HIGHWAY RUNOFF - CHARACTERIZATION, STORMWATER CONTROLS AND IRON OXIDE COATED SANDS AS ENGINEERING AMENDMENTS IN SAND FILTER

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HIGHWAY RUNOFF - CHARACTERIZATION, STORMWATER CONTROLS AND IRON OXIDE COATED SANDS AS ENGINEERING AMENDMENTS IN SAND FILTER

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To my family
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SUMMARY

Most highway and construction runoff originates from non-point or diffused sources. This runoff contains environmental pollutants, which when transferred to sensitive receiving waters, can result in deterioration of receiving water quality and downstream aquatic habitat. Unlike point source runoff such as industrial and sewage treatment plant discharge, which is comparatively easy to monitor, control and treat, non-point source runoff needs to be extensively researched to characterize its constituents and properties. This allows determination of the effect on receiving waters, in order to devise effective and economic techniques to contain or treat it. Commonly, stormwater controls or best management practices (BMPs) are incorporated by agencies and state department of transportations to treat or contain highway runoff depending on the purpose of a stormwater control.

The work performed in this study consists of two parts: first, characterization of stormwater runoff from an interstate highway in Georgia for comparison of conditions before, during, and after construction, and second, study of the field performance of a sand filter BMP, along with engineered amendments used for sorptive and thermal pollution control. In the first part of this study, highway runoff quality in Georgia, within the Georgia Department of Transportation (GDOT) right of way, was characterized. Furthermore, factors affecting highway runoff quality were investigated. In-situ parameters were analyzed for temporal changes in water quality indicators.

The effect of construction runoff and highway runoff during construction or precipitation events can contribute to either acute or chronic pollution of receiving water.
In this study, the effect of construction runoff on a receiving stream was also investigated and compared with periods during and after construction. Temporal analysis of stream water quality indicators was conducted using wavelets to observe the behavior of stream water quality indicators at different temporal scales.

In the second part of this study, a sand filter located in Georgia was studied for its performance in reducing contaminants and compared with other sand filters in United States, with an emphasis on design parameters. Sand filters, especially the ones with preceding sedimentation basins, perform well in removal of floatables, suspended solids and pollutants associated with suspended solids. Additionally, the potential of using iron oxide coated sands as engineered amendments in sand filters was tested as a means to enhance the BMPs performance in removing dissolved fractions of pollutants as well as diffusing thermal pollution. Laboratory prepared iron oxide coated sands as simulants were used to study their thermal behavior and interaction with dissolved fraction of metals.
CHAPTER 1. INTRODUCTION

1.1 BACKGROUND

Pollution related to stormwater from non-point sources has been a focus of regulatory agencies and jurisdictions, including state department of transportations. After the revision of Clean Water Act of 1987, regulatory emphasis was given to the issue of non-point source pollution by the National Pollutant Discharge Elimination System, where agencies had to limit the discharge requirements for runoffs in their area. Non-point source runoff includes multiple sources, such as runoff from highways, parking lots, bridges and construction zones. Increase in urbanization and construction results in changing of topography (vegetative cover, grading and impervious surfaces) and stream flow (runoff volume, peak runoff discharge, runoff velocity). Additionally vehicular traffic contributes pollutants to runoff originating from such sources. The primary source of the pollutants are a result of anthropogenic causes – vehicles (fuel, tire and brake linings, exhaust emissions) [1]; roadside structures (guardrails) [1]; atmospheric deposition [2]; construction activity (concrete pours, spills and paints). This runoff from highways is a significant source of pollution for receiving waters like streams, rivers and lakes [3, 4]. Thus structural and non-structural stormwater best management practices (BMPs) are incorporated by agencies to attenuate and mitigate runoff from highways or construction zones. With a growing number of structural BMPs being used, research has been performed on how to select a BMP for a particular site, how to improve designs, and
how to use engineered media in enhancing the quality of effluent that is discharged to the receiving waters.

1.2 RESEARCH MOTIVATION

According to the National Water Quality Inventory Report [5], an assessment of 5.7 million km of rivers and streams [representing 16% of the total in the US] revealed that 44% were found to be impaired, i.e., not able to support one or more of its designated uses. Furthermore, 3% of the assessed streams were considered threatened, with deteriorating water quality. Of all the impaired rivers and streams, the top reported sources of impairment included runoff from agricultural activities, hydro-modification, habitat alteration, unspecified non-point sources, atmospheric deposition, and urban runoff from stormwater [5]. According to the water quality assessment report for Georgia [6], for the 19% of the total rivers and streams [112896 km] that were assessed, 58% were found to be impaired. In all the impaired rivers and streams, the pollutant contribution from non-point sources was highest at 68%, while urban stormwater related runoff contributions to the impairment was second highest, at 25.3%. Also, construction zones can lie in catchments, which are a habitat for threatened or endangered aquatic species. In Georgia, the Georgia Department of Transportation (GDOT) is responsible for managing the states’ roads and highways. For them to maintain the runoff water-quality by limiting contaminant discharge to receiving waters, it is critical to understand several questions regarding runoff originating from highway surfaces in Georgia and performance of installed stormwater BMPs before effective and economical solutions can
be found to treat the pollutants in the highway runoff before the runoff is discharged to receiving waters.

These questions include:

- What are the primary pollutants observed that need remediation before discharge to receiving waters?
- How is the quality of pollutants in the runoff affected by different factors like antecedent dry period and rainfall intensity?
- Is it possible to avoid laboratory analysis of all the pollutants by using surrogate parameters instead?
- How do the water quality indicators behave temporally on GDOT right of way during precipitation events?
- What is the impact of runoff during precipitation events or construction zone runoff on receiving waters?
- How to select a specific stormwater BMP for a particular site?
- What is the performance of existing stormwater BMPs installed either during or post construction?
- How does this performance vary for different pollutants?
- How do design variables affect performance of a BMP?
- How does the performance compare with the performance of other BMPs?
- Do the BMPs help achieve compliance with water quality standards?
- Does the behavior of runoff or receiving water vary temporally?
- Is there a requirement for engineered amendments to improve the performance of BMPs?
These questions form a starting point for the research work and through this dissertation an attempt has been made to address these important and relevant questions so that it could benefit state agencies in tackling highway runoff pollution.

1.3 RESEARCH SCOPE

The scope of work in this research covered the following three areas, as summarized in the following sections.

1.3.1 Stream Water Quality During a Construction Event

In 2007-2008, the Georgia Department of Transportation (GDOT) monitored the water quality of Canton Creek at the intersection of Georgia Highway 20 and Interstate 575 (City of Canton, Georgia, USA) during the active construction phase. Because the Etowah watershed is the habitat for the federally listed threatened Cherokee darter fish, GDOT installed construction Best Management Practices (BMPs) during the active construction phase to mitigate discharge into the receiving stream. In-stream monitoring of the water quality within Canton Creek was performed at five locations (two upstream and three downstream of a discharge culvert under construction) to measure the dissolved oxygen, temperature, turbidity and pH at 15-minute intervals during three phases of the interchange reconstruction and construction of the culvert (before construction, during construction, after construction). Several transient events were observed in the water quality time series. In the present study, temporal analysis of the time series was performed for the three phases of construction using wavelet analysis. The aim was to
determine behavior of water quality indicators across various scales at the five locations during the three phases of construction in order to identify alterations in the water quality that were attributable to the construction activity. Wavelet analysis enabled the partitioning of the water quality signals into different temporal scales such that the short term and long term impact of the construction activities on water quality could be evaluated. It also facilitated the separation of the transient effects due to construction from the more periodic effects of natural processes and hence determine of behavior water quality indicators across various time scales at the five locations during the three phases of construction.

1.3.2 Highway Runoff Characterization and Stormwater Control Performance

Three aspects pertaining to post construction monitoring at our study site were investigated: characterization of the highway runoff quality originating from I-575; assessment of the sand filter performance during precipitation events; and investigation of the behavior of conventional parameters (specific conductivity, temperature and pH) measured in-situ at varying temporal scales using wavelet analysis. The study was conducted to answer several questions pertaining to the runoff originating from highway surfaces in Georgia, including identification of the primary pollutants emanating from Georgia roads that need remediation before discharge to receiving waters, identification of the factors that affect the quality of pollutant concentrations in highway runoff, scope of total suspended solids and total dissolved solids as surrogates for metals and nutrients, determination of the degree of pollution control or effluent quality discharges from the
BMP provide under normal conditions, comparison of the performance as a function of pollutant type, comparison of BMP performance and ability to achieve compliance with water quality standards, comparison of BMP performance with other similar structural BMPs installed elsewhere in United States, analysis of sand filter design parameters compiled from a database to assess their performance in treating highway runoff.

