERENCES


Ohio Department of Transportation (ODOT). (2010). Schematic plan 2/590. WAS-7-24096 Part 1. [Construction Drawings].


Appendix A: TSS Results

Event Number: 1
Event Date: 8/11/10
Time: 6:11 AM
Event Type: Rain
Event Duration (minutes): 40
Influent sampling time (min): 2
Test Type: TSS
Number of antecedent dry days: -

Table A.1: Event 1 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:09 AM</td>
<td>0.03</td>
<td>0.0234</td>
<td>0</td>
<td>1409.07</td>
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<td>6:10 AM</td>
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<td>0.0266</td>
<td>1</td>
<td>231.70</td>
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<td>E-1</td>
<td>6:16 AM</td>
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</table>

Estimating the average concentrations and removal efficiencies

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<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>820.38</td>
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<td>1982.23</td>
<td>1982.23</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
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<td>-141.62</td>
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</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Event Number 2
Event Date 8/11/10
Time 4:38 PM
Event Type Rain
Event Duration (minutes) 55
Influent sampling time (min) -
Test Type TSS
Number of antecedent dry days 0.41

Table A.2: Event 2 TSS Results

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<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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<td>Effluent</td>
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<td>4:43 PM</td>
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<td>-</td>
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<td>253.43</td>
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<td>Effluent</td>
<td>E-3</td>
<td>4:45 PM</td>
<td>-</td>
<td>-</td>
<td>4</td>
<td>250.70</td>
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<td>Effluent</td>
<td>E-4</td>
<td>4:46 PM</td>
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<td>-</td>
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<td>Effluent</td>
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<td>4:47 PM</td>
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Estimating the average concentrations and removal efficiencies

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<th>EMC (mg/l)</th>
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<th>Simultaneous EMC (mg/l)</th>
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<td>Removal %</td>
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</table>

* Time was set according to the first effluent sample
Appendix A: TSS Results

Figure A.1: TSS Results- Event 2- 08/11/2010

Notes:
1- No influent samples were collected for this event; therefore, the flow and the removal efficiency cannot be estimated.
Appendix A: TSS Results

Event Number 3
Event Date 8/14/10
Time 5.31 PM
Event Type Rain
Event Duration (minutes) 20
Influent sampling time (min) 4
Test Type TSS
Number of antecedent dry days 3.00

Table A.3: Event 3 TSS Results

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<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
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<td>5.31 PM</td>
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<tr>
<td>Influent</td>
<td>I-2</td>
<td>5.34 PM</td>
<td>0.17</td>
<td>0.4379</td>
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<td>699.43</td>
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<tr>
<td>Effluent</td>
<td>E-1</td>
<td>5.34 PM</td>
<td>-</td>
<td>0.0234</td>
<td>3</td>
<td>297.13</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-2</td>
<td>5.35 PM</td>
<td>-</td>
<td>0.0234</td>
<td>4</td>
<td>190.13</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-3</td>
<td>8.38 PM</td>
<td>-</td>
<td>0.0234</td>
<td>187</td>
<td>1423.63</td>
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<tr>
<td>Effluent</td>
<td>E-4</td>
<td>8.39 PM</td>
<td>-</td>
<td>0.0302</td>
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<td>Effluent</td>
<td>E5-10</td>
<td>9.36 PM-10.15 PM</td>
<td>-</td>
<td>0.0234</td>
<td>265</td>
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<td>Effluent</td>
<td>E11-13</td>
<td>10.17 PM-10.21 PM</td>
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<td>0.0234</td>
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<tr>
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<td>E14-17</td>
<td>10.23 PM-12.21 AM</td>
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<td>0.0234</td>
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<td>E-18</td>
<td>12.23 AM</td>
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<td>Effluent</td>
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<td>53.70</td>
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<td>Effluent</td>
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Estimating the average concentrations and removal efficiencies

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<td>2312.98</td>
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<td>Effluent</td>
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<td>259.06</td>
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<td>Removal %</td>
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<td>88.80</td>
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</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.2: TSS Results- Event 3- 08/14/2010
Appendix A: TSS Results

Event Number 4
Event Date 8/21/2010
Time 3:39 PM
Event Type Rain
Event Duration (minutes) 340
Influent sampling time (min) 330
Test Type TSS
Number of antecedent dry days 6.91

Table A.4: Event 4 TSS Results

<table>
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<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:36 PM</td>
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<td>I-2</td>
<td>3:21 PM</td>
<td>0.13</td>
<td>0.8369</td>
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<tr>
<td>Influent</td>
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<td>4:09 PM</td>
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<td>0.1586</td>
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<tr>
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<td>7:21 PM</td>
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<td>0.0234</td>
<td>285</td>
<td>638.27</td>
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<tr>
<td>Influent</td>
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<tr>
<td>Influent</td>
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<td>173.17</td>
</tr>
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<td>167.37</td>
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<tr>
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<td>-</td>
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<td>E-4</td>
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<td>0.0234</td>
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<td>274.30</td>
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<td>128.33</td>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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<tr>
<td>Removal %</td>
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<td>-0.77</td>
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* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.3: TSS Results - Event 4 - 08/21/2010
Appendix A: TSS Results

Event Number 5
Event Date 8/22/10
Time 12:00 AM
Event Type Rain
Event Duration (minutes) 10
Influent sampling time (min) 7
Test Type TSS
Number of antecedent dry days 0.34

Table A.5: Event 5 TSS Results

<table>
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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>4:28 AM</td>
<td>0.02</td>
<td>0.0234</td>
<td>0</td>
<td>453.27</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>4:31 AM</td>
<td>0.04</td>
<td>0.0234</td>
<td>3</td>
<td>190.63</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>4:33 AM</td>
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<td>0.0574</td>
<td>5</td>
<td>109.10</td>
</tr>
<tr>
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<td>I-4</td>
<td>8:56 AM</td>
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<td>0.0234</td>
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<td>92.53</td>
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<td>Effluent</td>
<td>E-1</td>
<td>4:42 AM</td>
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<td>0.0234</td>
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<td>4:43 AM</td>
<td>-</td>
<td>0.0234</td>
<td>15</td>
<td>168.07</td>
</tr>
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<td>Effluent</td>
<td>E-3</td>
<td>4:46 AM</td>
<td>-</td>
<td>0.0234</td>
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<td>82.53</td>
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<td>4:48 AM</td>
<td>-</td>
<td>0.0234</td>
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<td>34.00</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-5</td>
<td>4:49 AM</td>
<td>-</td>
<td>0.0234</td>
<td>21</td>
<td>34.47</td>
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<td>E-6</td>
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<td>0.0234</td>
<td>22</td>
<td>28.67</td>
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<td>Effluent</td>
<td>E-7</td>
<td>4:52 AM</td>
<td>-</td>
<td>0.0234</td>
<td>24</td>
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<td>Effluent</td>
<td>E-8</td>
<td>4:53 AM</td>
<td>-</td>
<td>0.0234</td>
<td>25</td>
<td>27.40</td>
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<td>Effluent</td>
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<td>-</td>
<td>0.0234</td>
<td>28</td>
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<td>0.0234</td>
<td>29</td>
<td>20.82</td>
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<tr>
<td>Effluent</td>
<td>E-11</td>
<td>4:59 AM</td>
<td>-</td>
<td>0.0234</td>
<td>31</td>
<td>47.18</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-12</td>
<td>5:00 AM</td>
<td>-</td>
<td>0.0234</td>
<td>32</td>
<td>10.11</td>
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<td>Effluent</td>
<td>E-13</td>
<td>5:02 AM</td>
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<td>0.0234</td>
<td>34</td>
<td>18.13</td>
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<tr>
<td>Effluent</td>
<td>E-14</td>
<td>5:03 AM</td>
<td>-</td>
<td>0.0234</td>
<td>35</td>
<td>14.67</td>
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<tr>
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<td>E-15</td>
<td>5:06 AM</td>
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<td>0.0234</td>
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Estimating the average concentrations and removal efficiencies

<table>
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<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>184.13</td>
<td>211.38</td>
<td>251.00</td>
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<tr>
<td>Effluent</td>
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<td>48.43</td>
<td>48.43</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>77.09</td>
<td>80.70</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.4: TSS Results- Event 5- 08/22/2010
Appendix A: TSS Results

Event Number 6
Event Date 9/3/10
Time 2:40 PM
Event Type Rain
Event Duration (minutes) 20
Influent sampling time (min) 3
Test Type TSS
Number of antecedent dry days 12.38

Table A.6: Event 6 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:47 PM</td>
<td>0.14</td>
<td>0.3145</td>
<td>0</td>
<td>669.20</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>2:48 PM</td>
<td>0.14</td>
<td>0.3145</td>
<td>1</td>
<td>720.30</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>2:47 PM</td>
<td>-</td>
<td>0.0234</td>
<td>0</td>
<td>163.93</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-2</td>
<td>2:49 PM</td>
<td>-</td>
<td>0.0234</td>
<td>2</td>
<td>144.50</td>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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<tr>
<td>Influent</td>
<td>694.75</td>
<td>694.75</td>
<td>694.75</td>
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<td>154.22</td>
<td>154.22</td>
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<tr>
<td>Removal %</td>
<td>-</td>
<td>77.80</td>
<td>77.80</td>
</tr>
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</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.5: Results- Event 6-09/03/2010
Appendix A: TSS Results

Event Number 7
Event Date 9/11/10
Time 7:44 PM
Event Type Rain
Event Duration (minutes) 3
Influent sampling time (min) 2
Test Type TSS
Number of antecedent dry days 8.21

Table A.7: Event 7 TSS Results

<table>
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<tr>
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<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>7:46 PM</td>
<td>0.01</td>
<td>0.0889</td>
<td>0</td>
<td>608.20</td>
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<tr>
<td>Influent</td>
<td>I-2</td>
<td>10:46 PM</td>
<td>0.01</td>
<td>0.0266</td>
<td>180</td>
<td>327.87</td>
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<tr>
<td>Effluent</td>
<td>E-1</td>
<td>7:52 PM</td>
<td>-</td>
<td>0.0302</td>
<td>6</td>
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<td>Effluent</td>
<td>E-2</td>
<td>7:54 PM</td>
<td>-</td>
<td>0.0340</td>
<td>8</td>
<td>146.97</td>
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<td>Effluent</td>
<td>E-3</td>
<td>7:56 PM</td>
<td>-</td>
<td>0.0074</td>
<td>10</td>
<td>109.20</td>
</tr>
<tr>
<td>Effluent</td>
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<td>-</td>
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<td>E5</td>
<td>8:00 PM</td>
<td>-</td>
<td>0.0037</td>
<td>14</td>
<td>99.87</td>
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<tr>
<td>Effluent</td>
<td>E6</td>
<td>8:01 PM</td>
<td>-</td>
<td>0.0234</td>
<td>15</td>
<td>57.27</td>
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Estimating the average concentrations and removal efficiencies

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<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
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<tr>
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<td>543.57</td>
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<td>124.83</td>
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<tr>
<td>Removal %</td>
<td>-</td>
<td>73.33</td>
<td>79.48</td>
</tr>
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* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.6: TSS Results- Event 7- 09/11/2010
Appendix A: TSS Results

Event Number 8
Event Date 9/16/10
Time 8:30 AM
Event Type Rain
Event Duration (minutes) 32
Influent sampling time (min) 15
Test Type TSS
Number of antecedent dry days 4.53

Table A.8:
*Event 8 TSS Results*

<table>
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<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.1388</td>
<td>0</td>
<td>967.97</td>
</tr>
<tr>
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<td>0.8224</td>
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<td>0.0471</td>
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<td>234.60</td>
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<td>E-3</td>
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<td>-</td>
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<td>0.0266</td>
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<td>0.93</td>
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<tr>
<td>Effluent</td>
<td>E-5</td>
<td>10:21 AM</td>
<td>-</td>
<td>0.0380</td>
<td>108</td>
<td>263.77</td>
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<tr>
<td>Effluent</td>
<td>E-6</td>
<td>10:23 AM</td>
<td>-</td>
<td>0.0340</td>
<td>110</td>
<td>92.73</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-7</td>
<td>10:25 AM</td>
<td>-</td>
<td>0.0037</td>
<td>112</td>
<td>98.27</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-8</td>
<td>10:26 AM</td>
<td>-</td>
<td>0.0340</td>
<td>113</td>
<td>98.13</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-9</td>
<td>10:27 AM</td>
<td>-</td>
<td>0.0340</td>
<td>114</td>
<td>108.00</td>
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<td>0.0234</td>
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<tr>
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<td>2:21 PM</td>
<td>-</td>
<td>0.0340</td>
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<td>E-13</td>
<td>2:25 PM</td>
<td>-</td>
<td>0.0340</td>
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<td>249.73</td>
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<tr>
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<td>E-14</td>
<td>2:26 PM</td>
<td>-</td>
<td>0.0340</td>
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<td>301.47</td>
</tr>
<tr>
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<td>E-15</td>
<td>2:28 PM</td>
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<td>0.0340</td>
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<td>354.47</td>
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<tr>
<td>Effluent</td>
<td>E-17</td>
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<td>0.0340</td>
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<td>318.53</td>
</tr>
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<td>-</td>
<td>0.0340</td>
<td>359</td>
<td>359.00</td>
</tr>
<tr>
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<td>E-19</td>
<td>3:16 PM</td>
<td>-</td>
<td>0.0266</td>
<td>403</td>
<td>344.29</td>
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<tr>
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<td>3:47 PM</td>
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<td>0.0340</td>
<td>434</td>
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<td>E-21</td>
<td>3:48 PM</td>
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Estimating the average concentrations and removal efficiencies

<table>
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<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>446.74</td>
<td>663.37</td>
<td>663.37</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>237.80</td>
<td>221.87</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>64.15</td>
<td>66.55</td>
</tr>
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</table>

* Time was set according to the first influent sample

Figure A.7: TSS Results- Event 8- 09/16/2010
Appendix A: TSS Results

Event Number 9
Event Date 9/22/10
Time 6:37 PM
Event Type Rain
Event Duration (minutes) -
Influent sampling time (min) 3
Test Type TSS
Number of antecedent dry days 6.42

Table A.9: Event 9 TSS Results

<table>
<thead>
<tr>
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<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:37 PM</td>
<td>-</td>
<td>0.0521</td>
<td>0</td>
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</tr>
<tr>
<td>Influent</td>
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<td>6:39 PM</td>
<td>-</td>
<td>0.1040</td>
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<td>462.28</td>
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<tr>
<td>Effluent</td>
<td>E-1</td>
<td>6:47 PM</td>
<td>-</td>
<td>0.0380</td>
<td>10</td>
<td>178.05</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-2</td>
<td>6:49 PM</td>
<td>-</td>
<td>0.0047</td>
<td>12</td>
<td>158.59</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-3</td>
<td>6:51 PM</td>
<td>-</td>
<td>0.0340</td>
<td>14</td>
<td>116.96</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-4</td>
<td>6:53 PM</td>
<td>-</td>
<td>0.0090</td>
<td>16</td>
<td>114.31</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-5</td>
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<td>-</td>
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<td>E-8</td>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.8: TSS Results- Event 9- 09/22/2010

TSS Results- Event 9- 09/22/2010

Influent

Effluent
Appendix A: TSS Results

Event Number: 10  
Event Date: 9/24/10  
Time: 10:08 PM  
Event Type: Rain  
Event Duration (minutes): 8  
Influent sampling time (min): 4  
Test Type: TSS  
Number of antecedent dry days: 2.15

Table A.10:  
Event 10 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</tr>
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Estimating the average concentrations and removal efficiencies

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<td>-</td>
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* Time was set according to the first influent sample

Figure A.9: TSS Results- Event 10- 09/24/2010
Appendix A: TSS Results

Event Number 11
Event Date 9/27/10
Time 2:30 AM
Event Type Rain
Event Duration (minutes) 5
Influent sampling time (min) 6
Test Type TSS
Number of antecedent dry days 2.18

Table A.11:
Event 11 TSS Results

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<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
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<tr>
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<td>Influent</td>
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Estimating the average concentrations and removal efficiencies

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<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
<tbody>
<tr>
<td>Influent</td>
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<td>Effluent</td>
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<tr>
<td>Removal %</td>
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</tr>
</tbody>
</table>
Appendix A: TSS Results

Event Number 12
Event Date 9/27/2010
Time 3:41 AM
Event Type Rain
Event Duration (minutes) 25
Influent sampling time (min) 2
Test Type TSS
Number of antecedent dry days 0.05

Table A.12: 
Event 12 TSS Results

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<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
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<tbody>
<tr>
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Estimating the average concentrations and removal efficiencies

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<tr>
<td>Removal %</td>
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<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Appendix A: TSS Results

Event Number 13
Event Date 9/28/10
Time 2:41 AM
Event Type Rain
Event Duration (minutes) 51
Influent sampling time (min) 59
Test Type TSS
Number of antecedent dry days 0.96
Total Volume of Flow (ft$^3$) 2715.10

Table A.13: Event 13 TSS Results

<table>
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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta 1$</th>
<th>$\Delta 2$</th>
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<td>50.60</td>
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<tr>
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<td>Effluent</td>
<td>E-11</td>
<td>3:42 AM</td>
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<td>0.1040</td>
<td>51</td>
<td>12.06</td>
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</tr>
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<td>E-12</td>
<td>3:47 AM</td>
<td>-</td>
<td>0.0963</td>
<td>56</td>
<td>15.88</td>
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</table>

**Estimating the average concentrations and removal efficiencies**

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
<tbody>
<tr>
<td>Influent</td>
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<td>Removal%</td>
<td>-</td>
<td>49.98</td>
<td>49.98</td>
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</tbody>
</table>

* Time was set according to the first influent sample

**Notes:**

1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)

2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.