1.3.3 Iron Oxide Coated Sands as Engineered Amendments to Sand Filters

This part of the study was conducted to assess the scope of iron oxide coated sands as amendments in sand filters to improve effluent water quality and thermal pollution which are not being mitigated. Thermal conductivity is the fundamental soil parameter, which needs to be investigated to understand heat transfer processes. While thermal conductivity measurements for soils have been performed for over 60 years, little effort has focused on understanding of the influence of soil coatings on the thermal conductivity of granular materials. In nature, such iron oxide coated soils are formed as a result of chemical weathering and exist as residual soils, primarily in hot and humid climates throughout the world. In the present study, laboratory thermal needle probe tests, based on transient line heat source method, were conducted to investigate the effect of iron oxide coatings on the thermal conductivity of laboratory prepared coated sands. Tests were conducted laboratory prepared on a) uncoated sands b) hematite coated sands and c) goethite coated sands. Effect of density, porosity and stress dependency on the thermal conductivity of coated soils was evaluated. Furthermore, it was observed that sand filters perform well for suspended solids and pollutants attached to solids due to settlement and physical straining. On the other hand, performance of sand filters in
treated dissolved metal pollutants is average. Therefore role of iron oxide coated sands in removing dissolved metals was assessed as metals are one of the most important factors contributing to the pollution due to highway runoff. Batch sorption tests using synthetic stormwater containing three metals – Copper, Lead and Zinc were conducted on laboratory prepared a) uncoated sands b) hematite coated sands and c) goethite coated sands to check the adsorption behavior of coated sands in removing the metals.

1.3.4 Summary of Chapters

A brief summary of the topics covered in the chapters is covered in this section.

1.1.1.1 Chapter 1. Highway Runoff Characterization

The chapter includes

- Post-construction highway runoff monitoring and characterization results for a site in Georgia.
- Hydrology of the monitoring site.
- Initial storm monitoring and first flush characterization of the highway runoff.
- Assessment of environmental factors affecting highway runoff quality at the monitoring site.
- Assessment of total suspended solids and total dissolved solids as surrogates for the estimation of total metal and nutrient concentrations.
- Temporal analysis of the highway runoff quality parameters and correlation using wavelets analysis.
1.1.1.2 Chapter 2. Temporal Behavior of Receiving Water

This chapter includes

- In-situ monitoring results of water quality parameters for a receiving stream during the active phase of construction.
- Temporal analysis of water quality indicators upstream and downstream of a culvert for the periods before, during and after construction.
- Effect of perturbation events like construction pours and precipitation events on the receiving water quality during the active phase of the culvert construction.

1.1.1.3 Chapter 4. Assessment of the Sand Filter Performance

This chapter includes

- Comparison of sand filter performance in pollutant removal with studies conducted elsewhere in the United States.
- Sand filter performance with an emphasis on typical design parameters.
- Monitoring results for a sand filter at an existing site in Georgia.

1.1.1.4 Chapter 5. Thermal Behavior of Iron Oxide Coated Sands

This chapter includes

- Preparation of goethite and hematite coated iron oxide coated sands in the laboratory.
- Effect of applied vertical stress on the thermal conductivity of uncoated and iron oxide coated sands under applied vertical stress in a modified oedometer cell.
- Effect of porosity and dry density on the thermal conductivity of uncoated and iron oxide coated sands.
Comparison of test results for uncoated and iron oxide coated sands with previously conducted studies on pure sands and natural soils.

1.1.1.5 Chapter 6. Metal adsorption by Iron Oxide Coated Sands

This chapter includes

- Results of competitive sorption of metals primarily found in highway runoff by uncoated and iron oxide coated sands.
- Assessment of adsorption constants for uncoated and iron oxide coated sands using Freundlich and linear isotherms.

1.1.1.6 Chapter 7. Conclusion

An overall conclusion of the research work, practical implications and suggestions for future research is covered in this chapter.

1.1.1.7 Appendix

Other research tasks which have been conducted during the course of this study, but not covered in the chapters is included in the appendix.

- Appendix A covers temporal analysis of in-situ water quality indicators for a sand filter measured at the inlet and the outlet of the sand filter.
- Appendix B includes a study conducted for the selection of a site specific stormwater BMP from an array of available BMPs based on user criteria.
- Appendix C covers post construction background sampling results conducted on the Canton Creek to assess the impact of commercial center on the stream water quality.
CHAPTER 2. HIGHWAY RUNOFF: CHARACTERIZATION

2.1 INTRODUCTION

In a comprehensive nationwide study, the quality and effect of urban stormwater runoff across several sites in the United States was investigated [7]. Among several conclusions, it was observed that stormwater runoff contained elevated level of pollutants and was one of the factors responsible for water quality impairment in receiving waters [7]. In other studies, it has been reported that stormwater runoff from non-point sources is one of the major causes of pollution of streams, rivers, and other aquatic bodies in the United States [8-10]. According to the National Water Quality Inventory Report [5], an assessment of 5.7 million km of rivers and streams [representing 16% of the total in the US] revealed that 44% were found to be impaired, i.e., not able to support one or more of its designated uses. Furthermore, 3% of the assessed streams were considered threatened, with deteriorating water quality. Of all the impaired rivers and streams, the top reported sources of impairment included runoff from agricultural activities, hydro-modification, habitat alteration, unspecified non-point sources, atmospheric deposition, and urban runoff from stormwater [5]. According to water quality assessment report for Georgia [6], for the 19% of the total rivers and streams [112896 km] that were assessed, 58% were found to be impaired. In all the impaired rivers and streams, the pollutant contribution from non-point sources was highest at 68%, while urban stormwater related runoff contributions to the impairment was second highest, at 25.34%.
As a result, to prevent pollution of receiving waters during or post-construction, structural and non-structural best management practices are constructed to either attenuate or treat stormwater runoff before being discharged to receiving waters. Post-construction stormwater controls can be divided into several categories on the basis of the primary method of treatment. These include gravity settling and floatation - detention ponds, retention ponds, wetlands, tanks and vaults [11-14], filtration and sorption – media filters, biofilters, compost filters [14-17], infiltration – infiltration trenches, infiltration basins, porous pavement, swales [18-20], biological – biofilters [21, 22], wetlands, proprietary – wet vaults, vortex separators, modular wetland systems [21, 23-25].

GDOT has installed a variety of stormwater BMPs to attenuate and treat pavement runoff, with an emphasis on the removal of post-development total suspended solids loadings in the water quality volume (first 3.05 cm of rainfall) by 80%, as measured on an average annual basis [26]. The concentration of total suspended solids was selected as a representative stormwater pollutant because, along with being a good indicator of pollution (solids concentration and attached pollutants), it can be easily removed by settling and filtration.

As a part of the ongoing efforts with regards to non-point source pollution, GDOT installed a stormwater BMP (sand filter) during a major interchange reconstruction project located on I-575 and State Road 20 (SR-20) in the City of Canton, Cherokee County, GA. Motivation for the construction of the Canton sand filter was to limit roadway runoff to the habitat of the Cherokee darter fish, which is a threatened species endemic to the Etowah river system in North Georgia. The sand filter was constructed under an agreement between GDOT and the U.S. Fish and Wildlife Service. This study addresses three objectives in relation to the Canton BMP: 1) assess the quality of the
post-construction highway runoff quality at this site and compare it with existing state and federal standards for freshwater, including factors affecting highway runoff quality (i.e., antecedent dry period, rainfall intensity, and the role of total suspended solids and total dissolved solids as surrogate parameters are also investigated); 2) evaluate sand filter performance in reduction of concentrations of selected parameters between the inlet and outlet of the sand filter, evaluation of design parameters and comparison of sand filter performance with studies conducted in other parts of the country; and 3) temporal scale based analysis of continuously collected in-situ water quality indicators (pH, specific conductivity and temperature) during the monitoring program. Wavelet analysis was used as a tool to investigate the behavior of continuously collected stormwater runoff data because temporal analysis of stormwater data can give insight into important processes involved during a storm event (i.e., runoff, indicator water quality pollutants, and correlations among the different variables). This chapter covers only objective 1 and objective 3 through discussion of highway runoff quality characterization. Objective 2, which includes assessment of sand filter performance, will be covered in detail in chapter 5.

2.2 METHODOLOGY

2.2.1 Site Description

The site selected for monitoring stormwater runoff was located in the City of Canton, Cherokee County, Georgia (Figure 1) on the I-575 at SR-20. I-575 is a 50 km long interstate spur located in north Georgia (Inset 4a), which connects the Atlanta metropolitan area with the north Georgia mountains. It has a high traffic volume, with an annual average daily traffic of 56,100 (2007) at the section (Inset 4b) of the highway where this site was located. GDOT, which manages I-575, modified a 2.4 km segment of I-575 during a major interchange reconstruction project between I-575 and SR-20 in
2007-08. As a part of the project, GDOT also installed a stormwater BMP (sand filter) (Inset 4c) to attenuate stormwater runoff from I-575 and to mitigate suspended solids loading on Canton Creek, which received the effluent. The motivation for the construction of the Canton sand filter was to limit highway runoff to the habitat of the Cherokee darter fish, which is a threatened species endemic to the Etowah river system in North Georgia. Thus, post construction stormwater runoff from I-575 was monitored to study the highway runoff characteristics at this site.

Figure 1. BMP Location. Inset 4a shows its location in Canton, Cherokee County, Georgia. Inset 4b shows I-575 ramp from which highway runoff quality was collected and assessed. Inset 4c shows the sand filter post a precipitation event.
Table 1 summarizes the physical characteristics of this site. The surrounding land use at this site is mixed residential and commercial. Adjacent land does not contribute to the highway runoff during a storm event. I-575 is a four lane asphalt highway with two lanes running in each direction. Also there are two concrete ramps, a diamond exit ramp from I-575 northbound to SR 20, as well as a southbound diamond entrance ramp from SR 20 to I-575 southbound. The runoff originating from the 81179.9 m² asphalt-concrete highway catchment during an event is collected by the storm drain system and discharged into the stormwater BMP.

Table 1. Study Site Description

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drainage area</td>
<td>81179.9 m²</td>
</tr>
<tr>
<td>Imperviousness</td>
<td>&gt; 90%</td>
</tr>
<tr>
<td>Pavement Type</td>
<td>Concrete, Asphalt</td>
</tr>
<tr>
<td>Runoff Coefficient</td>
<td>0.65</td>
</tr>
<tr>
<td>Average Annual Daily Traffic</td>
<td>56100</td>
</tr>
<tr>
<td>Average Annual Rainfall</td>
<td>1366.27 mm</td>
</tr>
<tr>
<td>Surrounding Land Use</td>
<td>Commercial, Residential</td>
</tr>
</tbody>
</table>

2.2.2 BMP Description

The constructed sand filter is located adjacent to I-575 and lies within the GDOT right of way. During the construction phase of the interchange reconstruction project, it was used as a temporary sedimentation basin to collect construction runoff and stormwater runoff before being discharged into Canton creek. Post construction, it receives stormwater runoff directly from I-575 before it discharges the attenuated and treated runoff into Canton Creek (Table 2).
Table 2. Canton BMP Description

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMP Test Site Name</td>
<td>Canton Sand Filter</td>
</tr>
<tr>
<td>BMP Type</td>
<td>Well defined inlets and outlets</td>
</tr>
<tr>
<td>Treatment Category</td>
<td>Runoff attenuation, Sedimentation, Filtration</td>
</tr>
<tr>
<td>BMP Volume</td>
<td>15,282 m$^3$</td>
</tr>
<tr>
<td>Inlets, Intermediate, Outlets</td>
<td>3,1,1</td>
</tr>
<tr>
<td>Inlet Description</td>
<td>2 concrete pipes (1.22 m, 0.61m), 1 concrete channel</td>
</tr>
<tr>
<td>Intermediate Description</td>
<td>1 concrete pipe (0.91 m)</td>
</tr>
<tr>
<td>Outlet Description</td>
<td>1 concrete pipe (1.22 m)</td>
</tr>
<tr>
<td>Catchment Area</td>
<td>90,933 m$^2$</td>
</tr>
<tr>
<td>Regional Watershed</td>
<td>Etowah</td>
</tr>
<tr>
<td>Upstream BMP</td>
<td>Inflow received directly from I-575</td>
</tr>
<tr>
<td>Downstream BMP</td>
<td>Effluent discharged to Canton Creek</td>
</tr>
</tbody>
</table>

The sand filter consists of two sections. The first section consists of a sedimentation basin to settle heavy solids. It collects highway runoff from 3 inlets – two storm drain pipes and a single concrete flume. Inlets 1, 2 and 3 have catchment areas 71022.3 m$^2$, 1416.4 m$^2$ and 8741.21 m$^2$ respectively. Thus, major contribution to the influent volume is from Inlet 1. The sedimentation basin is separated from the sand filter by a rock filter dam which temporarily holds the runoff in the sedimentation basin. The sedimentation basin is connected to the sand filter via a 91.4 cm diameter concrete pipe which drains the temporary held runoff in the sedimentation basin to the sand filter. This intermediate location works as the inlet to the sand filter. The second section of the BMP consists of a sand filter. The sand filter consists of three layers— a 15.2 cm top compost layer, a 53.3 cm thick sand filter bed at the center overlying a variable thickness gravel layer with a minimum thickness of 22.8 cm at the bottom. An underdrain system
consisting of 15.2 cm diameter perforated poly vinyl chloride pipes collects the filtered effluent and discharges it to Canton Creek via a 121.92 cm diameter concrete pipe.

Figure 2. Sampling locations at the Canton Creek sand filter. Inset 2a shows the plan of the sand filter. Inset 2b shows the profile of the sand filter.

2.2.3 Monitoring Program

For the stormwater monitoring program, three automatic samplers (Sigma 900 MAX PS1 Portable Automatic Sampler) were used. Each automatic sampler was equipped with four one-gallon polyethylene bottles for sample collection. Flow was measured with an integral HACH Sigma Area-Velocity flow meter (#4041) using a pressure transducer for depth of flow measurement and a pair of ultrasonic transducers for velocity measurement. The area-velocity sensors were installed and secured at the
base of the pipes. In-situ parameters pH, specific conductance (SC), and temperature (T) were measured with an integral pH-temperature probe (Hach, #8793), and integral conductivity probe (Hach, #3227). The three sensors were also securely placed at the base of the pipes to continuously record the three parameters. Rainfall depths at the site were measured with a tipping bucket rain logger (Sigma). In-situ parameters (temperature, conductivity, pH, flow depth and rainfall) were recorded at an interval of 5 minutes throughout the duration of an event. The recorded data were transferred to a personal computer using Hach Insight software. Stormwater samples were collected for each sampler using three bottles to capture the first flush for the first 30-45 minutes of the storm. In the fourth bottle, 200 ml grab samples were collected at an interval of 15 minutes for the whole event. Sample collection was automated, and the triggering condition for the initiation of the sample collection was set as 2.5 cm of flow depth. This was selected to ensure that the intake pipe was sufficiently submerged to collect an accurate volume of the sample. The mouth of the intake pipe had a strainer to prevent clogging of the intake pipe, and the samples were collected by a peristaltic pump. The sampler controller was programmed to rinse the intake pipe once before the collection of a sample.
A total of twelve events were monitored over the course of the study (Table 3).