3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.

4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.

5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.

6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.10: TSS Results- Event 13- 09/28/2010

Figure A.11: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 13- 09/28/2010
Appendix A: TSS Results

**Event Number** 14  
**Event Date** 10/3/10  
**Time** 3:20 AM  
**Event Type** Rain  
**Event Duration (minutes)** 19  
**Influent sampling time (min)** 50  
**Test Type** TSS  
**Number of antecedent dry days** 5.03  
**Total Volume of Flow (ft$^3$)** 1569.19

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)$^3$</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta 1$</th>
<th>$\Delta 2$</th>
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<td>3:31 AM</td>
<td>0.02</td>
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<td>0.025</td>
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<td>161.75</td>
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<td>143.741</td>
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<td>0.398</td>
<td>0.198</td>
<td>0.264</td>
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<td>32.77</td>
<td>0.600</td>
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<td>2754.83</td>
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<td>0.082</td>
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<td>I-9</td>
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<td>40</td>
<td>26.23</td>
<td>0.900</td>
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<td>2800.13</td>
<td>0.987</td>
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<td>73.93</td>
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<tr>
<td>Effluent</td>
<td>E-4</td>
<td>3:46 AM</td>
<td>-</td>
<td>0.1121</td>
<td>15</td>
<td>70.37</td>
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<td>Effluent</td>
<td>E-5</td>
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<td>56.32</td>
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</table>
Estimating the average concentrations and removal efficiencies

<table>
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<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
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<tr>
<td>Influent</td>
<td>92.08</td>
<td>82.97</td>
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<td>Effluent</td>
<td>-</td>
<td>69.39</td>
<td>69.39</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>16.36</td>
<td>49.42</td>
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</tbody>
</table>

* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.12: TSS Results- Event 14- 10/03/2010

Figure A.13: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 14- 10/03/2010
Appendix A: TSS Results

Event Number 15
Event Date 10/4/10
Time 11:12 PM
Event Type Rain
Event Duration (minutes) -
Influent sampling time (min) 20
Test Type TSS
Number of antecedent dry days 1.83

Table A.15:
Event 15 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>11:12 PM</td>
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<td>0.1040</td>
<td>0</td>
<td>72.77</td>
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<tr>
<td>Influent</td>
<td>I-2</td>
<td>11:18 PM</td>
<td>-</td>
<td>0.0963</td>
<td>6</td>
<td>48.25</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>11:22 PM</td>
<td>-</td>
<td>0.0963</td>
<td>10</td>
<td>47.32</td>
</tr>
<tr>
<td>Influent</td>
<td>I-4</td>
<td>11:24 PM</td>
<td>-</td>
<td>0.1040</td>
<td>12</td>
<td>47.05</td>
</tr>
<tr>
<td>Influent</td>
<td>I-5</td>
<td>11:27 PM</td>
<td>-</td>
<td>0.0963</td>
<td>15</td>
<td>51.55</td>
</tr>
<tr>
<td>Influent</td>
<td>I-6</td>
<td>11:31 PM</td>
<td>-</td>
<td>0.0819</td>
<td>19</td>
<td>30.75</td>
</tr>
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</table>

Estimating the average concentrations and removal efficiencies

<table>
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<tr>
<th>Sample Type</th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>50.36</td>
<td>49.62</td>
<td>-</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.14: TSS Results- Event 15-10/04/2010
Appendix A: TSS Results

Event Number: 16
Event Date: 10/5/10
Time: 5:08 AM
Event Type: Rain
Event Duration (minutes): 11
Influent sampling time (min): 29
Test Type: TSS
Number of antecedent dry days: 0.25

Table A.16: Event 16 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>5:18 AM</td>
<td>0.04</td>
<td>0.3643</td>
<td>0</td>
<td>419.65</td>
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<tr>
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<td>Influent</td>
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<td>5:26 AM</td>
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<td>0.6114</td>
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<td>Influent</td>
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<td>5:31 AM</td>
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<td>0.4000</td>
<td>13</td>
<td>109.58</td>
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<tr>
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<td>5:36 AM</td>
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<td>0.3145</td>
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<td>87.83</td>
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<tr>
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<td>I-6</td>
<td>5:41 AM</td>
<td>0.04</td>
<td>0.2156</td>
<td>23</td>
<td>70.18</td>
</tr>
<tr>
<td>Influent</td>
<td>I-7</td>
<td>5:46 AM</td>
<td>0.04</td>
<td>0.2033</td>
<td>28</td>
<td>65.85</td>
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<td>Effluent</td>
<td>E-1</td>
<td>5:22 AM</td>
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<td>E-2</td>
<td>5:24 AM</td>
<td>-</td>
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<td>125.03</td>
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<td>E-3</td>
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Estimating the average concentrations and removal efficiencies:

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<th>Simultaneous EMC (mg/l)</th>
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</thead>
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<td>116.76</td>
<td>116.76</td>
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<tr>
<td>Removal %</td>
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<td>31.29</td>
<td>51.63</td>
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</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.15: TSS Results - Event 16 - 10/05/2010
Appendix A: TSS Results

Event Number 17
Event Date 10/14/10
Time 2:12 AM
Event Type Rain
Event Duration (minutes) 40
Influent sampling time (min) 51
Test Type TSS
Number of antecedent dry days 8.88
Total Volume of Flow (ft³) 1901.13

Table A.17: Event 17 TSS Results

<table>
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<th>Sample Type</th>
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<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
</tr>
</thead>
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<td>0.1801</td>
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<td>177.35</td>
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<td>33.759</td>
<td>0.031</td>
<td>325.65</td>
<td>0.121</td>
<td>0.003</td>
<td>0.090</td>
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<tr>
<td>Influent</td>
<td>I-2</td>
<td>2:23 AM</td>
<td>0.04</td>
<td>0.3643</td>
<td>5</td>
<td>110.80</td>
<td>0.216</td>
<td>121.590</td>
<td>0.112</td>
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<td>2:33 AM</td>
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<td>0.4187</td>
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<td>Influent</td>
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<td>2:53 AM</td>
<td>0.04</td>
<td>0.4000</td>
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Estimating the average concentrations and removal efficiencies

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<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.16: TSS Results- Event 17- 10/14/2010

Figure A.17: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 17- 10/17/2010
Appendix A: TSS Results

Event Number 18
Event Date 10/18/10
Time 11:58 PM
Event Type Rain
Event Duration (minutes) -
Influent sampling time (min) 174
Test Type TSS
Number of antecedent dry days 4.91
Total Volume of Flow (ft$^3$) 1268.27

Table A.18: Event 18 TSS Results

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<th>Sample Type</th>
<th>Sample ID</th>
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<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta 1$</th>
<th>$\Delta 2$</th>
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</table>

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.18: TSS Results- Event 18- 10/18/2010

Figure A.19: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 18- 10/18/2010
Appendix A: TSS Results

Event Number 19
Event Date 10/25/10
Time 7:24 AM
Event Type Rain
Event Duration (minutes) 57
Influent sampling time (min) 60
Test Type TSS
Number of antecedent dry days 6.31
Total Volume of Flow (ft$^3$) 2505.45

Table A.19: Event 19 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
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<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta1$</th>
<th>$\Delta2$</th>
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<td>8:14 AM</td>
<td>0.03</td>
<td>0.1915</td>
<td>44</td>
<td>264.43</td>
<td>0.833</td>
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<td>18833.61</td>
<td>0.962</td>
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<td>0.047</td>
</tr>
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<td>Influent I-11</td>
<td>I-11</td>
<td>8:19 AM</td>
<td>0.03</td>
<td>0.1801</td>
<td>49</td>
<td>248.15</td>
<td>0.917</td>
<td>1244.458</td>
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<td>19213.32</td>
<td>0.981</td>
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<td>0.024</td>
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<tr>
<td>Influent I-12</td>
<td>I-12</td>
<td>8:24 AM</td>
<td>0.04</td>
<td>0.1801</td>
<td>54</td>
<td>244.00</td>
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<td>1300.546</td>
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<td>19586.67</td>
<td>1.000</td>
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<td>0.000</td>
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</table>

Estimating the average concentrations and removal efficiencies
<table>
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<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
<tbody>
<tr>
<td><strong>Influent</strong></td>
<td>521.55</td>
<td>434.39</td>
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</tr>
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<td><strong>Effluent</strong></td>
<td>-</td>
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<tr>
<td><strong>Removal %</strong></td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample

**Notes:**

1. Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2. Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3. Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4. Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5. $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6. $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.20: TSS Results- Event 19- 10/25/2010

Figure A.21: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 19- 10/25/2010
Appendix A: TSS Results

Event Number: 20
Event Date: 11/3/10
Time: 10:28 PM
Event Type: Rain
Event Duration (minutes): 119
Influent sampling time (min): 51
Test Type: TSS
Number of antecedent dry days: 9.63
Total Volume of Flow (ft$^3$): 2538.42

Table A.20: Event 20 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta 1$</th>
<th>$\Delta 2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>10:35 PM</td>
<td>0.01</td>
<td>0.1691</td>
<td>0</td>
<td>217.95</td>
<td>0.137</td>
<td>35.564</td>
<td>0.041</td>
<td>438.50</td>
<td>0.120</td>
<td>-0.018</td>
<td>0.078</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>10:39 PM</td>
<td>0.01</td>
<td>0.2283</td>
<td>4</td>
<td>176.60</td>
<td>0.216</td>
<td>89.602</td>
<td>0.104</td>
<td>711.61</td>
<td>0.194</td>
<td>-0.022</td>
<td>0.090</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>10:44 PM</td>
<td>0.01</td>
<td>0.2551</td>
<td>9</td>
<td>145.35</td>
<td>0.314</td>
<td>165.337</td>
<td>0.192</td>
<td>1026.69</td>
<td>0.280</td>
<td>-0.034</td>
<td>0.089</td>
</tr>
<tr>
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<td>I-4</td>
<td>10:49 PM</td>
<td>0.01</td>
<td>0.2551</td>
<td>14</td>
<td>125.75</td>
<td>0.412</td>
<td>241.072</td>
<td>0.279</td>
<td>1299.28</td>
<td>0.354</td>
<td>-0.057</td>
<td>0.075</td>
</tr>
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<td>10:54 PM</td>
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<td>0.2551</td>
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<td>112.40</td>
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<td>317.627</td>
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<td>0.421</td>
<td>-0.089</td>
<td>0.053</td>
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<td>0.608</td>
<td>388.503</td>
<td>0.450</td>
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<tr>
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<td>0.2839</td>
<td>29</td>
<td>118.15</td>
<td>0.706</td>
<td>466.809</td>
<td>0.541</td>
<td>2026.65</td>
<td>0.553</td>
<td>-0.153</td>
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<td>11:09 PM</td>
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<td>0.4379</td>
<td>34</td>
<td>137.23</td>
<td>0.804</td>
<td>578.657</td>
<td>0.670</td>
<td>2537.14</td>
<td>0.692</td>
<td>-0.112</td>
<td>0.022</td>
</tr>
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<td>I-9</td>
<td>11:14 PM</td>
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<td>0.4987</td>
<td>39</td>
<td>157.80</td>
<td>0.902</td>
<td>728.321</td>
<td>0.844</td>
<td>3205.74</td>
<td>0.875</td>
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<td>0.031</td>
</tr>
<tr>
<td>Influent</td>
<td>I-10</td>
<td>11:19 PM</td>
<td>0.03</td>
<td>0.4187</td>
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<td>129.28</td>
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<td>3665.58</td>
<td>1.000</td>
<td>0.000</td>
<td>0.000</td>
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<table>
<thead>
<tr>
<th>Sample Type</th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
<tbody>
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<td>-</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.22: TSS Results- Event 20- 11/03/2010

Figure A.23: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 20- 11/03/2010
Appendix A: TSS Results

Event Number 21
Event Date 11/16/10
Time 10:59 AM
Event Type Rain
Event Duration (minutes) 248
Influent sampling time (min) 148
Test Type TSS
Number of antecedent dry days 2.13
Total Volume of Flow (ft$^3$) 4857.50

Table A.21: Event 21 TSS Results

<table>
<thead>
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<th>Sample Type</th>
<th>Sample ID</th>
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<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
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<tr>
<td>Influent I-1</td>
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<td>12:56 PM</td>
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<td>0.2693</td>
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<td>158.23</td>
<td>0.034</td>
<td>2990.346</td>
<td>0.616</td>
<td>361.97</td>
<td>0.019</td>
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<td>-0.597</td>
</tr>
<tr>
<td>Influent I-2</td>
<td>I-2</td>
<td>1:00 PM</td>
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<td>0.1206</td>
<td>4</td>
<td>154.93</td>
<td>0.061</td>
<td>3044.366</td>
<td>0.627</td>
<td>489.00</td>
<td>0.025</td>
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<td>-0.601</td>
</tr>
<tr>
<td>Influent I-3</td>
<td>I-3</td>
<td>1:05 PM</td>
<td>0.10</td>
<td>0.1295</td>
<td>9</td>
<td>183.15</td>
<td>0.095</td>
<td>3081.118</td>
<td>0.634</td>
<td>690.55</td>
<td>0.036</td>
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<td>-0.599</td>
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<td>0.1206</td>
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<td>3117.847</td>
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<tr>
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<tr>
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<td>2:05 PM</td>
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<td>0.0963</td>
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<td>162.50</td>
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<td>3430.208</td>
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<tr>
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<td>0.11</td>
<td>0.1040</td>
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<td>152.18</td>
<td>0.507</td>
<td>3436.450</td>
<td>0.707</td>
<td>2281.97</td>
<td>0.118</td>
<td>-0.389</td>
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<tr>
<td>Influent I-10</td>
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<td>2:09 PM</td>
<td>0.11</td>
<td>0.1388</td>
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<td>0.527</td>
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<td>-0.404</td>
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<tr>
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<td>I-11</td>
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<td>I-21</td>
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<td>-</td>
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<td>-</td>
</tr>
<tr>
<td>Effluent</td>
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<td>2:50 PM</td>
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<td>114</td>
<td>640.05</td>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.24: TSS Results- Event 21- 11/16/2010