Table 3. Rainfall Events

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Antecedent Dry Period (days)</th>
<th>Rainfall Depth (mm)</th>
<th>Rainfall Duration (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7/13/2010</td>
<td>3</td>
<td>27.94</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>2/25/2011</td>
<td>15</td>
<td>12.30</td>
<td>2.92</td>
</tr>
<tr>
<td>3</td>
<td>2/28/2011</td>
<td>3</td>
<td>18.03</td>
<td>2.92</td>
</tr>
<tr>
<td>4</td>
<td>3/5/2011</td>
<td>5</td>
<td>46.70</td>
<td>29.33</td>
</tr>
<tr>
<td>5</td>
<td>3/9/2011</td>
<td>3</td>
<td>81.50</td>
<td>15.58</td>
</tr>
<tr>
<td>6</td>
<td>3/15/2011</td>
<td>5</td>
<td>28.10</td>
<td>7.00</td>
</tr>
<tr>
<td>7</td>
<td>3/26/2011</td>
<td>2</td>
<td>40.10</td>
<td>15.17</td>
</tr>
<tr>
<td>8</td>
<td>4/4/2011</td>
<td>3</td>
<td>40.30</td>
<td>3.50</td>
</tr>
<tr>
<td>9</td>
<td>4/11/2011</td>
<td>6</td>
<td>10.60</td>
<td>2.67</td>
</tr>
<tr>
<td>10</td>
<td>4/15/2011</td>
<td>3</td>
<td>57.40</td>
<td>8.58</td>
</tr>
<tr>
<td>11</td>
<td>5/3/2011</td>
<td>5</td>
<td>7.11</td>
<td>10.0</td>
</tr>
<tr>
<td>12</td>
<td>6/24/2013</td>
<td>6</td>
<td>10.16</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Due to the large number of monitoring locations (three inlets, one intermediate and one outlet location), it was impractical to measure all the locations simultaneously. All three inlets were assessed during events E1, E11 and E12. During event E1, 4 manual grab samples were taken at 15, 30 and 45 minutes at each inlet location, along with the first sample, which was collected as soon as the flow was observed at the inlets. For the event E11, automatic grab samples were collected at an interval of 5, 15 and 30 minutes after the initiation of automatic sampling. For E12, all three inlets were monitored using in-situ sensors. Inlet 1 was selected as representative of the three inlets because it received runoff from the largest catchment area and discharged the greatest volume of stormwater of the three inlets. To evaluate the stormwater control performance, monitoring was carried out at Inlet 1, the intermediate location between the sedimentation basin and the sand filter, and the outlet of the sand filter. Apart from the in-situ parameters that were recorded continuously, the automatically collected samples were
brought from the site to the Geo-environmental laboratory at the Georgia Institute of Technology within 24 hours (usually with 12 hours) after the completion of sampling program to avoid sample deterioration. The samples were preserved for testing as per procedures for different water quality parameters [27]. An adequate volume of a sample was passed through a 45μm filter paper and preserved separately to test for dissolved parameter concentrations. The runoff samples were tested for total suspended solids, turbidity, specific conductivity, pH, total dissolved solids, nutrients (total nitrogen, nitrate and nitrite and total phosphorous) and metals (total cadmium, total copper, total lead, total zinc, dissolved cadmium, dissolved copper, dissolved lead and dissolved zinc). Samples were analyzed for metals using Perkin Elmer Optima 7300 DV Inductively Coupled Plasma Optical Emission Spectrometer (ICP-OES). Nutrients were measured using a Shimadzu UV-1800-Vis Spectrophotometer. All lab ware, sample bottles and intake tubing utilized for testing or collection of samples were rinsed with 1% nitric acid (HNO₃ and de-ionized water (Barnstead, E-pure).

2.2.4 Wavelet Analysis

In-situ water quality indicator data (temperature, pH, and conductivity) that are collected continuously during a storm event consist of a series of discrete observations representing a time series, or a signal, which carry information regarding various processes within a system. Such dynamic environmental signals are non-stationary as a result of internal processes and external perturbations. Effect of processes on the system can vary either spatially and temporally. In non-stationary signals, the statistical parameters of the signal, such as the mean and variance, do not remain constant through time. Wavelet analysis is a signal processing technique that enables extraction of both time and frequency content from a multi-scale, non-stationary signal [28-30]. The
wavelet analysis procedure involves decomposing the original time series with a wavelet function which results in wavelet coefficients. The wavelet coefficients are indicative of the correlation between the collected data and the wavelet function. In the past few years wavelet transform has emerged as a frequently used method of dynamic analysis of signals. In this study, methodology suggested by Torrence and Compo, Grinsted [31, 32] is used in which the continuous wavelet transform is obtained by decomposing the recorded data set \( D(t) \) with a wavelet function \( \psi(t) \), resulting in generation of coefficients \( W \) [31]. The coefficients are an indicator of correlation between the wavelet function and the signal. In this study, the Morlet wavelet is used:

\[
\psi_0(\eta) = \pi^{-1/4} e^{i \omega_0 \eta} e^{-\frac{1}{2} \eta^2}
\]

where \( \omega_0 \) is dimensionless frequency and \( \eta \) is dimensionless time [31]. \( \omega_0 = 6 \) was selected as it provides a good trade-off between time and frequency localization.

Local and Global Power Spectrum

The continuous wavelet transform of a time series \( (x_n, n = 1, \ldots, N) \) with uniform time steps \( \delta t \) is defined as the convolution of \( x_n \) with scaled and normalized wavelet [31]. Hence

\[
W_n^X(s) = \sqrt{\frac{\delta t}{s}} \sum_{n=1}^{N} x_n \psi_0 \left[ \left( n' - n \right) \frac{\delta t}{s} \right]
\]

Wavelet power is defined as \( \left| W_n^X(s) \right|^2 \). The continuous wavelet transform has edge artifacts because the wavelet is not completely localized in time. Therefore, a cone of influence is used in which edge effects cannot be ignored [31]. The cone of influence can be described as the area in which the wavelet power caused by a discontinuity at the edge
has dropped to $\epsilon^2$ of the value at the edge [31]. The power spectrum obtained provides variance of the time series in both time and frequency domains and can be called as a local power spectrum. This spectrum can be averaged along the time axis to calculate the global power spectrum:

$$W^2(a,b) = \frac{1}{N} \sum_{n=0}^{N-1} |W_n(a,b)|^2$$

The distribution of the local wavelet power spectrum at each time $t$ and scale $a$ is given by:

$$\frac{|W_n(a,b)|^2}{\sigma^2} \Rightarrow \frac{1}{2} P_k \chi^2_2$$

Where, $\sigma^2$ is the variance, $\chi^2$ is the chi-square value obtained for the chosen confidence level, $P_k$ is the mean spectrum at the Fourier frequency $k$ that corresponds to $a$. For the red noise background spectrum, $P_k$ is obtained as:

$$P_k = \frac{1 - \alpha^2}{1 + \alpha^2 - 2\alpha \cos(2\pi k/N)}$$

Where $\alpha$ is the assumed lag-1 autocorrelation coefficient is taken here to be 0.72. Red background spectrum is used to calculate the confidence intervals for the contour lines of the local wavelet power spectrum [31].

Cross Wavelet Transform

The physical relationship between two signals in the time frequency domain can be obtained using wavelet cross spectrum analysis. A wavelet cross-spectrum provides the
opportunity to quantify the correlation between the wavelet power spectrums of two variables \((D_1, D_2)\):

\[
p_{D_1D_2}(a,b) = W_{D_1}^{*}(a,b) W_{D_2}(a,b)
\]

Circular mean of the phase over regions with higher than 5% statistical significance that are outside the cone of influence to quantify the phase relationship. The circular mean for a set of angles \(\{a_i, i = 1...n\}\) is defined as [32]:

\[
a_n = \text{arg}(D_1, D_2) \text{ with } D_1 = \sum_{i=1}^{n} \cos(a_i) \text{ and } D_2 = \sum_{i=1}^{n} \sin(a_i)
\]

**Wavelet Coherence**

Cross wavelet power reveals areas with high common power. Wavelet coherence of two time series can be calculated as [32]:

\[
R^2_n(s) = \frac{|S\left(s^{-1}W_{D_1D_2}^{D_1D_2}(s)\right)|^2}{S\left(s^{-1}W_{D_1}(s)\right)^2 \cdot S\left(s^{-1}W_{D_2}(s)\right)^2}
\]

\[
S(W) = S_{\text{scale}}\left(S_{\text{time}}\left(W_n(s)\right)\right)
\]

\[
S_{\text{time}}(W) = \left(W_n(s) * c_1 \frac{s^{-1}}{s^2}\right)_t
\]

\[
S_{\text{time}}(W) = \left(W_n(s) * c_2 \Pi(0.6s)\right)_n
\]

Where \(c_1\) and \(c_2\) are normalization constants and \(\Pi\) is the rectangle function. The factor of 0.6 is the empirically determined scale decorrelation length for the Morlet wavelet. Wavelet coherence gives areas of correlation between two parameters.
2.3 RESULTS AND DISCUSSION

Twelve events were monitored during the course of this study, with varying antecedent dry periods, total rainfall, duration, and rainfall intensities (Table 3). All but two events were monitored between the months of February 2011 through May 2011. Event 1 was monitored in July 2010, while Event 12 was monitored in June 2013.

2.3.1 Highway Runoff Characteristics

2.3.1.1 Hydrology

The rainfall depth recorded at the site varied between 0.71 cm and 8.15 cm and the rainfall durations at the site varied between relatively short events (0.77 hours) to long events (29.33 hours). Hydrograph and hyetograph for highway runoff recorded at inlet 1 and the outlet for two selected events (E8 and E9) are presented in Figure 3.

The rainfall depth recorded for the two events was 40.3 mm and 10.6 mm respectively. Small lag time and the sharp rising and falling limbs of the runoff recorded at the inlet is indicative of quick response of the catchment and accelerated rate of runoff flows at modified, or urban sites [33]. For the event E8, the peak discharge at the inlet was 0.75 m3/s, whereas for E9 the discharge was 0.19 m3/s. The peak flow for the two events at the outlet of the structure was reduced by 82% and 89% respectively. Furthermore, there was a delay in the peak flow at the outlet by 215 and 290 minutes respectively. Flow at the inlet for the two events lasted for 255 and 270 minutes in both the events. Whereas flow at the outlet persisted for a considerably longer period of time in both the events. Thus, the outlet hydrograph indicates that the peak flows were being
successfully attenuated in the stormwater control. For some events, the total drawdown time in the stormwater control was higher than the design residence time of 24 hours. Also, events showed that the rainfall amount affected the total retention time between the inlet and the outlet, where the retention time was higher for smaller events. The results of events E8 and E9 are typical of events monitored at the site. Quick response of the catchment is important to consider especially during the intial part of the storm as temperature uptake from highway surfaces during day time and pollutant concentrations after prolonged antecedent dry periods can lead to acute effects on receiving waters. For this site, successful detention indicates that particle associated pollutants can be removed by primarily by settling.
Figure 3. Hydrology data for events 8 and 9. It includes discharge measured at inlet and outlet of the BMP and rainfall data.
2.3.1.2 Initial Storm Monitoring

During event E1 and E11, the three inlets of the BMP were monitored to assess the quality of highway runoff entering the stormwater control, especially during the initial phase of the runoff. This phase is associated with higher concentrations of total pollutants during the buildup in the intervening antecedent dry period between two events [34, 35]. Runoff during E1 was characterized using grab samples taken at 15 minute intervals for the first 45 minutes of the storm. Additionally, the three inlets were also monitored using automated samplers during E11 at 5, 15 and 30 minutes after initiation of flow, with measurement of total suspended solids, turbidity, specific conductivity and pH (Table 4). Total suspended solids results for E1 indicated a significant reduction in the concentration in the inflow within the first 45 minutes of the event for all the inlet locations. Additionally, inlet 1 had the highest observed concentration for total suspended solids (144.13 mg/L) in the first 15 minutes followed by inlets 3 (99.2 mg/L) and 2 (71 mg/L) respectively. Total suspended solids results for E11 could not be obtained as the volume of the collected sample was insufficient for a total suspended solids analysis. For turbidity, a decrease in the concentration was observed for the first 15 minutes during events E1 and E11. Again, maximum turbidity was observed for inlet 1 (45.46 NTU) followed by inlets 3 and 2 respectively. No consistent trend for the remaining period of the monitored storm was observed. High total suspended solids and turbidity concentrations during the first 15 minutes of the storm are indicative of mobilized particles due to a sudden burst of rainfall [36]. As the runoff volume increases with the rising limb, there is a decrease in the concentration of particles. For E1, a drop in
conductivity was observed for the first 15 minutes for the three inlets. This could be a result of contribution from the immediate vicinity of the catchment. For the remainder of the monitored storm during E1, an increase in conductivity was observed. For E11, inlet 1 showed an increase in conductivity. Specific conductivity is an estimate of the amount of total dissolved solids present in water. This indicates that after the initial burst of rainfall there was an increase in the concentration of dissolved solids in the runoff.

Additionally, pH variation for the first 45 minutes for events E1, E8, E9 and E10 at three inlets did not show any trend. Though, in event E1 the runoff was slightly acidic and varied between 6.5 and 7. In events E8, E9 and E10 the runoff was basic with pH varying between 8 and 9.1.

Table 4. First Flush Results for Event 1 and 11

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Time (min)</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0-5</td>
<td>15</td>
<td>30</td>
<td>45</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>104.78</td>
<td>10.71</td>
<td>4.95</td>
<td>1.15</td>
</tr>
<tr>
<td>C (µS/cm)</td>
<td>106.5,133.5¹</td>
<td>63.2,134.4¹</td>
<td>82.1,163.4¹</td>
<td>103.7,137.7²</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>2.0</td>
<td>1.85</td>
<td>1.5</td>
<td>1.85²</td>
</tr>
<tr>
<td>NOx (mg/L)</td>
<td>0.82</td>
<td>0.85</td>
<td>0.72</td>
<td>0.84²</td>
</tr>
<tr>
<td>TCu (µg/L)</td>
<td>5.6</td>
<td>5</td>
<td>5.3</td>
<td>5.6²</td>
</tr>
<tr>
<td>TPb (µg/L)</td>
<td>0.64</td>
<td>0.72</td>
<td>0.33</td>
<td>0.75²</td>
</tr>
<tr>
<td>TZn (µg/L)</td>
<td>11.4</td>
<td>15.85</td>
<td>9.5</td>
<td>11.65²</td>
</tr>
</tbody>
</table>

¹ Event 11
² Event Mean Concentration

Parameter values are mean values for locations 1,2 and 3 unless specified.
2.3.1.3 Highway Runoff Characterization

Highway runoff water quality parameters were analyzed for selected pollutants in samples collected at the inlet of the stormwater control, and compared with existing Georgia water quality criteria and other highway runoff characterization studies conducted in the United States (Table 5). Each mean value for a parameter represents an average value of all the individual storm events EMCs. The mean pH values were marginally higher than Georgia water quality criteria for freshwater indicating slightly basic nature of runoff from I-575. Mean values for rest of the parameters were within limits for freshwater criteria. Mean values for the pollutants compared with other studies of comparable annual average daily traffic indicated that pollutant concentrations at the current site were lower than other sites. Mean total suspended solid values measured at the site were 3.5 to 4.4 times lower than mean value for total suspended solids in the two national studies (Table 5). Additionally, results for total and dissolved fractions of metals indicate lower concentrations as compared with other studies (Table 5). Dissolved lead was not detected in the runoff in any of the storm events. An important thing to note here is that contribution of the dissolved fraction of metals is quite low as compared to the total metal concentrations, indicating that > 50% total metal concentration measured can be attributed to particle associated concentrations. This is an encouraging trend for this site as removal of metals is facilitated by settling or straining the particle attached pollutants in the influent. Mean total nitrogen concentration, for influent was high as compared with the national study (Table 5). A similar trend was observed for mean nitrates and nitrites concentration, although mean total phosphorous concentration
measured at the site was lower than mean concentrations measured in the national studies.