Figure A.25: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 21- 11/16/2010
Appendix A: TSS Results

Event Number 22
Event Date 11/23/10
Time 6:21 AM
Event Type Rain
Event Duration (minutes) 52
Influent sampling time (min) 108
Test Type TSS
Number of antecedent dry days 6.81
Total Volume of Flow (ft³) 3042.81

Table A.22:
Event 22 TSS Results

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Estimating the average concentrations and removal efficiencies

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<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.26: TSS Results- Event 22- 11/23/2010

Figure A.27: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 22- 11/23/2010
Appendix A: TSS Results

Event Number  23
Event Date  11/24/10
Time  6:02 PM
Event Type  Rain
Event Duration (minutes)  294
Influent sampling time (min)  274
Test Type  TSS
Number of antecedent dry days  1.49
Total Volume of Flow (ft³)  1995.24

Table A.23: Event 23 TSS Results

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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
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<th>Δ2</th>
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- Effluent E-1 6:22 PM 0.0574 0 424.85 - - - - - -
- Effluent E-2 6:25 PM - 0.0690 3 363.20 - - - - - -
- Effluent E-3 6:27 PM - 0.0690 5 349.63 - - - - - -
- Effluent E-4 6:29 PM - 0.0753 7 343.05 - - - - - -
- Effluent E-5 6:31 PM - 0.0753 9 342.55 - - - - - -
- Effluent E-6 6:33 PM - 0.0690 11 343.23 - - - - - -
- Effluent E-7 6:35 PM - 0.0690 13 345.20 - - - - - -
- Effluent E-8 6:37 PM - 0.0690 15 332.50 - - - - - -
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- Effluent E-10 6:41 PM - 0.0690 19 317.43 - - - - - -
- Effluent E-11 6:43 PM - 0.0753 21 282.40 - - - - - -
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- Effluent E-14 6:49 PM - 0.0819 27 251.70 - - - - - -
- Effluent E-15 6:52 PM - 0.0753 30 272.35 - - - - - -
- Effluent E-16 6:54 PM - 0.0819 32 300.30 - - - - - -
- Effluent E-17 6:56 PM - 0.0819 34 279.40 - - - - - -
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- Effluent E-20 7:08 PM - 0.0819 46 252.95 - - - - - -
- Effluent E-21 7:10 PM - 0.0819 48 228.25 - - - - - -
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- Effluent E-23 7:14 PM - 0.0819 52 240.85 - - - - - -
- Effluent E-24 7:19 PM - 0.0753 57 208.60 - - - - - -
Estimating the average concentrations and removal efficiencies

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</table>

* Time was set according to the first effluent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.28: TSS Results- Event 23- 11/24/2010

Figure A.29: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 23- 11/24/2010
Appendix A: TSS Results

Event Number 24
Event Date 11/30/10
Time 2:01 AM
Event Type Rain
Event Duration (minutes) 151
Influent sampling time (min) 116
Test Type TSS
Number of antecedent dry days 5.33
Total Volume of Flow (ft³) 2296.21

Table A.24:
Event 24 TSS Results

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<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
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<th>Δ2</th>
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Estimating the average concentrations and removal efficiencies

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<td>Removal %</td>
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* Time was set according to the first effluent sample

Notes:
1- Point to point EMC is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.30: TSS Results- Event 24- 11/30/2010

Figure A.31: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 24- 11/30/2010
Appendix A: TSS Results

Event Number 25
Event Date 12/12/10
Time 12:54 AM
Event Type Rain
Event Duration (minutes) 766
Influent sampling time (min) 125
Test Type TSS
Number of antecedent dry days 11.95
Total Volume of Flow (ft$^3$) 14976.66

Table A.25:

Event 25 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6- $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

![Figure A.32: TSS Results- Event 25- 12/12/2010](image)

![Figure A.33: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 25- 12/12/2010](image)
Appendix A: TSS Results

Event Number 26
Event Date 12/22/10
Time 8:18 PM
Event Type Snowmelt
Event Duration (minutes) -
Influent sampling time (min) -
Test Type TSS
Number of antecedent dry days 10.81

Table A.26:
Event 26 TSS Results

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<th>Flow (cfs)</th>
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<td>88.45</td>
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<td>-</td>
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<tr>
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<td>11:27 AM</td>
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<td>-</td>
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<td>130.10</td>
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<td>11:29 AM</td>
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<td>-</td>
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<td>-</td>
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Estimating the average concentrations and removal efficiencies

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<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<tr>
<td>Removal %</td>
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</table>

* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.
** Effluent samples were collected on December 25th, 2010.
Appendix A: TSS Results

Figure A.34: TSS Results (Influent)- Event 26- 12/22/2010

Figure A.35: TSS Results (Effluent)- Event 26- 12/25/2010
## Appendix A: TSS Results

**Event Number**: 27  
**Event Date**: 12/30/2010  
**Time**: 4:53 AM  
**Event Type**: Rain  
**Event Duration (minutes)**: 360  
**Influent sampling time (min)**: -  
**Test Type**: TSS  
**Number of antecedent dry days**: 7.36

### Table A.27: Event 27 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
<tbody>
<tr>
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<td>0</td>
<td>882.75</td>
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<tr>
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<td>6:12 AM</td>
<td>-</td>
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<td>760.20</td>
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<tr>
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<td>E-3</td>
<td>6:14 AM</td>
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<td>-</td>
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<td>667.50</td>
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<td>6:16 AM</td>
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<td>-</td>
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<td>634.15</td>
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<tr>
<td>Effluent</td>
<td>E-5</td>
<td>6:18 AM</td>
<td>-</td>
<td>-</td>
<td>10</td>
<td>396.20</td>
</tr>
<tr>
<td>Effluent</td>
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<td>6:20 AM</td>
<td>-</td>
<td>-</td>
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<td>352.45</td>
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<td>6:22 AM</td>
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<td>-</td>
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<td>342.90</td>
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<td>E-8</td>
<td>6:24 AM</td>
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<td>-</td>
<td>16</td>
<td>327.40</td>
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<tr>
<td>Effluent</td>
<td>E-9</td>
<td>6:26 AM</td>
<td>-</td>
<td>-</td>
<td>18</td>
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<td>E-10</td>
<td>6:28 AM</td>
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<td>-</td>
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<td>6:32 AM</td>
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<td>-</td>
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<td>-</td>
<td>-</td>
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<td>429.40</td>
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<td>244.80</td>
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<tr>
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<td>6:44 AM</td>
<td>-</td>
<td>-</td>
<td>36</td>
<td>215.50</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-19</td>
<td>6:46 AM</td>
<td>-</td>
<td>-</td>
<td>38</td>
<td>239.85</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-20</td>
<td>6:48 AM</td>
<td>-</td>
<td>-</td>
<td>40</td>
<td>284.85</td>
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<td>6:50 AM</td>
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<td>285.95</td>
</tr>
<tr>
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<td>E-22</td>
<td>6:52 AM</td>
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Estimating the average concentrations and removal efficiencies

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Influent</td>
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<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Effluent</td>
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<tr>
<td>Removal %</td>
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* Time was set according to the first effluent sample

Figure A.36: TSS Results- Event 27- 12/30/2010
### Appendix A: TSS Results

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</tr>
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<td>Time</td>
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</tr>
<tr>
<td>Event Type</td>
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<td>Event Duration (minutes)</td>
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</tr>
<tr>
<td>Influent sampling time (min)</td>
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<tr>
<td>Test Type</td>
<td>TSS</td>
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<tr>
<td>Number of antecedent dry days</td>
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#### Table A.28:  
**Event 28 TSS Results**

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
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<td>95.33</td>
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<td>1:12 PM</td>
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<td>-</td>
<td>29</td>
<td>83.55</td>
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<td>Effluent</td>
<td>E-16</td>
<td>1:14 PM</td>
<td>-</td>
<td>-</td>
<td>31</td>
<td>95.55</td>
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<td>Effluent</td>
<td>E-17</td>
<td>1:16 PM</td>
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<td>-</td>
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<td>99.65</td>
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<td>81.65</td>
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<tr>
<td>Effluent</td>
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<td>1:24 PM</td>
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<td>41</td>
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</table>
Estimating the average concentrations and removal efficiencies

<table>
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<th>EMC (mg/l)</th>
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<th>Simultaneous EMC (mg/l)</th>
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<tr>
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</tr>
<tr>
<td>Removal %</td>
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<td>76.95</td>
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</tbody>
</table>

* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.

** Effluent samples were collected on January 7th, 2011.
Appendix A: TSS Results

Figure A.37: TSS Results (Influent)- Event 28- 01/06/2011

Figure A.38: TSS Results (Effluent)- Event 28- 01/07/2011
### Appendix A: TSS Results

Event Number: 29
Event Date: 1/1/11
Time: 11:38 PM
Event Type: Rain**
Event Duration (minutes): 147
Influent sampling time (min): 119
Test Type: TSS
Number of antecedent dry days: 4.22
Total Volume of Flow (ft³): 1582.37

#### Table A.29: Event 29 TSS Results

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<th>Sample ID</th>
<th>Time</th>
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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
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</thead>
<tbody>
<tr>
<td>Influent I-1</td>
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<td>0.1586</td>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first influent sample
** This event was preceded by a light snow event (Jan 13th, 2011) which was unsampled. Therefore, the high TSS concentrations observed in event 29 might be due to the mix between the snow residuals and the storm water runoff

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- \( \Delta_1 \) is the difference between the normalized cumulative mass and the normalized cumulative time.
6- \( \Delta_2 \) is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

![TSS Results- Event 29- 01/07/2011](image1)

Figure A.39: TSS Results- Event 29- 01/07/2011

![Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 29- 01/17/2011](image2)

Figure A.40: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 29- 01/17/2011
Appendix A: TSS Results

Event Number 30
Event Date 1/26/11
Time 9:07 AM
Event Type Rain and Snow
Event Duration (minutes) 508
Influent sampling time (min) 10
Test Type TSS
Number of antecedent dry days 5.03

Table A.30:
Event 30 TSS Results

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<th>Relative time (min)*</th>
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<td>5</td>
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<tr>
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<td>5:53 PM</td>
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<td>65.95</td>
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<td>E-17</td>
<td>6:19 PM</td>
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<td>0.0574</td>
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</tr>
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Estimating the average concentrations and removal efficiencies

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<tbody>
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</tr>
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<td>Removal %</td>
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</table>

* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.
** Effluent samples were collected on January 23rd, 2011.
Appendix A: TSS Results

Figure A.41: TSS Results- Event 30 (Influent)- 01/26/2011

Figure A.42: TSS Results- Event 30 (Effluent)- 01/23/2011
Appendix A: TSS Results

Event Number 31-1
Event Date 2/1/11
Time 6:08 AM
Event Type Rain
Event Duration (minutes) 301
Influent sampling time (min) 18
Test Type TSS
Number of antecedent dry days 4.01

Table A.31:
Event 31-1 TSS Results

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<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
<tbody>
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<td>6:37 AM</td>
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<td>0.0963</td>
<td>12</td>
<td>1584.38</td>
</tr>
<tr>
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<td>I-2</td>
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<td>0.1121</td>
<td>261</td>
<td>1020.65</td>
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<tr>
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<td>10:47 AM</td>
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<td>0.1388</td>
<td>262</td>
<td>989.40</td>
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<tr>
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<td>I-4</td>
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<td>0.1586</td>
<td>266</td>
<td>1039.98</td>
</tr>
<tr>
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<td>I-5</td>
<td>10:56 AM</td>
<td>0.12</td>
<td>0.1388</td>
<td>271</td>
<td>798.23</td>
</tr>
<tr>
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<td>0.1121</td>
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<td>1358.93</td>
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<td>1137.30</td>
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<td>1018.63</td>
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<tr>
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<td>0.0574</td>
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<td>731.38</td>
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<td>E-15</td>
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Estimating the average concentrations and removal efficiencies

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<tr>
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* Time was set according to the first effluent sample

Figure A.43: TSS Results- Event 31-1- 02/01/2011
Table A.32:  
**Event 31-2 TSS Results**

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
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<th>Δ2</th>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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|          |         |            |                    |                         |
|          |         |            |                    |                         |
|          |         |            |                    |                         |
|          |         |            |                    |                         |

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6- $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.44: TSS Results- Event 31-2- 02/01/2011

Figure A.45: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 31-2- 02/01/2011
Appendix A: TSS Results

Event Number: 32  
Event Date: 02/07/11  
Time: 2:55 PM  
Event Type: Rain  
Event Duration (minutes): 340  
Influent sampling time (min): 93  
Test Type: TSS  
Number of antecedent dry days: 1.92  
Total Volume of Flow \( \text{(ft}^3 \text{)} \): 6049.37

Table A.33:  
**Event 32 TSS Results**

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<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative TSS</th>
<th>Cumulative Flow Volume ( \text{(ft}^3 \text{)} )</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
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<td>0.1040</td>
<td>0</td>
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Effluent samples were collected on February 8.

Time was set for influent and effluent separately according to the first influent and effluent samples respectively.

Estimating the average concentrations and removal efficiencies

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</table>

** Effluent samples were collected on February 8th, 2011.

* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.

** Effluent samples were collected on February 8th, 2011.

### Estimating the average concentrations and removal efficiencies

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<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Effluent</td>
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<tr>
<td>Removal %</td>
<td></td>
<td>88.56</td>
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</table>
Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- \( \Delta_1 \) is the difference between the normalized cumulative mass and the normalized cumulative time.
6- \( \Delta_2 \) is the difference between the normalized cumulative mass and the normalized flow volume.

Figure A.46: TSS Results (Influent)- Event 32- 02/08/2011
Appendix A: TSS Results

Figure A.47: TSS Results (Effluent)- Event 32- 02/08/2011

Figure A.48: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 32- 02/08/2011
Appendix A: TSS Results

Event Number 33
Event Date 2/21/11
Time 9:33 AM
Event Type Rain
Event Duration (minutes) 809
Influent sampling time (min) 284
Test Type TSS
Number of antecedent dry days 12.25
Total Volume of Flow (ft$^3$) 4002.98

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<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
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<td>89.15</td>
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</table>

* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.
Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- $\Delta_1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6- $\Delta_2$ is the difference between the normalized cumulative mass and the normalized flow volume.