Table 5. Water Quality Data Along With Selected Studies from Other Parts of US

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean</th>
<th>Median</th>
<th>CoV</th>
<th>WQ Criteria</th>
<th>National Data</th>
<th>California</th>
<th>Texas</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS (mg/L)</td>
<td>40.71</td>
<td>32.11</td>
<td>0.87</td>
<td>-</td>
<td>142</td>
<td>180</td>
<td>117.8</td>
</tr>
<tr>
<td>TDS (mg/L)</td>
<td>79.04</td>
<td>80.58</td>
<td>0.29</td>
<td>-</td>
<td>-</td>
<td>87.3 - 135.6</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity (NTU)</td>
<td>39.49</td>
<td>20.02</td>
<td>1.09</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>T (°C)</td>
<td>15.76</td>
<td>16.33</td>
<td>0.13</td>
<td>&lt; 32.2</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>pH</td>
<td>8.66</td>
<td>8.55</td>
<td>0.05</td>
<td>6 - 8.5</td>
<td>-</td>
<td>6.7 - 7.4</td>
<td>-</td>
</tr>
<tr>
<td>SC (μS/cm)</td>
<td>118.51</td>
<td>120.88</td>
<td>0.29</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TPb (μg/L)</td>
<td>6.74</td>
<td>7</td>
<td>0.7</td>
<td>30(1.2)</td>
<td>400</td>
<td>182</td>
<td>33.0</td>
</tr>
<tr>
<td>DPb (μg/L)</td>
<td>ND</td>
<td>ND</td>
<td>ND</td>
<td>-</td>
<td>-</td>
<td>4.9</td>
<td>-</td>
</tr>
<tr>
<td>TCu (μg/L)</td>
<td>34.23</td>
<td>26.06</td>
<td>0.660</td>
<td>-</td>
<td>-</td>
<td>10.1</td>
<td>-</td>
</tr>
<tr>
<td>DCu (μg/L)</td>
<td>10.31</td>
<td>14</td>
<td>0.96</td>
<td>-</td>
<td>-</td>
<td>2.8</td>
<td>-</td>
</tr>
<tr>
<td>TZn (μg/L)</td>
<td>110.98</td>
<td>103.15</td>
<td>0.24</td>
<td>-</td>
<td>329</td>
<td>202</td>
<td>507</td>
</tr>
<tr>
<td>DZn (μg/L)</td>
<td>17.31</td>
<td>12</td>
<td>0.72</td>
<td>-</td>
<td>-</td>
<td>416</td>
<td>-</td>
</tr>
<tr>
<td>TN (mg/L)</td>
<td>2.22</td>
<td>1.85</td>
<td>0.39</td>
<td>-</td>
<td>2.59</td>
<td>1.9</td>
<td>-</td>
</tr>
<tr>
<td>NOx (mg/L)</td>
<td>0.884</td>
<td>0.84</td>
<td>0.23</td>
<td>0.76</td>
<td>0.86</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>TP (mg/L)</td>
<td>0.283</td>
<td>0.237</td>
<td>0.4</td>
<td>0.43</td>
<td>0.42</td>
<td>-</td>
<td>0.33</td>
</tr>
</tbody>
</table>

1. ND = Not Detected
2. Georgia Water Quality Criteria
3. AADT = 30,000 [37]
3a. Phosphorous as orthophosphate
4. [7]
5. [38]
6. AADT = 58,150 [39]
7. AADT = 43,000 [40]
8. Inputs on California and Texas data [41]
2.3.1.4 Factors Affecting Highway Runoff

Simple linear regression and multiple linear regressions were performed to assess the effect of antecedent dry period (ADP) and rainfall intensity (RI) on the measured pollutant concentrations. The results for simple linear regression between parameters and antecedent dry period indicated low $R^2$ values (0 – 0.42). This is in agreement with previous studies where correlation between antecedent dry period and pollutant concentrations could not be established [42]. In the intervening dry period between two storms, there is a process of net pollutant build up (i.e., there is an accumulation of pollutants on the pavement surface as well as competing process of pollutant removal) [3]. In case of correlation between the pollutant concentrations and rainfall intensity, good correlation was found for TSS, turbidity, and total phosphorus (TP). The results were statistically significant at a confidence level of 90% ($p < 0.1$). For other pollutants, no, or very weak, correlations were observed with rainfall intensity. While some studies have found a positive correlation between pollutant concentrations and storm intensity, other studies indicate a negative correlation. Increase in pollutant washoff with increasing rainfall intensity is ascribed to the fact that many pollutants are associated with particles, which are more easily mobilized in high intensity storms. Metals and organic compounds are among the pollutants associated with particles in the runoff, and therefore would be expected to be positively correlated with rainfall intensity. It is generally accepted that constituent load (i.e., mass of constituent removed from highway per unit time and/or area is positively correlated with rainfall intensity). Incorporating the effect of both antecedent dry period and rainfall intensity resulted in improved correlations. $R^2$ values
for TSS improved to 0.79. The results were statistically significant at a confidence level of 90% (p < 0.1). Furthermore, improved correlations were observed for total nitrogen, nitrates, and nitrites and total phosphorus concentrations with R² values 0.79, 0.61 and 0.78, respectively. Total nitrogen and total phosphorus were statistically significant at the 90% confidence level. No change in correlations was observed for metals as R² were between 0.04 for total zinc (TZn) and 0.3 for total copper (TCu). This shows that there is a very poor correlation between metal concentrations and antecedent dry period as well as rainfall intensity.

Table 6. Factors Affecting Highway Runoff Quality

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Effect of ADP</th>
<th>Effect of RI</th>
<th>Effect of ADP and RI</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R²</td>
<td>P</td>
<td>R²</td>
</tr>
<tr>
<td>TSS</td>
<td>0.008</td>
<td>0.86</td>
<td><strong>0.77</strong></td>
</tr>
<tr>
<td>Turbidity</td>
<td>0.04</td>
<td>0.7</td>
<td><strong>0.65</strong></td>
</tr>
<tr>
<td>TDS</td>
<td>0.37</td>
<td>0.2</td>
<td><strong>0.52</strong></td>
</tr>
<tr>
<td>TCu</td>
<td>0.12</td>
<td>0.49</td>
<td>0.2</td>
</tr>
<tr>
<td>TPb</td>
<td>0.26</td>
<td>0.29</td>
<td>0.017</td>
</tr>
<tr>
<td>TZn</td>
<td>0.02</td>
<td>0.79</td>
<td>0.023</td>
</tr>
<tr>
<td>TN</td>
<td>0.42</td>
<td>0.16</td>
<td>0.31</td>
</tr>
<tr>
<td>NOx</td>
<td>0.23</td>
<td>0.33</td>
<td>0.33</td>
</tr>
<tr>
<td>TP</td>
<td>0.0002</td>
<td>0.97</td>
<td><strong>0.78</strong></td>
</tr>
</tbody>
</table>
2.3.1.5 Solids as Surrogate Parameters

Total suspended solids in highway runoff is of particular interest due to the tendency for contaminants to sorb to the surface of suspended solids. Simple and multiple linear regression analysis using a linear model was performed using total suspended solids and total dissolved solids as predictor variables to estimate metal (TPb, TZn, TCu) and nutrient (TN, NOx, TP) concentrations. Correlation plots show that nearly all measured parameters were positively correlated with TSS, with nutrients showing a stronger correlation. Copper and lead demonstrated no correlation with suspended solids, while zinc had a slight positive correlation with suspended solids. A multiple regression analysis could improve the variance explained by the simple linear regression models by relating and identifying possible contaminant equilibria between the suspended and dissolved solid fractions.

Table 7. Total Suspended Solids and Total Dissolved Solids as Surrogate Parameters

<table>
<thead>
<tr>
<th>Parameters</th>
<th>TSS</th>
<th>TSS and TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$y = a + bx$</td>
<td>$R^2$</td>
</tr>
<tr>
<td>TCu</td>
<td>38.46-0.21TSS</td>
<td>0.09</td>
</tr>
<tr>
<td>TPb</td>
<td>7.13+0.02TSS</td>
<td>0.02</td>
</tr>
<tr>
<td>TZn</td>
<td>96.6+0.27TSS</td>
<td>0.12</td>
</tr>
<tr>
<td>TN</td>
<td>1.26+0.02TSS</td>
<td>0.56</td>
</tr>
<tr>
<td>NOx</td>
<td>0.66+0.005TSS</td>
<td>0.71</td>
</tr>
<tr>
<td>TP</td>
<td>0.12+0.002TSS</td>
<td>0.62</td>
</tr>
</tbody>
</table>
2.3.2 Wavelet Analysis

2.3.2.1 Time-Frequency Analysis

Local wavelet spectrum and global wavelet spectrum for a selected event (E10 and E11) is presented for four parameters (temperature, pH, specific conductivity and flow depth) recorded at the inlet using in-situ sensors in Figure 4 and Figure 5. Original collected data is plotted for the duration of time for which flow was observed at the inlet. Two significant bumps were observed in the original temperature data in the first 2 hrs of the recorded data. The rise in temperature of inflow was approximately 0.7 °C and 1.5 °C during the significant fluctuations. This increase in temperature corresponds with the sudden increase in flow depth due to a burst of rainfall. Rise in temperature can be indicative of heat uptake by the runoff from the pavement surface, although there can be cooling down effects due to flow in drain pipes [43]. pH exhibited a dominant frequency throughout the recorded event. The pH of the runoff recorded was basic and, excluding the first hour of the runoff in which the pH rose to greater than 9, the pH fluctuated between 7.5 and 8.5. For specific conductivity, which is a measure of the presence of free ions in the runoff, a significant drop was observed during the initial phase of the storm. The drop in concentration corresponded with the flow depth and decreased from 131 µS/cm to 19 µS/cm during this phase. After the initial burst, a gradual stabilization in conductivity was observed. During the initial burst of rainfall, advection was more rapid than dissolution of ions, which resulted in a drop in the conductivity. However, as flow
reduced and ion dissolution increased, the net result was an increase in specific conductivity [44].

Figure 4. Local and global wavelet spectrum plots for event 10. From left to right, original signal, local wavelet spectrum and global wavelet spectrum plots for event 10. Four parameters – temperature, pH, conductivity and flow depth are depicted.
Figure 5. Local and global wavelet spectrum plots for event 12. From left to right, original signal, local wavelet spectrum and global wavelet spectrum plots for event 12. Four parameters – temperature, pH, conductivity and flow depth are depicted.
According to the local wavelet spectrum Figure 4, for temperature and pH, three observations can be made. One, increasing power is seen for the 10 to 80 minute band for the first 4 hours of the event in temperature series. This power is above the 5% significance level. Similar relatively higher power is observed for pH, although it is not significant at the 5% level. Two, a relatively low power but significant 10 – 20 minute band is observed throughout the event for temperature. This significant but high power band is also observed for pH indicating there might be a relationship between pH and temperature at this time period. Also, this indicates an important temporal scale for this catchment for the two parameters indicative of physico-chemical reactions and perturbations. From conductivity and flow depth local wavelet spectrums indicate an increase in power with increasing period even though for conductivity it not above the 5% significance. The flow depth is significant and exhibits higher power during the initial part of the storm. The relationship between parameters is examined next with cross wavelet spectrum and wavelet coherence. The increase in power for all the parameters can be observed clearly by the variance plots which show an increasing trend. Local peaks in temperature and pH data can be observed at the 16 minute period. Furthermore, it can be observed if we see the trend across time that wavelet power is higher during the initial part of the storm for all parameters. This indicates the importance of water quality parameters during the initial part of the precipitation event. Local and global wavelet spectrums for E11 are also depicted but the wavelet power observed is low due to low fluctuations in the data. However, global wavelet spectrum indicates and increasing trend, similar to E10.
2.3.2.2 Cross Wavelet Transform and Wavelet Coherence

Cross wavelet transform and wavelet coherence can be used to examine relationships between different parameters in the time-frequency space, and is helpful to establish causal relationships between the water quality indicators. In Figure 6, cross wavelet transform and wavelet coherence have been presented for temperature-flow depth, pH-flow depth and specific conductivity-flow depth. Similarly, in Figure 7 cross wavelet transform and wavelet coherence is presented for temperature-pH, pH- specific conductivity and specific conductivity- temperature. A cross wavelet transform gives regions of high common power in the time-frequency space. It also provides phase relationships between two parameters, which combined with cross wavelet transform, gives an indication of relationship between the two parameters.

Temperature- flow depth, pH-flow depth and specific conductivity-flow depth indicate common areas of increasing power from 10 min band to 80 minute band from the beginning of the storm to 3 hrs. These areas of common power increase with increasing period. This indicates that that temperature, pH and conductivity might be correlated with flow depth. The areas of common power are higher for the decreases with the increasing duration of the storm. This indicates that relationship between flow depth and the three selected parameters is significant during the initial part of the storm. Also, these power bands are within the 5% significance level.

Common areas of increasing power are also observed for temperature-pH and conductivity-temperature from 10 to 80 minute band till 3 hour of the storm. This was significant at the 5% level. Increasing power was observed for pH and specific conductivity for the time and period but not significant at the 5% level. Wavelet coherence plots for temperature- flow depth, pH-flow depth and specific conductivity-
flow depth reveal high correlation at period band greater than 60 minutes. Also, correlation is observed for smaller band at less than 10 minutes scale. Wavelet coherence plots for temperature-pH and specific conductivity-temperature are highly correlated at high power bands.

Figure 6. Cross wavelet transform and wavelet coherence plots (E10) for temperature-depth, pH-depth and conductivity-depth. The cross wavelet spectrum shows areas of high common power. Wavelet coherence shows areas of high correlation.
Figure 7 Cross wavelet transform and wavelet coherence plots (E10) for temperature-pH, pH-conductivity and conductivity-temperature. The cross wavelet spectrum shows areas of high common power. Wavelet coherence shows areas of high correlation.
2.4 CONCLUSIONS

In summary, highway runoff characterization and temporal analysis yielded the following results:

- Quantitative characterization of highway runoff at the site for selected parameters indicated that the parameters were well below state standards and other studies conducted elsewhere in the United States, with the exception of pH.
- No correlation between pollutants and antecedent dry period was observed; however, pollutants had correlations with rainfall intensity. Combination of antecedent dry period and rainfall resulted in improved correlations.
- Primary pollutants for a particular catchment can vary depending on the primary sources contributing to the runoff quality. However, for the current site heavy metals and nutrients were consistently observed in the samples. Also, for the current site a combination of total suspended solids and total dissolved solids can be used as a surrogate for nutrient measurements.
- The levels of dissolved metals (copper, lead, zinc) coming from the roadway were low, with only copper exceeding state standards in two storm events.
- Effluent dissolved concentrations of lead and zinc were below state standards in all but one instance, while effluent dissolved copper exceeded state standards in five events.
- Variance of temperature pH, conductivity and flow depth increases with increasing time periods indicating contribution to total variance of the original signal is more at higher time scales and fluctuations are low in comparison at lower time scales. Temperature and pH indicate a dominant scale at a period of 15
minutes so when we design a sand filter this time scale needs to be taken into account.

- Temperature, pH and conductivity exhibit correlation with flow depth with increasing period indicating that the interaction between water quality indicators is higher for greater time periods. Also, correlation between parameters across time indicate higher correlation during initial part of the event. From results it can be concluded that monitoring initial part of the storm at a frequency of higher than a sample every 15 minutes to understand the behavior of highway runoff is critical. Also higher correlations indicate that during initial part of the storm we can expect other parameters to behave similarly if we have to reduce the number of parameters being monitored.
CHAPTER 3. TEMPORAL BEHAVIOR OF RECEIVING WATER

3.1 INTRODUCTION

In 2007, the Georgia Department of Transportation (GDOT) monitored the water quality of Canton Creek at the intersection of Georgia Highway 20 (SR 20) and Interstate 575 (I 575) (City of Canton, Georgia, USA) during a major interchange reconstruction project in the surrounding Etowah watershed. Because runoff from active construction sites is known to contain elevated levels of pollutants, including suspended or dissolved solids, nutrients, heavy metals and other contaminants that may be adsorbed to the suspended solids or dissolved in the runoff, it is important to contain and treat runoff from active construction sites [45-48]. Additionally, because the Etowah watershed is the habitat for the federally listed threatened Cherokee darter fish, GDOT incorporated several best management practices to contain runoff from the areas of active construction during the construction phase. Silt fences (two rows of type ‘C’ silt fence and one row of type ‘A’ silt fence) were installed along the outside perimeter of the project and along the stream buffer to capture sediment from fills over 3.04 meters high and under all bridges. GDOT also contained and treated the first 9.4 cm (3.7 inches) of pavement runoff from each rainfall event by channeling it through sand-filter detention ponds. The ponds were constructed within the project budget and were also designed to permanently treat roadside runoff for total suspended solids, heavy metals, petrochemicals, and thermal pollution. During the construction phase these detention ponds were used as a temporary sedimentation basin to collect receiving water during rain events, preventing direct
discharge of highway stormwater runoff to the Canton Creek. Additional controls included erosion control mats, which were installed on the sedimentation basin slopes, and riprap protection, which was provided at the temporary sedimentation basin inlets and slopes adjacent to the culvert to prevent erosion.