Figure A.49: TSS Results (Influent)- Event 33- 02/21/2011
Appendix A: TSS Results

Figure A.50: TSS Results (Effluent)- Event 33- 02/21/2011

Figure A.51: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 32- 02/21/2011
Appendix A: TSS Results

Event Number 34
Event Date 2/24/11
Time 7:24 PM
Event Type Rain
Event Duration (minutes) 613
Influent sampling time (min) 104
Test Type TSS
Number of antecedent dry days 0.14
Total Volume of Flow (ft$^3$) 4006.44

Table A.35: Event 34 TSS Results

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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
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<th>Δ2</th>
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Estimating the average concentrations and removal efficiencies

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Removal %</td>
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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- \( \Delta 1 \) is the difference between the normalized cumulative mass and the normalized cumulative time.
6- \( \Delta 2 \) is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

![TSS Results - Event 34 - 02/24/2011](image1)

Figure A.52: TSS Results - Event 34 - 02/24/2011

![Normalized Mass Vs Normalized Time and Normalized Flow Volume - Event 34 - 02/24/2011](image2)

Figure A.53: Normalized Mass Vs Normalized Time and Normalized Flow Volume - Event 34 - 02/24/2011
Appendix A: TSS Results

Event Number: 35
Event Date: 3/5/11
Time: 10:53 AM
Event Type: Rain
Event Duration (minutes): 1380
Influent sampling time (min): -
Test Type: TSS
Number of antecedent dry days: 4.71

Table A.36: 
Event 35 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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</thead>
<tbody>
<tr>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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* Time was set according to the first effluent sample

Figure A.54: TSS Results- Event 35- 03/05/2011
Appendix A: TSS Results

| Event Number | 36 |
| Event Date   | 3/10/11 |
| Time         | 9:00 AM |
| Event Type   | Rain |
| Event Duration (minutes) | 882 |
| Influent sampling time (min) | - |
| Test Type    | TSS |
| Number of antecedent dry days | 0.21 |

Table A.37: Event 36 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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<td>0.1040</td>
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Estimating the average concentrations and removal efficiencies

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* Time was set for influent and effluent separately according to the first influent and effluent samples respectively.
** Effluent samples were collected on March 15th, 2011.
Appendix A: TSS Results

Figure A.55: TSS Results (Influent)- Event 36- 03/10/2011

Figure A.56: TSS Results (Effluent)- Event 36- 03/15/2011
Appendix A: TSS Results

Event Number 37-1
Event Date 3/18/11
Time 6:10 PM
Event Type Rain
Event Duration (minutes) 104
Influent sampling time (min) 89
Test Type TSS
Number of antecedent dry days 2.81
Total Volume of Flow (ft$^3$) 610.36

Table A.38: Event 37-1 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
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<th>Δ2</th>
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<td>0.1388</td>
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<td>0.1586</td>
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Estimating the average concentrations and removal efficiencies

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<tr>
<td>Removal%</td>
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<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample

Notes:

1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)

2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.

3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.

4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.

5- $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.

6- $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.57: TSS Results- Event 37-1- 03/18/2011

Figure A.58: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 37-1- 03/18/2011
Appendix A: TSS Results

Event Number             37-2
Event Date               3/21/11
Time                     3:38 AM
Event Type               Rain
Event Duration (minutes) 417
Influent sampling time (min) -
Test Type                TSS
Number of antecedent dry days 2.39

Table A.39:
*Time was set according to the first influent sample

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<th>Sample ID</th>
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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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<td>1900.40</td>
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Estimating the average concentrations and removal efficiencies

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.59: TSS Results- Event 37-2- 03/21/2011
Appendix A: TSS Results

Event Number: 38-1
Event Date: 3/27/11
Time: 1:14 AM
Event Type: Light Snow
Event Duration (minutes): 93
Influent sampling time (min): 86
Test Type: TSS
Number of antecedent dry days: 2.76
Total Volume of Flow (ft³): 1362.91

Table A.40: Event 38-1 TSS Results

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<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
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<th>Δ2</th>
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<td>0.081</td>
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Estimating the average concentrations and removal efficiencies

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Removal %</td>
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* Time was set according to the first effluent sample
Appendix A: TSS Results

Figure A.60: TSS Results- Event 38-1- 03/27/2011

Figure A.61: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event 38-1- 03/27/2011
Appendix A: TSS Results

Event Number 38-2  
Event Date 3/30/11  
Time 1:23 PM  
Event Type Rain  
Event Duration (minutes) 213  
Influent sampling time (min) 27  
Test Type TSS  
Number of antecedent dry days 3.51

Table A.41:  
Event 38-2 TSS Results

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<th>Sample ID</th>
<th>Time</th>
<th>Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
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Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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<td>Effluent</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td></td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.62: TSS Results- Event 38-2- 03/30/2011

TSS Results - Event 38-2- 03/30/2011

TSS Concentration (mg/l)

Time (min)
Appendix A: TSS Results

Event Number 39-1
Event Date 4/8/11
Time 8:54 AM
Event Type Rain
Event Duration (minutes) 482
Influent sampling time (min) 38
Test Type TSS
Number of antecedent dry days 3.25

Table A.42: Event 39-1 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>9:07 AM</td>
<td>0.04</td>
<td>0.1586</td>
<td>0</td>
<td>261.90</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>9:14 AM</td>
<td>0.05</td>
<td>0.0963</td>
<td>7</td>
<td>267.45</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>9:22 AM</td>
<td>0.07</td>
<td>0.1485</td>
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<td>191.10</td>
</tr>
<tr>
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<td>I-4</td>
<td>9:27 AM</td>
<td>0.08</td>
<td>0.1915</td>
<td>20</td>
<td>220.15</td>
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<tr>
<td>Influent</td>
<td>I-5</td>
<td>9:32 AM</td>
<td>0.10</td>
<td>0.2033</td>
<td>25</td>
<td>206.75</td>
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<td>30</td>
<td>157.75</td>
</tr>
<tr>
<td>Influent</td>
<td>I-7</td>
<td>9:42 AM</td>
<td>0.11</td>
<td>0.1040</td>
<td>35</td>
<td>134.80</td>
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</table>

Estimating the average concentrations and removal efficiencies

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<tr>
<th>Sample Type</th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
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<td>205.87</td>
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<td>Effluent</td>
<td>-</td>
<td>-</td>
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<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.63: TSS Results- Event 39-1- 04/08/2011
Appendix A: TSS Results

Event Number 39-2
Event Date 4/11/11
Time 6:21 PM
Event Type Rain
Event Duration (minutes) 388
Influent sampling time (min) 188
Test Type TSS
Number of antecedent dry days 3.27
Total Volume of Flow (ft$^3$) 1904.76

Table A.43:  Event 39-2 TSS Results

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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>$\Delta 1$</th>
<th>$\Delta 2$</th>
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<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>8:59 PM</td>
<td>0.11</td>
<td>0.1121</td>
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<td>119.45</td>
<td>0.027</td>
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<td>0.348</td>
<td>113.80</td>
<td>0.069</td>
<td>0.043</td>
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<tr>
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<td>I-2</td>
<td>9:02 PM</td>
<td>0.12</td>
<td>0.1206</td>
<td>3</td>
<td>65.30</td>
<td>0.043</td>
<td>563.403</td>
<td>0.362</td>
<td>153.96</td>
<td>0.094</td>
<td>0.051</td>
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</tr>
<tr>
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<td>0.12</td>
<td>0.1206</td>
<td>8</td>
<td>44.20</td>
<td>0.069</td>
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<td>0.053</td>
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<td>0.1040</td>
<td>123</td>
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<td>0.1206</td>
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<td>11:47 PM</td>
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<td>-0.011</td>
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</table>
Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Effluent</td>
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<td>-</td>
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<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample

Notes:

1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples).
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6- $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.64: TSS Results- Event 39-2- 04/11/2011

Figure A.65: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event 39-2- 04/11/2011
Appendix A: TSS Results

Event Number          R1
Event Date            5/8/11
Time                  12:12 AM
Event Type            Rain
Event Duration (minutes) 99
Influent sampling time (min) 55
Test Type             TSS
Number of antecedent dry days 4.18
Total Volume of Flow (ft³) 274.36

Table A.44:

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>1:16 AM</td>
<td>0.02</td>
<td>0.0266</td>
<td>86</td>
<td>72.00</td>
<td>0.091</td>
<td>106.878</td>
<td>0.461</td>
<td>16.30</td>
<td>0.141</td>
<td>0.050</td>
<td>-0.320</td>
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<tr>
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<td>44.85</td>
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<td>45.65</td>
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<td>0.311</td>
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<td>0.552</td>
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<td>27.88</td>
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<tr>
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<tr>
<td>12:14 AM</td>
<td>E-11</td>
<td>0.0340</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th>Influent</th>
<th>Effluent</th>
</tr>
</thead>
<tbody>
<tr>
<td>32.02</td>
<td>-</td>
</tr>
<tr>
<td>-</td>
<td>43.65</td>
</tr>
</tbody>
</table>

| Removal % | -34.53 |

* Time was set according to the first effluent sample.
** Effluent first sample was at 11:50 PM on May 7th, 2011.

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- \( \Delta 1 \) is the difference between the normalized cumulative mass and the normalized cumulative time.
6- \( \Delta 2 \) is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.66: TSS Results- Event R1- 05/08/2011

Figure A.67: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event R1- 05/08/2011
Appendix A: TSS Results

Event Number          R2-1  
Event Date            5/14/11  
Time                  12:27 AM  
Event Type            Rain  
Event Duration (minutes) 8  
Influent sampling time (min)  24  
Test Type             TSS  
Number of antecedent dry days  1.32

Table A.45:
Event R2-1 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>12:30 AM</td>
<td>0.08</td>
<td>0.5646</td>
<td>0</td>
<td>1414.95</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>12:35 AM</td>
<td>0.10</td>
<td>0.6114</td>
<td>5</td>
<td>759.48</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>12:39 AM</td>
<td>0.10</td>
<td>0.2033</td>
<td>9</td>
<td>160.30</td>
</tr>
<tr>
<td>Influent</td>
<td>I-4</td>
<td>12:44 AM</td>
<td>0.10</td>
<td>0.0574</td>
<td>14</td>
<td>56.47</td>
</tr>
<tr>
<td>Influent</td>
<td>I-5</td>
<td>12:49 AM</td>
<td>0.10</td>
<td>0.0302</td>
<td>19</td>
<td>30.98</td>
</tr>
<tr>
<td>Influent</td>
<td>I-6</td>
<td>12:51 AM</td>
<td>0.10</td>
<td>0.0340</td>
<td>21</td>
<td>27.40</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>12:30 AM</td>
<td>-</td>
<td>0.0234</td>
<td>0</td>
<td>474.00</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-2</td>
<td>12:32 AM</td>
<td>-</td>
<td>0.0266</td>
<td>2</td>
<td>435.00</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-3</td>
<td>12:37 AM</td>
<td>-</td>
<td>0.0266</td>
<td>7</td>
<td>138.05</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-4</td>
<td>12:42 AM</td>
<td>-</td>
<td>0.0302</td>
<td>12</td>
<td>136.90</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-5</td>
<td>12:47 AM</td>
<td>-</td>
<td>0.0266</td>
<td>17</td>
<td>75.87</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-6</td>
<td>12:52 AM</td>
<td>-</td>
<td>0.0234</td>
<td>22</td>
<td>49.71</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-7</td>
<td>12:54 AM</td>
<td>-</td>
<td>0.0380</td>
<td>24</td>
<td>54.96</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-8</td>
<td>12:56 AM</td>
<td>-</td>
<td>0.0340</td>
<td>26</td>
<td>37.90</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-9</td>
<td>12:58 AM</td>
<td>-</td>
<td>0.0340</td>
<td>28</td>
<td>49.76</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-10</td>
<td>1:00 AM</td>
<td>-</td>
<td>0.0340</td>
<td>30</td>
<td>35.18</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-11</td>
<td>1:02 AM</td>
<td>-</td>
<td>0.0340</td>
<td>32</td>
<td>43.45</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-12</td>
<td>1:04 AM</td>
<td>-</td>
<td>0.0340</td>
<td>34</td>
<td>27.69</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-13</td>
<td>1:06 AM</td>
<td>-</td>
<td>0.0340</td>
<td>36</td>
<td>37.00</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-14</td>
<td>1:08 AM</td>
<td>-</td>
<td>0.0340</td>
<td>38</td>
<td>32.80</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-15</td>
<td>1:12 AM</td>
<td>-</td>
<td>0.0302</td>
<td>42</td>
<td>20.91</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-16</td>
<td>1:14 AM</td>
<td>-</td>
<td>0.0266</td>
<td>44</td>
<td>21.94</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-17</td>
<td>1:16 AM</td>
<td>-</td>
<td>0.0302</td>
<td>46</td>
<td>19.78</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-18</td>
<td>1:18 AM</td>
<td>-</td>
<td>0.0302</td>
<td>48</td>
<td>25.64</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-19</td>
<td>1:21 AM</td>
<td>-</td>
<td>0.0302</td>
<td>51</td>
<td>21.71</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-20</td>
<td>1:23 AM</td>
<td>-</td>
<td>0.0266</td>
<td>53</td>
<td>22.29</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-21</td>
<td>1:25 AM</td>
<td>-</td>
<td>0.0266</td>
<td>55</td>
<td>20.55</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-22</td>
<td>1:27 AM</td>
<td>-</td>
<td>0.0266</td>
<td>57</td>
<td>14.67</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-23</td>
<td>1:30 AM</td>
<td>-</td>
<td>0.0302</td>
<td>60</td>
<td>14.86</td>
</tr>
</tbody>
</table>

Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>866.81</td>
<td>408.26</td>
<td>408.26</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>78.72</td>
<td>111.93</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>80.72</td>
<td>72.58</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample

Figure A.68: TSS Results- Event R2-1- 05/14/2011
Appendix A: TSS Results

Event Number  R2-2
Event Date    5/14/11
Time          5:25 AM
Event Type    Rain
Event Duration (minutes)  8
Influent sampling time (min)  29
Test Type     TSS
Number of antecedent dry days  0.21

Table A.46:  
Event R2-2 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I1</td>
<td>5:29 AM</td>
<td>0.04</td>
<td>0.0889</td>
<td>0</td>
<td>1270.00</td>
</tr>
<tr>
<td>Influent</td>
<td>I2</td>
<td>5:30 AM</td>
<td>0.04</td>
<td>0.1388</td>
<td>1</td>
<td>580.55</td>
</tr>
<tr>
<td>Influent</td>
<td>I3</td>
<td>5:34 AM</td>
<td>0.06</td>
<td>0.3819</td>
<td>5</td>
<td>243.80</td>
</tr>
<tr>
<td>Influent</td>
<td>I4</td>
<td>5:39 AM</td>
<td>0.06</td>
<td>0.1915</td>
<td>10</td>
<td>87.25</td>
</tr>
<tr>
<td>Influent</td>
<td>I5</td>
<td>5:44 AM</td>
<td>0.06</td>
<td>0.0690</td>
<td>15</td>
<td>51.25</td>
</tr>
<tr>
<td>Influent</td>
<td>I6</td>
<td>5:49 AM</td>
<td>0.06</td>
<td>0.0380</td>
<td>20</td>
<td>33.45</td>
</tr>
<tr>
<td>Influent</td>
<td>I7</td>
<td>5:55 AM</td>
<td>0.06</td>
<td>0.0340</td>
<td>26</td>
<td>26.05</td>
</tr>
</tbody>
</table>

Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>328.02</td>
<td>327.48</td>
<td>-</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.69: TSS Results- Event R2-2- 05/14/2011
Appendix A: TSS Results

Event Number: R2-3
Event Date: 5/14/11
Time: 4:02 PM
Event Type: Rain
Event Duration (minutes): 13
Influent sampling time (min): 26
Test Type: TSS
Number of antecedent dry days: 0.44

Table A.47:
Event R2-3 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I1</td>
<td>4:06 PM</td>
<td>0.06</td>
<td>0.2839</td>
<td>0</td>
<td>1673.25</td>
</tr>
<tr>
<td>Influent</td>
<td>I2</td>
<td>4:09 PM</td>
<td>0.13</td>
<td>1.2910</td>
<td>3</td>
<td>800.20</td>
</tr>
<tr>
<td>Influent</td>
<td>I3</td>
<td>4:14 PM</td>
<td>0.18</td>
<td>0.9748</td>
<td>8</td>
<td>323.80</td>
</tr>
<tr>
<td>Influent</td>
<td>I4</td>
<td>4:19 PM</td>
<td>0.18</td>
<td>0.2990</td>
<td>13</td>
<td>91.45</td>
</tr>
<tr>
<td>Influent</td>
<td>I5</td>
<td>4:24 PM</td>
<td>0.18</td>
<td>0.1121</td>
<td>18</td>
<td>44.50</td>
</tr>
<tr>
<td>Influent</td>
<td>I6</td>
<td>4:29 PM</td>
<td>0.18</td>
<td>0.0574</td>
<td>23</td>
<td>30.10</td>
</tr>
</tbody>
</table>

Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>440.72</td>
<td>493.88</td>
<td>-</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.70: TSS Results- Event R2-3- 05/14/2011
Appendix A: TSS Results

Event Number: R2-4
Event Date: 5/14/11
Time: 7:49 PM
Event Type: Rain
Event Duration (minutes): 19
Influent sampling time (min): 21
Test Type: TSS
Number of antecedent dry days: 0.16

Table A.48:
Event R2-4 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I1</td>
<td>8:01 PM</td>
<td>0.02</td>
<td>0.0380</td>
<td>0</td>
<td>92.80</td>
</tr>
<tr>
<td>Influent</td>
<td>I2</td>
<td>8:04 PM</td>
<td>0.02</td>
<td>0.0380</td>
<td>3</td>
<td>61.65</td>
</tr>
<tr>
<td>Influent</td>
<td>I3</td>
<td>8:08 PM</td>
<td>0.03</td>
<td>0.0424</td>
<td>7</td>
<td>55.45</td>
</tr>
<tr>
<td>Influent</td>
<td>I4</td>
<td>8:14 PM</td>
<td>0.03</td>
<td>0.0471</td>
<td>13</td>
<td>60.15</td>
</tr>
<tr>
<td>Influent</td>
<td>I5</td>
<td>8:19 PM</td>
<td>0.03</td>
<td>0.0380</td>
<td>18</td>
<td>53.45</td>
</tr>
</tbody>
</table>

Estimating the average concentrations and removal efficiencies

<table>
<thead>
<tr>
<th></th>
<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>64.30</td>
<td>64.70</td>
<td>-</td>
</tr>
<tr>
<td>Effluent</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Removal %</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.71: TSS Results- Event R2-4- 05/14/2011
Appendix A: TSS Results

Event Number R3
Event Date 5/19/11
Time 8:47 PM
Event Type Rain
Event Duration (minutes) 228
Influent sampling time (min) 196
Test Type TSS
Number of antecedent dry days 1.50
Total Volume of Flow (ft$^3$) 731.74

Table A.49:
Event R3 TSS Results

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>8:55 PM</td>
<td>0.01</td>
<td>0.0380</td>
<td>1</td>
<td>153.50</td>
<td>0.026</td>
<td>23.964</td>
<td>0.045</td>
<td>49.60</td>
<td>0.044</td>
<td>0.018</td>
<td>-0.001</td>
</tr>
<tr>
<td>Influent</td>
<td>I-2</td>
<td>8:56 PM</td>
<td>0.01</td>
<td>0.0340</td>
<td>2</td>
<td>142.40</td>
<td>0.031</td>
<td>26.001</td>
<td>0.049</td>
<td>57.82</td>
<td>0.051</td>
<td>0.021</td>
<td>0.002</td>
</tr>
<tr>
<td>Influent</td>
<td>I-3</td>
<td>8:58 PM</td>
<td>0.01</td>
<td>0.0471</td>
<td>4</td>
<td>145.55</td>
<td>0.041</td>
<td>31.652</td>
<td>0.060</td>
<td>81.11</td>
<td>0.072</td>
<td>0.031</td>
<td>0.012</td>
</tr>
<tr>
<td>Influent</td>
<td>I-4</td>
<td>9:01 PM</td>
<td>0.01</td>
<td>0.0574</td>
<td>7</td>
<td>121.23</td>
<td>0.056</td>
<td>42.676</td>
<td>0.081</td>
<td>116.56</td>
<td>0.103</td>
<td>0.047</td>
<td>0.022</td>
</tr>
<tr>
<td>Influent</td>
<td>I-5</td>
<td>9:06 PM</td>
<td>0.01</td>
<td>0.0630</td>
<td>12</td>
<td>109.63</td>
<td>0.082</td>
<td>62.651</td>
<td>0.118</td>
<td>175.23</td>
<td>0.155</td>
<td>0.073</td>
<td>0.037</td>
</tr>
<tr>
<td>Influent</td>
<td>I-6</td>
<td>9:11 PM</td>
<td>0.02</td>
<td>0.0521</td>
<td>17</td>
<td>102.13</td>
<td>0.107</td>
<td>80.559</td>
<td>0.152</td>
<td>220.41</td>
<td>0.195</td>
<td>0.088</td>
<td>0.043</td>
</tr>
<tr>
<td>Influent</td>
<td>I-7</td>
<td>9:16 PM</td>
<td>0.02</td>
<td>0.0753</td>
<td>22</td>
<td>102.55</td>
<td>0.133</td>
<td>101.290</td>
<td>0.191</td>
<td>285.98</td>
<td>0.253</td>
<td>0.120</td>
<td>0.062</td>
</tr>
<tr>
<td>Influent</td>
<td>I-8</td>
<td>9:21 PM</td>
<td>0.03</td>
<td>0.1206</td>
<td>27</td>
<td>114.10</td>
<td>0.158</td>
<td>131.707</td>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first effluent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.72: TSS Results- Event R3- 05/19/2011

Figure A.73: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event R3- 05/11/2011
### Appendix A: TSS Results

**Event Number**
- R4

**Event Date**
- 6/4/2011

**Time**
- 11:31 PM

**Event Type**
- Rain

**Event Duration (minutes)**
- 275

**Influent sampling time (min)**
- 115

**Test Type**
- TSS

**Number of antecedent dry days**
- 8.61

**Total Volume of Flow (ft³)**
- 4850.32

### Table A.50: Event R4 TSS Results

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<th>Relative time (min)*</th>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.74: TSS Results- Event R4- 06/04/2011

Figure A.75: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event R4- 06/04/2011
Appendix A: TSS Results

Event Number: R5-1
Event Date: 6/15/2011
Time: 10:08 PM
Event Type: Rain
Event Duration (minutes): 51
Influent sampling time (min): 63
Test Type: TSS
Number of antecedent dry days: 4.59
Total Volume of Flow (ft³): 603.50

Table A.51: Event R5-1 TSS Results

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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft³)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
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Estimating the average concentrations and removal efficiencies

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* Time was set according to the first influent sample
Appendix A: TSS Results

![TSS Results- Event R5-1- 06/05/2011](image1)

Figure A.76: TSS Results- Event R5-1- 06/05/2011

![Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event R5-1- 06/05/2011](image2)

Figure A.77: Normalized Mass Vs Normalized Time and Normalized Flow Volume-Event R5-1- 06/05/2011
Appendix A: TSS Results

Event Number  
R5-2

Event Date  
6/16/2011

Time  
9:29 AM

Event Type  
Rain

Event Duration (minutes)  
33

Influent sampling time (min)  
46

Test Type  
TSS

Number of antecedent dry days  
0.47

Total Volume of Flow (ft$^3$)  
187.17

Table A.52:

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<th>Time</th>
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<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
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Estimating the average concentrations and removal efficiencies

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<td>Removal %</td>
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* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.78: TSS Results- Event R5-2- 06/16/2011

Figure A.79: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event R5-2- 06/16/2011
Appendix A: TSS Results

Event Number: R6-1
Event Date: 6/23/2011
Time: 2:39 PM
Event Type: Rain
Event Duration (minutes): 4
Influent sampling time (min): 24
Test Type: TSS
Number of antecedent dry days: 1.78

Table A.53: Event R6-1 TSS Results

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<td>17</td>
<td>149.70</td>
</tr>
<tr>
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<td>I6</td>
<td>3:02 PM</td>
<td>0.09</td>
<td>0.0380</td>
<td>20</td>
<td>140.10</td>
</tr>
<tr>
<td>Influent</td>
<td>I7</td>
<td>3:04 PM</td>
<td>0.09</td>
<td>0.0340</td>
<td>22</td>
<td>207.05</td>
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</table>

Estimating the average concentrations and removal efficiencies

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<th>Simultaneous EMC (mg/l)</th>
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<td>Effluent</td>
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<td>-</td>
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<tr>
<td>Removal %</td>
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</tr>
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</table>

* Time was set according to the first influent sample
Appendix A: TSS Results

Figure A.80: TSS Results- Event R6-1- 06/23/2011
Appendix A: TSS Results

Event Number            R6-2
Event Date              6/23/2011
Time                    7:15 PM
Event Type              Rain
Event Duration (minutes) 42
Influent sampling time (min) 66
Test Type               TSS
Number of antecedent dry days 0.07
Total Volume of Flow (ft$^3$) 903.11

Table A.54: Event R6-2 TSS Results

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<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
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<td>0.02</td>
<td>0.0889</td>
<td>0</td>
<td>442.50</td>
<td>0.076</td>
<td>10.261</td>
<td>0.012</td>
<td>334.27</td>
<td>0.103</td>
<td>0.07</td>
<td>0.091</td>
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<td>7:24 PM</td>
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<td>149.95</td>
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<td>0.228</td>
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<td>0.1040</td>
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<td>53.45</td>
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<td>0.270</td>
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<td>0.1040</td>
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<td>0.394</td>
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<td>0.284</td>
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<td>0.0889</td>
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<td>0.470</td>
<td>247.741</td>
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<td>0.294</td>
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<td>7:49 PM</td>
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<td>0.0753</td>
<td>31</td>
<td>31.70</td>
<td>0.545</td>
<td>271.939</td>
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<td>0.300</td>
<td>-0.246</td>
<td>-0.007</td>
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<tr>
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<td>7:54 PM</td>
<td>0.16</td>
<td>1.0403</td>
<td>36</td>
<td>216.00</td>
<td>0.621</td>
<td>473.070</td>
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<td>2883.27</td>
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<tr>
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<td>0.697</td>
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<td>3192.58</td>
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<tr>
<td></td>
<td>Influent II4 8:19 PM 0.17 0.034 61 9.15 1.000 884.809 1.000 3248.10 1.000 0.000 0.000</td>
<td>Effluent E1 7:54 PM - 0.034 36 70.55 - - - - - - - -</td>
<td>Effluent E2 8:46 PM - 0.034 88 46.57 - - - - - - - -</td>
<td>Effluent E3 8:56 PM - 0.034 98 27.89 - - - - - - - -</td>
<td>Effluent E4 9:20 PM - 0.034 122 20.71 - - - - - - - -</td>
<td>Effluent E5 9:49 PM - 0.034 151 16.15 - - - - - - - -</td>
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Estimating the average concentrations and removal efficiencies

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<th>EMC (mg/l)</th>
<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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</thead>
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<td>Influent</td>
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<td>Removal %</td>
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<td>65.73</td>
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</table>

* Time was set according to the first influent sample

Notes:

1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- Δ1 is the difference between the normalized cumulative mass and the normalized cumulative time.
6- Δ2 is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.81: TSS Results- Event R6- 06/23/2011

Figure A.82: Normalized Mass Vs Normalized Time and Normalized Flow Volume- Event R6- 06/23/2011
Appendix A: TSS Results

Event Number: R7
Event Date: 7/18/2011
Time: 7:17 PM
Event Type: Rain
Event Duration (minutes): 38
Influent sampling time (min): 40
Test Type: TSS
Number of antecedent dry days: 6.76
Total Volume of Flow (ft$^3$): 1461.82

Table A.55: Event R7 TSS Results

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<th>Sample ID</th>
<th>Time</th>
<th>Cumulative Precipitation (inch)</th>
<th>Flow (cfs)</th>
<th>Relative time (min)*</th>
<th>Average TSS (mg/l)</th>
<th>Normalized Cumulative Time</th>
<th>Cumulative Flow Volume (ft$^3$)</th>
<th>Normalized Cumulative Flow</th>
<th>Cumulative Mass Delivered (g)</th>
<th>Normalized Cumulative Mass</th>
<th>Δ1</th>
<th>Δ2</th>
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<td>459.20</td>
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<td>450.45</td>
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<td>180.633</td>
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<td>5308.98</td>
<td>0.591</td>
<td>0.441</td>
<td>0.465</td>
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<tr>
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<td>2.4248</td>
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<td>195.70</td>
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<td>0.8516</td>
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<td>1253.457</td>
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<td>7:34 PM</td>
<td>0.1915</td>
<td>15</td>
<td>22.55</td>
<td>0.500</td>
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<td>0.945</td>
<td>8953.77</td>
<td>0.996</td>
<td>0.496</td>
<td>0.051</td>
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<td>Influent</td>
<td>I6</td>
<td>7:39 PM</td>
<td>0.0819</td>
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<td>16.80</td>
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<td>0.750</td>
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<td>0.0380</td>
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<td>26.00</td>
<td>0.875</td>
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<td>7:26 PM</td>
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<td>105.58</td>
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<td>80.46</td>
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<tr>
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<td>10:59 PM</td>
<td>0.0340</td>
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Estimating the average concentrations and removal efficiencies

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<th>Arithmetic Average</th>
<th>Simultaneous EMC (mg/l)</th>
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<td>Removal %</td>
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<td>43.63</td>
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</table>

* Time was set according to the first influent sample

Notes:
1- Simultaneous samples removal is determined by estimating the EMC for both influent and effluent samples collected within the same period of time (comparable samples)
2- Cumulative time is the time between the beginning of the event and the sample time. However, if the first sample was not collected immediately after the beginning of the event, its time is assumed to be 5 minutes.
3- Normalized cumulative time and normalized cumulative mass are computed with respect to the influent sampling time and the cumulative mass delivered at the last influent sample respectively.
4- Normalized flow volume is computed with respect to the cumulative flow volume delivered at the last influent sample.
5- $\Delta 1$ is the difference between the normalized cumulative mass and the normalized cumulative time.
6- $\Delta 2$ is the difference between the normalized cumulative mass and the normalized flow volume.
Appendix A: TSS Results

Figure A.83: TSS Results - Event R7 - 07/18/2011

Figure A.84: Normalized Mass Vs Normalized Time and Normalized Flow Volume - Event R7 - 07/18/2011
Appendix B: Particle Size Analysis

Event No. 9
Event date 9/22/2010

Table B.1: Event 9 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:37 PM</td>
<td>1.128</td>
<td>1.318</td>
<td>0.515</td>
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</tr>
<tr>
<td></td>
<td>I-2</td>
<td>6:39 PM</td>
<td>5.933</td>
<td>7.591</td>
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<td>3.531</td>
<td>4.455</td>
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<tr>
<td>Median</td>
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<td>3.531</td>
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Appendix B: Particle Size Analysis

Event No. 10
Event date 9/24/2010

Table B.2: Event 10 Particle Size Analysis

<table>
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<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
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<td>10:17 PM</td>
<td>0</td>
<td>5.218</td>
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<td>14.76</td>
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<tr>
<td></td>
<td>E-2</td>
<td>10:19 PM</td>
<td>2</td>
<td>9.689</td>
<td>10.38</td>
<td>4.071</td>
<td>21.1</td>
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<tr>
<td></td>
<td>E-5</td>
<td>10:22 PM</td>
<td>5</td>
<td>10.68</td>
<td>11.58</td>
<td>4.561</td>
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<td></td>
<td>E-9</td>
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<td>88</td>
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<td>10.86</td>
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<td>11:48 PM</td>
<td>91</td>
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<td>12.05</td>
<td>6.54</td>
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<td>11:50 PM</td>
<td>93</td>
<td>12.63</td>
<td>12.65</td>
<td>6.926</td>
<td>22.88</td>
</tr>
<tr>
<td></td>
<td>E-13</td>
<td>11:51 PM</td>
<td>94</td>
<td>11.39</td>
<td>11.16</td>
<td>6.3</td>
<td>21.43</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.492</td>
<td>10.814</td>
<td>5.155</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.105</td>
<td>11.330</td>
<td>5.856</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.311</td>
<td>1.894</td>
<td>1.898</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample

![Particle Size Distribution - Event 10- 09/24/2010](image_url)

Figure B.1: Particle Size Distribution- Event 10- 09/24/2010
Appendix B: Particle Size Analysis

Event No. 11  
Event date 9/27/2010

Table B.3:  
*Event 11 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:31 AM</td>
<td>8.737</td>
<td>9.436</td>
<td>4.083</td>
<td>18.41</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>2:35 AM</td>
<td>7.365</td>
<td>7.629</td>
<td>3.454</td>
<td>15.61</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>8.051</td>
<td>8.533</td>
<td>3.769</td>
<td>17.010</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>8.051</td>
<td>8.533</td>
<td>3.769</td>
<td>17.010</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>0.970</td>
<td>1.278</td>
<td>0.445</td>
<td>1.980</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No. 13
Event date 9/28/2010

Table B.4:  
*Event 13 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:51 AM</td>
<td>14.21</td>
<td>14.26</td>
<td>12.4</td>
<td>16.22</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>3:01 AM</td>
<td>9.362</td>
<td>13.64</td>
<td>3.04</td>
<td>15.25</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>11.786</td>
<td>13.950</td>
<td>7.720</td>
<td>15.735</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>3.428</td>
<td>0.438</td>
<td>6.619</td>
<td>0.686</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>2:55 AM</td>
<td>9.586</td>
<td>10.74</td>
<td>4.301</td>
<td>18.36</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>9.586</td>
<td>10.74</td>
<td>4.301</td>
<td>18.36</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No. 14
Event date 10/3/2010

Table B.5:
Event 14 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>3:31 AM</td>
<td>0</td>
<td>8.044</td>
<td>9.298</td>
<td>3.962</td>
<td>16.84</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>3:36 AM</td>
<td>5</td>
<td>10.53</td>
<td>11.15</td>
<td>4.833</td>
<td>19.58</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>3:41 AM</td>
<td>10</td>
<td>10.31</td>
<td>10.82</td>
<td>4.89</td>
<td>19.21</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>3:46 AM</td>
<td>15</td>
<td>10.52</td>
<td>11.01</td>
<td>5.074</td>
<td>19.47</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>9.851</td>
<td>10.570</td>
<td>4.690</td>
<td>18.775</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.415</td>
<td>10.915</td>
<td>4.862</td>
<td>19.340</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.209</td>
<td>0.858</td>
<td>0.496</td>
<td>1.299</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>3:38 AM</td>
<td>-</td>
<td>10.98</td>
<td>11.59</td>
<td>5.154</td>
<td>20.16</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>10.98</td>
<td>11.59</td>
<td>5.154</td>
<td>20.16</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.2: Particle Size Distribution- Event 14- 10/03/2010
Appendix B: Particle Size Analysis

Event No. 16
Event date 10/5/2010

Table B.6: Event 16 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean $\mu$m</th>
<th>$d_{50}$ $\mu$m</th>
<th>$d_{10}$ $\mu$m</th>
<th>$d_{90}$ $\mu$m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>5:21 AM</td>
<td>0</td>
<td>2.839</td>
<td>3.582</td>
<td>0.783</td>
<td>7.179</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>5:26 AM</td>
<td>5</td>
<td>2.566</td>
<td>2.930</td>
<td>0.857</td>
<td>6.114</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>5:31 AM</td>
<td>10</td>
<td>2.538</td>
<td>3.326</td>
<td>0.668</td>
<td>6.921</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>5:36 AM</td>
<td>15</td>
<td>3.681</td>
<td>4.758</td>
<td>0.868</td>
<td>9.777</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>5:46 AM</td>
<td>25</td>
<td>3.625</td>
<td>4.979</td>
<td>0.849</td>
<td>9.089</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.050</td>
<td>3.915</td>
<td>0.805</td>
<td>7.816</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.839</td>
<td>3.582</td>
<td>0.849</td>
<td>7.179</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.563</td>
<td>0.904</td>
<td>0.083</td>
<td>1.547</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>5:29 AM</td>
<td>8</td>
<td>3.011</td>
<td>3.742</td>
<td>0.907</td>
<td>6.935</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>5:30 AM</td>
<td>9</td>
<td>5.405</td>
<td>7.312</td>
<td>0.828</td>
<td>15.680</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>5:32 AM</td>
<td>11</td>
<td>6.453</td>
<td>8.747</td>
<td>1.142</td>
<td>17.100</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.956</td>
<td>6.600</td>
<td>0.959</td>
<td>13.238</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.

![Particle Size Distribution- Event 16- 10/25/2010](image)

Figure B.3: Particle Size Distribution- Event 16- 10/25/2010
Appendix B: Particle Size Analysis

Event No. 17
Event date 10/14/2010

Table B.7: Event 17 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d₅₀ (µm)</th>
<th>d₁₀ (µm)</th>
<th>d₉₀ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:18 AM</td>
<td>0</td>
<td>6.269</td>
<td>8.150</td>
<td>1.784</td>
<td>13.510</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>2:23 AM</td>
<td>5</td>
<td>8.503</td>
<td>10.190</td>
<td>2.159</td>
<td>28.330</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>2:28 AM</td>
<td>10</td>
<td>8.590</td>
<td>10.360</td>
<td>2.187</td>
<td>28.100</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>2:33 AM</td>
<td>15</td>
<td>7.608</td>
<td>9.524</td>
<td>2.113</td>
<td>18.470</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>2:38 AM</td>
<td>20</td>
<td>13.950</td>
<td>17.740</td>
<td>4.026</td>
<td>35.030</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>2:43 AM</td>
<td>25</td>
<td>15.130</td>
<td>19.680</td>
<td>4.412</td>
<td>36.100</td>
</tr>
<tr>
<td></td>
<td>I-7</td>
<td>2:48 AM</td>
<td>30</td>
<td>16.270</td>
<td>20.070</td>
<td>4.976</td>
<td>37.260</td>
</tr>
<tr>
<td></td>
<td>I-8</td>
<td>3:03 AM</td>
<td>45</td>
<td>14.660</td>
<td>18.760</td>
<td>4.292</td>
<td>35.580</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.373</td>
<td>14.309</td>
<td>3.244</td>
<td>29.048</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>11.270</td>
<td>14.050</td>
<td>3.107</td>
<td>31.680</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.996</td>
<td>5.169</td>
<td>1.297</td>
<td>8.867</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>2:38 AM</td>
<td>20</td>
<td>18.280</td>
<td>24.730</td>
<td>5.584</td>
<td>43.820</td>
</tr>
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<td>23.195</td>
<td>5.235</td>
<td>43.080</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>-</td>
<td>17.635</td>
<td>23.195</td>
<td>5.235</td>
<td>43.080</td>
</tr>
<tr>
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<td>0.912</td>
<td>2.171</td>
<td>0.494</td>
<td>1.047</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.

Figure B.4: Particle Size Distribution- Event 10- 09/24/2010
Appendix B: Particle Size Analysis

Event No. 18
Event date 10/18/2010

Table B.8: Event 18 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>12:08 AM</td>
<td>0</td>
<td>1.381</td>
<td>1.571</td>
<td>0.497</td>
<td>4.881</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>12:18 AM</td>
<td>10</td>
<td>0.981</td>
<td>0.804</td>
<td>0.474</td>
<td>2.122</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>12:28 AM</td>
<td>20</td>
<td>0.972</td>
<td>0.785</td>
<td>0.472</td>
<td>2.116</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>12:38 AM</td>
<td>30</td>
<td>0.965</td>
<td>0.770</td>
<td>0.471</td>
<td>2.126</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>12:58 AM</td>
<td>50</td>
<td>0.947</td>
<td>0.744</td>
<td>0.467</td>
<td>2.116</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>1:06 AM</td>
<td>58</td>
<td>0.965</td>
<td>0.765</td>
<td>0.470</td>
<td>2.124</td>
</tr>
<tr>
<td></td>
<td>I-7</td>
<td>2:14 AM</td>
<td>126</td>
<td>0.954</td>
<td>0.760</td>
<td>0.470</td>
<td>2.111</td>
</tr>
<tr>
<td></td>
<td>I-8</td>
<td>2:24 AM</td>
<td>136</td>
<td>3.002</td>
<td>4.282</td>
<td>0.649</td>
<td>7.079</td>
</tr>
<tr>
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<td>-</td>
<td>-</td>
<td>1.271</td>
<td>1.310</td>
<td>0.496</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.969</td>
<td>0.778</td>
<td>0.472</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.715</td>
<td>1.233</td>
<td>0.062</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>2:28 AM</td>
<td>140</td>
<td>2.966</td>
<td>4.121</td>
<td>0.676</td>
<td>7.114</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>2:33 AM</td>
<td>145</td>
<td>2.993</td>
<td>4.255</td>
<td>0.634</td>
<td>7.139</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>2:40 AM</td>
<td>152</td>
<td>0.999</td>
<td>0.794</td>
<td>0.474</td>
<td>2.156</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>2:47 AM</td>
<td>159</td>
<td>0.976</td>
<td>0.776</td>
<td>0.475</td>
<td>2.150</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.984</td>
<td>2.487</td>
<td>0.565</td>
</tr>
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<td></td>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.983</td>
<td>2.458</td>
<td>0.555</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.150</td>
<td>1.965</td>
<td>0.106</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample
Appendix B: Particle Size Analysis

Figure B.5: Particle Size Distribution- Event 18- 10/18/2010
Appendix B: Particle Size Analysis

Event No. 19
Event date 10/25/2010

Table B.9: Event 19 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>7:30 AM</td>
<td>0</td>
<td>19.580</td>
<td>4.690</td>
<td>0.745</td>
<td>1535.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>7:39 AM</td>
<td>9</td>
<td>1398.000</td>
<td>1475.000</td>
<td>1072.000</td>
<td>1736.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>7:49 AM</td>
<td>19</td>
<td>10.610</td>
<td>3.489</td>
<td>0.672</td>
<td>688.000</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>7:59 AM</td>
<td>29</td>
<td>741.800</td>
<td>922.900</td>
<td>406.400</td>
<td>1369.000</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>8:09 AM</td>
<td>39</td>
<td>97.620</td>
<td>668.600</td>
<td>0.925</td>
<td>1716.000</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>8:19 AM</td>
<td>49</td>
<td>1006.000</td>
<td>1070.000</td>
<td>674.600</td>
<td>1519.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>545.602</td>
<td>690.780</td>
<td>359.224</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>419.710</td>
<td>795.750</td>
<td>203.663</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>590.025</td>
<td>592.667</td>
<td>446.135</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

![Particle Size Distribution- Event 19- 10/25/2010](image_url)

Figure B.6: Particle Size Distribution- Event 19- 10/25/2010
Appendix B: Particle Size Analysis

Event No. 20
Event date 11/3/2010

Table B.10:
Event 20 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>10:35 PM</td>
<td>0</td>
<td>1331.000</td>
<td>1454.000</td>
<td>939.600</td>
<td>1697.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>10:54 PM</td>
<td>19</td>
<td>2.956</td>
<td>3.938</td>
<td>0.724</td>
<td>6.992</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>11:04 PM</td>
<td>29</td>
<td>2.509</td>
<td>3.310</td>
<td>0.630</td>
<td>5.908</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>11:14 PM</td>
<td>39</td>
<td>2.932</td>
<td>4.020</td>
<td>0.664</td>
<td>7.068</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>334.849</td>
<td>366.317</td>
<td>235.405</td>
<td>429.242</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.944</td>
<td>3.979</td>
<td>0.694</td>
<td>7.030</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>664.101</td>
<td>725.122</td>
<td>469.464</td>
<td>845.172</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.

Figure B.7: Particle Size Distribution- Event 20- 11/03/2010
Appendix B: Particle Size Analysis

Event No. 21
Event date 11/16/2010

Table B.11: Event 21 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time (min)</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>12:56 PM</td>
<td>0</td>
<td>1105.000</td>
<td>1134.000</td>
<td>622.900</td>
<td>1934.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>1:05 PM</td>
<td>9</td>
<td>1464.000</td>
<td>1576.000</td>
<td>971.400</td>
<td>1942.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>1:15 PM</td>
<td>19</td>
<td>1.109</td>
<td>1.138</td>
<td>0.540</td>
<td>2.165</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>1:25 PM</td>
<td>29</td>
<td>1.471</td>
<td>1.657</td>
<td>0.593</td>
<td>2.767</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>2:06 PM</td>
<td>70</td>
<td>1.065</td>
<td>1.077</td>
<td>0.535</td>
<td>2.070</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>2:14 PM</td>
<td>78</td>
<td>8.333</td>
<td>8.941</td>
<td>2.904</td>
<td>19.540</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>430.163</td>
<td>453.802</td>
<td>266.479</td>
<td>650.424</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>4.902</td>
<td>5.299</td>
<td>1.749</td>
<td>11.154</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>671.439</td>
<td>711.927</td>
<td>425.574</td>
<td>997.378</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>2:45 PM</td>
<td>109</td>
<td>2.136</td>
<td>2.483</td>
<td>0.678</td>
<td>4.309</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>2:50 PM</td>
<td>114</td>
<td>2.394</td>
<td>2.886</td>
<td>0.690</td>
<td>6.572</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>2:54 PM</td>
<td>118</td>
<td>2.265</td>
<td>2.686</td>
<td>0.676</td>
<td>6.061</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>2:58 PM</td>
<td>122</td>
<td>2.373</td>
<td>2.916</td>
<td>0.670</td>
<td>6.642</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>3:02 PM</td>
<td>126</td>
<td>2.354</td>
<td>2.708</td>
<td>0.692</td>
<td>6.670</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>3:06 PM</td>
<td>130</td>
<td>2.345</td>
<td>2.971</td>
<td>1.074</td>
<td>6.181</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>2.311</td>
<td>2.775</td>
<td>0.747</td>
<td>6.073</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>2.350</td>
<td>2.797</td>
<td>0.684</td>
<td>6.377</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>0.096</td>
<td>0.183</td>
<td>0.161</td>
<td>0.900</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample
Appendix B: Particle Size Analysis

Figure B.8: Particle Size Distribution- Event 21- 11/16/2010
Appendix B: Particle Size Analysis

Event No. 22
Event date 11/23/2010

Table B.12: Event 22 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:29 AM</td>
<td>0</td>
<td>28.870</td>
<td>5.713</td>
<td>0.952</td>
<td>1344.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>6:37 AM</td>
<td>8</td>
<td>1.034</td>
<td>0.941</td>
<td>0.489</td>
<td>2.148</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>6:47 AM</td>
<td>18</td>
<td>1.039</td>
<td>0.963</td>
<td>0.492</td>
<td>2.148</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>6:57 AM</td>
<td>28</td>
<td>1.037</td>
<td>0.983</td>
<td>0.491</td>
<td>2.140</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>7:17 AM</td>
<td>48</td>
<td>1.120</td>
<td>1.333</td>
<td>0.509</td>
<td>2.133</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>6.620</td>
<td>1.987</td>
<td>0.587</td>
<td>270.514</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>1.039</td>
<td>0.983</td>
<td>0.492</td>
<td>2.148</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>12.438</td>
<td>2.089</td>
<td>0.204</td>
<td>600.097</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>6:40 AM</td>
<td>11</td>
<td>0.927</td>
<td>0.719</td>
<td>0.469</td>
<td>3.868</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>6:44 AM</td>
<td>15</td>
<td>0.714</td>
<td>0.598</td>
<td>0.439</td>
<td>1.627</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>6:48 AM</td>
<td>19</td>
<td>8.379</td>
<td>0.701</td>
<td>0.452</td>
<td>1564.000</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>6:52 AM</td>
<td>23</td>
<td>1.003</td>
<td>0.960</td>
<td>0.508</td>
<td>2.051</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>6:56 AM</td>
<td>27</td>
<td>1.199</td>
<td>0.949</td>
<td>0.511</td>
<td>4.531</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>7:00 AM</td>
<td>31</td>
<td>0.893</td>
<td>0.724</td>
<td>0.470</td>
<td>2.053</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>2.186</td>
<td>0.775</td>
<td>0.475</td>
<td>263.022</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>0.965</td>
<td>0.722</td>
<td>0.470</td>
<td>2.961</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>3.038</td>
<td>0.146</td>
<td>0.029</td>
<td>637.348</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample
Appendix B: Particle Size Analysis

Figure B.9: Particle Size Distribution - Event 22 - 11/23/2010
Appendix B: Particle Size Analysis

Event No. 23  
Event date 11/24/2010

Table B.13:  
*Event 23 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:26 PM</td>
<td>4</td>
<td>1.436</td>
<td>1.508</td>
<td>0.892</td>
<td>2.148</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>6:36 PM</td>
<td>14</td>
<td>1.184</td>
<td>1.289</td>
<td>0.590</td>
<td>2.069</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>6:46 PM</td>
<td>24</td>
<td>1.235</td>
<td>1.392</td>
<td>0.585</td>
<td>2.133</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>6:56 PM</td>
<td>34</td>
<td>1.220</td>
<td>1.352</td>
<td>0.592</td>
<td>2.126</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>7:06 PM</td>
<td>44</td>
<td>0.999</td>
<td>0.979</td>
<td>0.520</td>
<td>1.967</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>7:16 PM</td>
<td>54</td>
<td>1.198</td>
<td>1.317</td>
<td>0.585</td>
<td>2.106</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td>1.212</td>
<td>1.306</td>
<td>0.627</td>
<td>2.092</td>
</tr>
<tr>
<td></td>
<td>Median</td>
<td></td>
<td></td>
<td>1.209</td>
<td>1.335</td>
<td>0.588</td>
<td>2.116</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
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<td></td>
<td>0.139</td>
<td>0.178</td>
<td>0.133</td>
<td>0.067</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>6:22 PM</td>
<td>0</td>
<td>1.143</td>
<td>1.239</td>
<td>0.556</td>
<td>2.097</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>6:27 PM</td>
<td>5</td>
<td>1.272</td>
<td>1.407</td>
<td>0.632</td>
<td>2.127</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>6:31 PM</td>
<td>9</td>
<td>1.274</td>
<td>1.396</td>
<td>0.645</td>
<td>2.144</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>6:35 PM</td>
<td>13</td>
<td>1.077</td>
<td>1.105</td>
<td>0.571</td>
<td>1.954</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>6:39 PM</td>
<td>17</td>
<td>1.150</td>
<td>1.256</td>
<td>0.558</td>
<td>2.093</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>6:43 PM</td>
<td>21</td>
<td>0.944</td>
<td>0.920</td>
<td>0.508</td>
<td>1.811</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td></td>
<td></td>
<td>1.143</td>
<td>1.221</td>
<td>0.578</td>
<td>2.038</td>
</tr>
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<td></td>
<td>1.147</td>
<td>1.248</td>
<td>0.565</td>
<td>2.095</td>
</tr>
<tr>
<td></td>
<td>St. Dev</td>
<td></td>
<td></td>
<td>0.125</td>
<td>0.185</td>
<td>0.051</td>
<td>0.130</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample.
Appendix B: Particle Size Analysis

![Particle Size Distribution - Event 23 - 11/23/2010](image)

**Figure B.10: Particle Size Distribution - Event 23 - 11/23/2010**
Appendix B: Particle Size Analysis

Event No. 24  
Event date 11/30/2010

Table B.14:  
*Event 24 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (µm)</th>
<th>Median (µm)</th>
<th>d_{10} (µm)</th>
<th>d_{90} (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:38 AM</td>
<td>0.694</td>
<td>0.591</td>
<td>0.441</td>
<td>1.978</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>0.694</td>
<td>0.591</td>
<td>0.441</td>
<td>1.978</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>2:26 AM</td>
<td>0.882</td>
<td>0.711</td>
<td>0.470</td>
<td>2.114</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>0.882</td>
<td>0.711</td>
<td>0.470</td>
<td>2.114</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No. 25
Event date 12/12/2010

Table B.15: Event 25 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d00 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>1:14 AM</td>
<td>7</td>
<td>1570.000</td>
<td>1611.000</td>
<td>1378.000</td>
<td>1795.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>1:24 AM</td>
<td>17</td>
<td>1007.000</td>
<td>1057.000</td>
<td>746.500</td>
<td>1300.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>1:34 AM</td>
<td>27</td>
<td>1338.000</td>
<td>1433.000</td>
<td>946.400</td>
<td>1738.000</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>1:44 AM</td>
<td>37</td>
<td>1409.000</td>
<td>1491.000</td>
<td>955.900</td>
<td>1893.000</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>1:54 AM</td>
<td>47</td>
<td>1103.000</td>
<td>1275.000</td>
<td>705.300</td>
<td>1519.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1285.400</td>
<td>1373.400</td>
<td>946.400</td>
<td>1649.000</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1338.000</td>
<td>1433.000</td>
<td>946.400</td>
<td>1738.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>229.029</td>
<td>214.259</td>
<td>266.673</td>
<td>238.471</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>1:07 AM</td>
<td>0</td>
<td>944.100</td>
<td>1379.000</td>
<td>793.900</td>
<td>1609.000</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>1:12 AM</td>
<td>5</td>
<td>977.700</td>
<td>1139.000</td>
<td>753.200</td>
<td>1608.000</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>1:19 AM</td>
<td>12</td>
<td>951.800</td>
<td>1387.000</td>
<td>811.800</td>
<td>1613.000</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>1:29 AM</td>
<td>22</td>
<td>1102.000</td>
<td>1340.000</td>
<td>813.600</td>
<td>1643.000</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>1:39 AM</td>
<td>32</td>
<td>1075.000</td>
<td>1317.000</td>
<td>797.500</td>
<td>1645.000</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>1:49 AM</td>
<td>42</td>
<td>970.800</td>
<td>1142.000</td>
<td>767.100</td>
<td>1610.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1003.567</td>
<td>1284.000</td>
<td>789.517</td>
<td>1621.333</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>974.250</td>
<td>1328.500</td>
<td>795.700</td>
<td>1611.500</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>67.455</td>
<td>114.060</td>
<td>24.417</td>
<td>17.648</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample
Appendix B: Particle Size Analysis

Figure B.11: Particle Size Distribution - Event 25 - 12/12/2010
Appendix B: Particle Size Analysis

Event No. 27
Event date 12/30/2010

Table B.16: 
Event 27 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>6:05 AM</td>
<td>0</td>
<td>1122.000</td>
<td>1381.000</td>
<td>891.900</td>
<td>1644.000</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>6:10 AM</td>
<td>5</td>
<td>1250.000</td>
<td>1413.000</td>
<td>968.000</td>
<td>1612.000</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>6:14 AM</td>
<td>9</td>
<td>1108.000</td>
<td>1389.000</td>
<td>878.900</td>
<td>1614.000</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>6:18 AM</td>
<td>13</td>
<td>1398.000</td>
<td>1537.000</td>
<td>913.000</td>
<td>1894.000</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>6:22 AM</td>
<td>17</td>
<td>1433.000</td>
<td>1547.000</td>
<td>984.200</td>
<td>1913.000</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>6:26 AM</td>
<td>21</td>
<td>1259.000</td>
<td>1376.000</td>
<td>824.600</td>
<td>1732.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1261.667</td>
<td>1440.500</td>
<td>910.100</td>
<td>1734.833</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1254.500</td>
<td>1401.000</td>
<td>902.450</td>
<td>1688.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>135.059</td>
<td>79.704</td>
<td>59.104</td>
<td>137.859</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample

Figure B.12: Particle Size Distribution - Event 27 - 12/30/2010
### Event 29 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>11:43 PM</td>
<td>0</td>
<td>1550.00</td>
<td>1698.00</td>
<td>1044.00</td>
<td>1942.00</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>12:02 AM</td>
<td>19</td>
<td>1320.00</td>
<td>1420.00</td>
<td>843.20</td>
<td>1882.00</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>12:12 AM</td>
<td>29</td>
<td>1364.00</td>
<td>1472.00</td>
<td>885.80</td>
<td>1892.00</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>12:22 AM</td>
<td>39</td>
<td>1323.00</td>
<td>1432.00</td>
<td>875.70</td>
<td>1803.00</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>12:32 AM</td>
<td>49</td>
<td>1393.00</td>
<td>1529.00</td>
<td>895.50</td>
<td>1912.00</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>1390.00</td>
<td>1510.20</td>
<td>908.84</td>
<td>1886.20</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>1364.00</td>
<td>1472.00</td>
<td>885.80</td>
<td>1892.00</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>94.438</td>
<td>113.284</td>
<td>78.077</td>
<td>51.848</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>11:52 PM</td>
<td>9</td>
<td>1336.00</td>
<td>1438.00</td>
<td>904.00</td>
<td>1809.00</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>11:56 PM</td>
<td>13</td>
<td>1445.00</td>
<td>1546.00</td>
<td>1001.00</td>
<td>1910.00</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>12:00 AM</td>
<td>17</td>
<td>1489.00</td>
<td>1615.00</td>
<td>1017.00</td>
<td>1927.00</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>12:04 AM</td>
<td>21</td>
<td>1468.00</td>
<td>1615.00</td>
<td>673.40</td>
<td>1928.00</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>12:08 AM</td>
<td>25</td>
<td>1419.00</td>
<td>1577.00</td>
<td>902.70</td>
<td>1923.00</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>12:12 AM</td>
<td>29</td>
<td>1486.00</td>
<td>1630.00</td>
<td>977.50</td>
<td>1929.00</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>1440.50</td>
<td>1570.17</td>
<td>912.60</td>
<td>1904.33</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>1456.50</td>
<td>1596.00</td>
<td>940.75</td>
<td>1925.00</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>57.587</td>
<td>71.692</td>
<td>126.74</td>
<td>47.226</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.
Appendix B: Particle Size Analysis

Figure B.13: Particle Size Distribution- Event 29- 01/11/2011
Appendix B: Particle Size Analysis

Event No. 31-1
Event date 2/1/2011

Table B.18:  
*Event 31-1 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:37 AM</td>
<td>12</td>
<td>1.082</td>
<td>1.074</td>
<td>0.512</td>
<td>2.215</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>10:47 AM</td>
<td>262</td>
<td>773.200</td>
<td>1153.000</td>
<td>514.600</td>
<td>1696.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>10:56 AM</td>
<td>271</td>
<td>1386.000</td>
<td>1487.000</td>
<td>919.900</td>
<td>1881.000</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>720.094</td>
<td>880.358</td>
<td>478.337</td>
<td>1193.072</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>773.200</td>
<td>1153.000</td>
<td>514.600</td>
<td>1696.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>693.985</td>
<td>779.580</td>
<td>460.765</td>
<td>1035.452</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>6:25 AM</td>
<td>0</td>
<td>1331.000</td>
<td>1476.000</td>
<td>910.800</td>
<td>1756.000</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>6:30 AM</td>
<td>5</td>
<td>1334.000</td>
<td>1457.000</td>
<td>952.600</td>
<td>1709.000</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>6:34 AM</td>
<td>9</td>
<td>1193.000</td>
<td>1381.000</td>
<td>780.500</td>
<td>1597.000</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>6:38 AM</td>
<td>13</td>
<td>1218.000</td>
<td>1388.000</td>
<td>907.800</td>
<td>1600.000</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>6:42 AM</td>
<td>17</td>
<td>1176.000</td>
<td>1142.000</td>
<td>780.700</td>
<td>1586.000</td>
</tr>
<tr>
<td></td>
<td>E-6</td>
<td>6:46 AM</td>
<td>21</td>
<td>1212.000</td>
<td>1348.000</td>
<td>826.400</td>
<td>1623.000</td>
</tr>
<tr>
<td></td>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>1244.000</td>
<td>1365.333</td>
<td>859.800</td>
<td>1645.167</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1215.000</td>
<td>1384.500</td>
<td>867.100</td>
<td>1611.500</td>
</tr>
<tr>
<td>St. Dev</td>
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<td>-</td>
<td>-</td>
<td>70.134</td>
<td>119.656</td>
<td>73.726</td>
<td>70.301</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample
Appendix B: Particle Size Analysis

Figure B.14: Particle Size Distribution- Event 31-1- 02/01/2011
Appendix B: Particle Size Analysis

Event No. 31-2
Event date 2/1/2011

Table B.19: Event 31-2 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>8:29 PM</td>
<td>0</td>
<td>1230.000</td>
<td>1398.000</td>
<td>810.100</td>
<td>1720.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>8:36 PM</td>
<td>7</td>
<td>1310.000</td>
<td>1435.000</td>
<td>940.100</td>
<td>1709.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>8:46 PM</td>
<td>17</td>
<td>1395.000</td>
<td>1524.000</td>
<td>962.800</td>
<td>1767.000</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>1311.667</td>
<td>1452.333</td>
<td>904.333</td>
<td>1732.000</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>1310.000</td>
<td>1435.000</td>
<td>940.100</td>
<td>1720.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>82.513</td>
<td>64.764</td>
<td>82.394</td>
<td>30.806</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.15: Particle Size Distribution- Event 31-2- 02/01/2011
Appendix B: Particle Size Analysis

Event No. 32
Event date 2/7/2011

Table B.20: Event 32 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>5:15 PM</td>
<td>0</td>
<td>1.014</td>
<td>0.923</td>
<td>0.497</td>
<td>2.122</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>5:20 PM</td>
<td>5</td>
<td>0.986</td>
<td>0.854</td>
<td>0.490</td>
<td>2.117</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>5:28 PM</td>
<td>13</td>
<td>1.309</td>
<td>1.388</td>
<td>0.534</td>
<td>3.228</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>5:38 PM</td>
<td>23</td>
<td>1.005</td>
<td>0.897</td>
<td>0.490</td>
<td>2.120</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>5:45 PM</td>
<td>30</td>
<td>1.755</td>
<td>1.985</td>
<td>0.620</td>
<td>4.185</td>
</tr>
<tr>
<td></td>
<td>I-6</td>
<td>5:53 PM</td>
<td>38</td>
<td>1.693</td>
<td>1.917</td>
<td>0.611</td>
<td>3.991</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.294</td>
<td>1.327</td>
<td>0.540</td>
<td>2.961</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.162</td>
<td>1.156</td>
<td>0.516</td>
<td>2.675</td>
</tr>
<tr>
<td>St. Dev</td>
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<td>-</td>
<td>-</td>
<td>0.355</td>
<td>0.521</td>
<td>0.061</td>
<td>0.975</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.16: Particle Size Distribution- Event 32- 02/07/2011
Appendix B: Particle Size Analysis

Event No. 33  
Event date 2/21/2011

Table B.21:  
Event 33 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>3:37 PM</td>
<td>0</td>
<td>1.297</td>
<td>1.379</td>
<td>0.506</td>
<td>3.257</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>3:47 PM</td>
<td>10</td>
<td>1.308</td>
<td>1.512</td>
<td>0.497</td>
<td>4.077</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>6:32 PM</td>
<td>175</td>
<td>46.770</td>
<td>45.040</td>
<td>11.560</td>
<td>239.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>16.458</td>
<td>15.977</td>
<td>4.188</td>
<td>82.111</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.308</td>
<td>1.512</td>
<td>0.506</td>
<td>4.077</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>26.251</td>
<td>25.169</td>
<td>6.385</td>
<td>135.870</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>3:56 AM</td>
<td>0</td>
<td>407.400</td>
<td>538.400</td>
<td>207.000</td>
<td>661.400</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>4:00 AM</td>
<td>4</td>
<td>547.600</td>
<td>640.100</td>
<td>262.500</td>
<td>823.000</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>4:04 AM</td>
<td>8</td>
<td>622.600</td>
<td>722.900</td>
<td>270.600</td>
<td>1101.000</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>525.867</td>
<td>633.800</td>
<td>246.700</td>
<td>861.800</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>547.600</td>
<td>640.100</td>
<td>262.500</td>
<td>823.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>109.234</td>
<td>92.411</td>
<td>34.619</td>
<td>222.354</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample
Figure B.17: Particle Size Distribution- Event 33- 02/21/2011
Appendix B: Particle Size Analysis

Event No. 34
Event date 2/24/2011

Table B.22: Event 34 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>10:27 PM</td>
<td>0</td>
<td>0.944</td>
<td>0.746</td>
<td>0.468</td>
<td>2.120</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>10:45 PM</td>
<td>18</td>
<td>94.550</td>
<td>200.200</td>
<td>25.080</td>
<td>254.200</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>10:55 PM</td>
<td>28</td>
<td>18.990</td>
<td>53.700</td>
<td>0.566</td>
<td>258.600</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>11:05 PM</td>
<td>38</td>
<td>23.280</td>
<td>64.380</td>
<td>1.005</td>
<td>418.600</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>11:15 PM</td>
<td>48</td>
<td>3.668</td>
<td>3.593</td>
<td>1.002</td>
<td>17.050</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>28.286</td>
<td>64.524</td>
<td>5.624</td>
<td>190.114</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>18.990</td>
<td>53.700</td>
<td>1.002</td>
<td>254.200</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>38.262</td>
<td>81.095</td>
<td>10.879</td>
<td>177.691</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.18: Particle Size Distribution- Event 34- 02/24/2011
Appendix B: Particle Size Analysis

Event No. 35
Event date 3/5/2011

Table B.23: Event 35 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d₅₀ (μm)</th>
<th>d₁₀ (μm)</th>
<th>d₉₀ (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>12:12 PM</td>
<td>0</td>
<td>25.970</td>
<td>62.320</td>
<td>0.580</td>
<td>553.600</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>12:17 PM</td>
<td>5</td>
<td>11.750</td>
<td>10.140</td>
<td>0.579</td>
<td>497.300</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>12:21 PM</td>
<td>9</td>
<td>57.290</td>
<td>77.960</td>
<td>2.944</td>
<td>519.000</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>31.670</td>
<td>50.140</td>
<td>1.368</td>
<td>523.300</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>25.970</td>
<td>62.320</td>
<td>0.580</td>
<td>519.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>23.299</td>
<td>35.513</td>
<td>1.365</td>
<td>28.395</td>
</tr>
</tbody>
</table>

Relative time was set according to the first effluent sample.

![Particle Size Distribution- Event 35- 03/05/2011](Image)
Appendix B: Particle Size Analysis

Event No. 36
Event date 3/10/2011

Table B.24: Event 36 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>9:53 AM</td>
<td>0</td>
<td>11.960</td>
<td>2.363</td>
<td>0.525</td>
<td>320.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>12:56 PM</td>
<td>183</td>
<td>141.000</td>
<td>259.300</td>
<td>50.640</td>
<td>602.700</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>76.480</td>
<td>130.832</td>
<td>25.583</td>
<td>461.350</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>76.480</td>
<td>130.832</td>
<td>25.583</td>
<td>461.350</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>91.245</td>
<td>181.682</td>
<td>35.437</td>
<td>199.899</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>5:19 AM</td>
<td>0</td>
<td>180.700</td>
<td>304.100</td>
<td>9.224</td>
<td>638.500</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>5:24 AM</td>
<td>5</td>
<td>340.100</td>
<td>595.800</td>
<td>96.100</td>
<td>657.800</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>5:28 AM</td>
<td>9</td>
<td>3.308</td>
<td>4.052</td>
<td>0.525</td>
<td>14.090</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>5:32 AM</td>
<td>13</td>
<td>0.904</td>
<td>0.669</td>
<td>0.453</td>
<td>2.121</td>
</tr>
<tr>
<td></td>
<td>E-5</td>
<td>5:36 AM</td>
<td>17</td>
<td>0.906</td>
<td>0.687</td>
<td>0.458</td>
<td>2.131</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>105.184</td>
<td>181.062</td>
<td>21.352</td>
<td>262.928</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.308</td>
<td>4.052</td>
<td>0.525</td>
<td>14.090</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>152.492</td>
<td>266.250</td>
<td>41.957</td>
<td>351.758</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent and effluent samples separately because effluent samples were collected on 03/15/2011.

Figure B.20: Particle Size Distribution- Event 36- 03/10/2011
Appendix B: Particle Size Analysis

Event No. 37-1
Event date 3/18/2011

Table B.1:

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>6:23 PM</td>
<td>0</td>
<td>0.709</td>
<td>0.625</td>
<td>0.452</td>
<td>1.641</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>6:32 PM</td>
<td>9</td>
<td>1.745</td>
<td>1.757</td>
<td>0.518</td>
<td>8.483</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>7:22 PM</td>
<td>59</td>
<td>5.230</td>
<td>1.754</td>
<td>0.513</td>
<td>147.200</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>7:32 PM</td>
<td>69</td>
<td>0.690</td>
<td>0.574</td>
<td>0.432</td>
<td>1.540</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.094</td>
<td>1.178</td>
<td>0.479</td>
<td>39.716</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.227</td>
<td>1.190</td>
<td>0.483</td>
<td>5.062</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>2.148</td>
<td>0.668</td>
<td>0.043</td>
<td>71.730</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.21: Particle Size Distribution- Event 37-1- 03/18/2011
Appendix B: Particle Size Analysis

Event No. 38-1
Event date 3/27/2011

Table B.25: Event 38-1 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>1:23 AM</td>
<td>0</td>
<td>1060.000</td>
<td>1114.000</td>
<td>695.900</td>
<td>1518.000</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>1:29 AM</td>
<td>6</td>
<td>0.691</td>
<td>0.586</td>
<td>0.438</td>
<td>1.746</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>1:59 AM</td>
<td>36</td>
<td>0.797</td>
<td>0.642</td>
<td>0.454</td>
<td>2.028</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>2:09 AM</td>
<td>46</td>
<td>0.747</td>
<td>0.618</td>
<td>0.448</td>
<td>1.963</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>265.559</td>
<td>278.962</td>
<td>174.310</td>
<td>380.934</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.772</td>
<td>0.630</td>
<td>0.451</td>
<td>1.996</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>529.628</td>
<td>556.692</td>
<td>347.727</td>
<td>758.044</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>1:27 AM</td>
<td>4</td>
<td>0.860</td>
<td>0.657</td>
<td>0.455</td>
<td>2.097</td>
</tr>
<tr>
<td></td>
<td>E-2</td>
<td>1:31 AM</td>
<td>8</td>
<td>0.819</td>
<td>0.644</td>
<td>0.453</td>
<td>2.006</td>
</tr>
<tr>
<td></td>
<td>E-3</td>
<td>1:35 AM</td>
<td>12</td>
<td>0.803</td>
<td>0.646</td>
<td>0.455</td>
<td>2.062</td>
</tr>
<tr>
<td></td>
<td>E-4</td>
<td>1:43 AM</td>
<td>20</td>
<td>0.626</td>
<td>0.558</td>
<td>0.429</td>
<td>1.470</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.777</td>
<td>0.626</td>
<td>0.448</td>
<td>1.909</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.811</td>
<td>0.645</td>
<td>0.454</td>
<td>2.034</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.103</td>
<td>0.046</td>
<td>0.013</td>
<td>0.295</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.

Figure B.22: Particle Size Distribution- Event 38-1- 03/27/2011
Appendix B: Particle Size Analysis

Event No. 39-1
Event date 4/8/2011

Table B.26: Event 39-1 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>9:22 AM</td>
<td>0</td>
<td>0.929</td>
<td>0.720</td>
<td>0.464</td>
<td>2.112</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>9:32 AM</td>
<td>10</td>
<td>0.931</td>
<td>0.777</td>
<td>0.479</td>
<td>2.086</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>9:42 AM</td>
<td>20</td>
<td>0.966</td>
<td>0.789</td>
<td>0.478</td>
<td>2.120</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.942</td>
<td>0.762</td>
<td>0.474</td>
<td>2.106</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.931</td>
<td>0.777</td>
<td>0.478</td>
<td>2.112</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.021</td>
<td>0.037</td>
<td>0.008</td>
<td>0.018</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample.

Figure B.23: Particle Size Distribution- Event 39-1- 04/08/2011
Appendix B: Particle Size Analysis

Event No. R2-1
Event date 5/14/2011

Table B.27:  
*Event R2-1 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>12:30 AM</td>
<td>3.550</td>
<td>5.022</td>
<td>0.783</td>
<td>9.737</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>3.324</td>
<td>4.389</td>
<td>0.922</td>
<td>8.097</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>3.324</td>
<td>4.389</td>
<td>0.922</td>
<td>8.097</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>0.320</td>
<td>0.895</td>
<td>0.197</td>
<td>2.319</td>
</tr>
<tr>
<td>Effluent</td>
<td>E-1</td>
<td>12:30 AM</td>
<td>1.369</td>
<td>1.489</td>
<td>0.747</td>
<td>2.173</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>1.369</td>
<td>1.489</td>
<td>0.747</td>
<td>2.173</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No. R2-2
Event date 5/14/2011

Table B.28: 
*Event R2-2 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (µm)</th>
<th>Median (µm)</th>
<th>d₁₀ (µm)</th>
<th>d₉₀ (µm)</th>
<th>S.D (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>5:29 AM</td>
<td>3.352</td>
<td>4.240</td>
<td>0.974</td>
<td>7.599</td>
<td>2.170</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>5:34 AM</td>
<td>1.278</td>
<td>1.427</td>
<td>0.622</td>
<td>2.162</td>
<td>1.593</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>2.315</td>
<td>2.834</td>
<td>0.798</td>
<td>4.881</td>
<td>1.882</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No. R3
Event date 5/19/2011

Table B.29: Event R3 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>8:55 PM</td>
<td>0</td>
<td>2.422</td>
<td>2.665</td>
<td>0.630</td>
<td>7.447</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>8:58 PM</td>
<td>3</td>
<td>1031.000</td>
<td>1088.000</td>
<td>870.000</td>
<td>1262.000</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>9:06 PM</td>
<td>11</td>
<td>1.288</td>
<td>1.409</td>
<td>0.537</td>
<td>3.038</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>9:16 PM</td>
<td>21</td>
<td>1114.000</td>
<td>1248.000</td>
<td>742.000</td>
<td>1930.000</td>
</tr>
<tr>
<td></td>
<td>I-5</td>
<td>9:26 PM</td>
<td>31</td>
<td>1419.000</td>
<td>1552.000</td>
<td>942.500</td>
<td>1921.000</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td></td>
<td>713.542</td>
<td>778.415</td>
<td>511.133</td>
<td>1024.697</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>1031.000</td>
<td>1088.000</td>
<td>742.000</td>
<td>1262.000</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>665.548</td>
<td>728.065</td>
<td>471.562</td>
<td>969.256</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.24: Particle Size Distribution- Event R3- 05/19/2011
Appendix B: Particle Size Analysis

Event No.  R4
Event date  6/4/2011

Table B.30:  
Event R4 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>11:47 PM</td>
<td>0</td>
<td>1.132</td>
<td>1.385</td>
<td>0.459</td>
<td>2.820</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>11:52 PM</td>
<td>5</td>
<td>0.717</td>
<td>0.613</td>
<td>0.447</td>
<td>1.719</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>12:02 AM</td>
<td>15</td>
<td>7.259</td>
<td>8.341</td>
<td>2.457</td>
<td>17.910</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.023</td>
<td>4.475</td>
<td>1.620</td>
<td>8.797</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.057</td>
<td>4.473</td>
<td>1.458</td>
<td>7.780</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>3.583</td>
<td>4.038</td>
<td>1.374</td>
<td>7.840</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.25: Particle Size Distribution- Event R4- 06/04/2011
Appendix B: Particle Size Analysis

Event No. R5-1
Event date 6/15/2011

Table B.31: 
*Event R5-1 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (µm)</th>
<th>d50 (µm)</th>
<th>d10 (µm)</th>
<th>d90 (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>10:17 PM</td>
<td>0</td>
<td>21.910</td>
<td>91.640</td>
<td>0.489</td>
<td>339.100</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>10:25 PM</td>
<td>8</td>
<td>0.610</td>
<td>0.555</td>
<td>0.429</td>
<td>0.843</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>10:45 PM</td>
<td>28</td>
<td>0.767</td>
<td>0.584</td>
<td>0.432</td>
<td>1.911</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td>10:45 PM</td>
<td>28</td>
<td>7.762</td>
<td>30.926</td>
<td>0.450</td>
<td>113.951</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td></td>
<td>0.767</td>
<td>0.584</td>
<td>0.432</td>
<td>1.911</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td></td>
<td>12.252</td>
<td>52.580</td>
<td>0.034</td>
<td>194.985</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

![Particle Size Distribution- Event R5-06/15/2011](image)
Appendix B: Particle Size Analysis

Event No. R6-1
Event date 6/23/2011

Table B.32:
Event R6-1 Particle Size Analysis

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Relative Time (min)</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>2:42 PM</td>
<td>0</td>
<td>5.829</td>
<td>6.804</td>
<td>1.496</td>
<td>17.310</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>2:49 PM</td>
<td>7</td>
<td>5.777</td>
<td>7.631</td>
<td>1.029</td>
<td>15.040</td>
</tr>
<tr>
<td></td>
<td>I-3</td>
<td>2:59 PM</td>
<td>17</td>
<td>2.538</td>
<td>3.279</td>
<td>0.694</td>
<td>6.562</td>
</tr>
<tr>
<td></td>
<td>I-4</td>
<td>3:04 PM</td>
<td>22</td>
<td>4.511</td>
<td>5.569</td>
<td>1.029</td>
<td>12.810</td>
</tr>
<tr>
<td>Average</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>4.664</td>
<td>5.821</td>
<td>1.062</td>
<td>12.931</td>
</tr>
<tr>
<td>Median</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>5.144</td>
<td>6.187</td>
<td>1.029</td>
<td>13.925</td>
</tr>
<tr>
<td>St. Dev</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>1.543</td>
<td>1.895</td>
<td>0.330</td>
<td>4.626</td>
</tr>
</tbody>
</table>

Relative time was set according to the first influent sample

Figure B.27: Particle Size Distribution- Event R6-1- 06/23/2011
Appendix B: Particle Size Analysis

Event No.       R6-2  
Event date      6/23/2011

Table B.33:  
*Event R6-2 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (µm)</th>
<th>d₅₀ (µm)</th>
<th>d₁₀ (µm)</th>
<th>d₉₀ (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>7:19 PM</td>
<td>3.906</td>
<td>4.806</td>
<td>1.200</td>
<td>8.936</td>
</tr>
<tr>
<td></td>
<td>I-2</td>
<td>7:29 PM</td>
<td>1.909</td>
<td>1.819</td>
<td>0.540</td>
<td>10.510</td>
</tr>
<tr>
<td>Average</td>
<td></td>
<td></td>
<td>2.908</td>
<td>3.313</td>
<td>0.870</td>
<td>9.723</td>
</tr>
<tr>
<td>Median</td>
<td></td>
<td></td>
<td>2.908</td>
<td>3.313</td>
<td>0.870</td>
<td>9.723</td>
</tr>
<tr>
<td>St. Dev</td>
<td></td>
<td></td>
<td>1.412</td>
<td>2.112</td>
<td>0.467</td>
<td>1.113</td>
</tr>
</tbody>
</table>
Appendix B: Particle Size Analysis

Event No.  R7
Event date  7/18/2011

Table B.34:
*Event R7 Particle Size Analysis*

<table>
<thead>
<tr>
<th>Sample Type</th>
<th>Sample ID</th>
<th>Time</th>
<th>Mean (μm)</th>
<th>d50 (μm)</th>
<th>d10 (μm)</th>
<th>d90 (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Influent</td>
<td>I-1</td>
<td>7:19 PM</td>
<td>1.998</td>
<td>2.374</td>
<td>0.630</td>
<td>5.063</td>
</tr>
</tbody>
</table>