3.2 BACKGROUND

Several factors are responsible for the generation of contaminants from construction activity zones, including activities such as clearing of vegetation, excavation of soils, pouring of concrete, and painting, all of which can have significant impact on the concentration of contaminants in the runoff leaving a site [49]. Another important factor is the storm event characteristics affecting the watershed during the period of construction. Intensity and duration of precipitation, catchment characteristics, and the extent of the construction zone can play an important role in the generation of pollution, as well as the proximity of an active construction zone to the receiving water systems [49].

While the erosion rate from undisturbed natural areas can actually be negative, indicating deposition, erosion rates from construction sites are estimated to range between 2 to 112 kilograms/square meters/year [49] [50, 51]; consequently, several Best Management Practices (BMPs) can be incorporated to reduce the contaminant load to the surface water systems in the proximity of a construction site. Implementation of such BMPs during the construction phase helps in attenuation and treatment of runoff from a construction site. Erosion control practices including geotextiles, mulching, rip rap, and control of construction runoff, including check dams, grass lined channels, temporary or
permanent sedimentation basins and rock dams, sediment traps, silt fences and vegetated buffers are examples of some of the BMPs that can be used to reduce contaminant loading during construction. Additionally, improved management of construction materials, such as control during concrete pours and accidental spills have also been suggested in several studies [48, 49, 52].

Several studies have assessed the performance of BMPs during the construction phase [53-58]. Most commonly, these studies conduct statistical difference (Analysis of Variance ANOVA) tests between upstream and downstream monitoring locations of the active construction zone to assess the performance of the construction BMPs [55, 56]. This statistical technique used for analysis is effective with water quality data collected at infrequent intervals because the resolution of collected data is low. With such tests, there is not significant information about the scale or frequency content of the collected monitoring data. In contrast, high-resolution water quality data recorded continuously at discrete periodic frequent intervals represents a time series or a signal that can be analyzed using additional techniques. These water quality signals are either stationary or non-stationary [59]: stationary processes include diurnal or seasonal variations which repeat periodically; however, non-stationary processes are transient processes in a signal which do not follow a regular periodic pattern and the signal consists of several frequency components. Mathematical operations like transforms are effective in studying these signals by mapping a function (signal) from one domain to another. This is useful because additional information, which was not obvious in the original function (signal), can be learned from the transformed function. The most famous technique is the Fourier transform [60] where the signal is transformed from time domain to a frequency domain.
Fourier transform can be used to identify spectral components of a signal, and has been used to study water quality data [59]. However, Fourier transforms work well with only stationary signals because they provide only frequency localization and no time localization; consequently, even though information about the frequency content is present in a signal, there is no information about the location of a particular frequency in time.

3.3 STUDY SITE

The project site was located near the city of Canton, Cherokee County, Georgia (Figure 8) on Interstate 575 (I-575) at State Road 20 (SR 20). The project was 2.4 kilometers in length and the total area under the project was 0.63 square kilometers. The annual average daily traffic on I-575 as of 2007 was 56,100. The site is located in the Etowah watershed basin, home of the federally listed threatened Cherokee darter fish. Canton Creek is located within the watershed and I-575 crosses the river’s flow path. The project has a drainage area of 36.2 square kilometers.
Figure 8. The location of the major interchange reconstruction project site at Canton Creek. Five sampling locations (U1, U2, D1, D2, and D3) are marked on Canton Creek, which flows underneath I-575, from east to west. Two sampling locations were located upstream.

### 4.3.1 Construction Details

The aim of the project was the reconstruction of an interchange between I-575 and SR 20, which included the addition of a diamond exit ramp from I-575 northbound to SR 20, as well as a southbound diamond entrance ramp from SR 20 to I-575 southbound. Existing ramps were also reconstructed and a collector distributor between the diamond
ramps and loop ramps was added. During the initial stage of the construction a culvert was constructed between 12 Jul 2007 and 26 Aug 2007 located on the Canton Creek. For the construction of the culvert, flow from the Canton Creek was initially diverted into two barrels of the existing culvert, while the two barrels not receiving the flow were extended. After the extensions were completed, the flow from Canton Creek was then diverted to the extended barrels, while the culvert extensions were constructed for the remaining two barrels not receiving the flow.

4.3.2 Stream Monitoring

GDOT monitored the water quality of Canton Creek from February 13, 2007, to October 31, 2008. The water quality monitoring was conducted in response to a request by the U.S. Fish and Wildlife Service because Canton Creek, which lies within the Etowah River Basin, is an imperiled aquatic ecosystem. To monitor the water quality in Canton Creek, five locations were selected: two upstream locations (denoted U1 and U2) and three downstream locations (denoted D1, D2 and D3). The upstream monitoring points were located at a distance of 61 meters and 152 meters from the culvert. Whereas, downstream locations were situated at a distance of 61 meters, 152 meters and 305 meters. The upstream and downstream placement of samplers ensured that the impact of the construction of the culvert on the water quality of Canton Creek could be ascertained. ISCO 3700/6700 samplers were used to measure real time in-stream water quality, including dissolved oxygen, temperature, turbidity, and pH. The monitoring probes were placed at the center of the stream, and the parameters were measured at an interval of 15-minutes. Monitoring yielded a wealth of information in terms of the construction
project’s impact on the quality of the receiving water, which was analyzed using the method of Maximal Overlap Discrete Wavelet Transform (MODWT). It is a similar wavelet technique as used in the first chapter, however the study conducted for the highway runoff was conducted using a continuous wavelet transform. Whereas, the current methodology is a special case of discrete wavelet transform.

3.4 METHODOLOGY

The high-resolution water quality data selected for analysis were gathered from 18th April 2007 through 18th November 2007 (Figure 2), and the culvert on Canton Creek was constructed from 13th July 2007 through 26th August 2007. The total data set included N = 20480 values for each parameter. The time series was divided into three sets according to the stages of construction: before construction (18th April 2007 – 13th July 2007), during construction (13th July 2007 – 26th August 2007) and after construction (26th August 2007 – 18th November 2007). Before and after construction, data sets had N = 8192 values for each parameter, while during construction data set contained N = 4096 values for each parameter. Collection of high resolution water quality monitoring data resulted in some gaps in the time series due to regular maintenance, calibration of the probes, and replacement of batteries. Consequently, there were some gaps in the water quality data collected from the site. Usually the length of the gaps was small and only 1 or 2 values were missing from the data. Because MODWT requires that no gaps be present in the data to be analyzed, linear interpolation was considered sufficient to fill the gaps without any significant effect on the water quality time series [61]. Data before 18th April and after 26th August was excluded from the data set because there were a
significant number of missing values in the collected water quality time series and linear interpolation would have introduced significant errors in the water quality time series data. Additionally, for convenience and homogeneity, the sample size selected to be analyzed for each phase of construction was chosen to be a multiple of 2 \( (N = 2^j) \), although this is not a requirement for a MODWT analysis.

3.4.1 MODWT Analysis

MODWT is a modified form of Discrete Wavelet Transform (DWT). Unlike DWT which is an orthogonal and a non-redundant transform, MODWT is a highly redundant and a non-orthogonal transform [62]. The filtered coefficients that result after each decomposition are discarded in DWT, but all the down sampled coefficients are retained in a MODWT analysis. MODWT has several advantages that make it a better option for statistical time series analysis as compared to a DWT. Firstly, MODWT can be used for sample sizes with all values of \( N \), while DWT can only be used for sample sizes which are multiple of \( 2^j \). Also, due to the redundant nature of the MODWT, as the number of sample values at each resolution scale remains the same without being discarded, the data points at each level are aligned and useful for a more meaningful analysis. In this study, the methodology suggested by [62-64] was followed, a brief summary of the method follows.

For a time series \( X \) with a number of values \( N \), the \( j \)th level MODWT wavelet \((\tilde{W}_j)\) and scaling \((\tilde{V}_j)\) coefficients are given by [62]: 
\[ \tilde{W}_{j,t} = \sum_{l=0}^{L_j-1} \tilde{h}_{j,l} X_{j-l \mod N} \]

\[ \tilde{V}_{j,t} = \sum_{l=0}^{L_j-1} \tilde{g}_{j,l} X_{j-l \mod N} \]

Where:

\[ \tilde{h}_{j,l} \equiv h_{j,l} / 2^{j/2} \]

and

\[ \tilde{g}_{j,l} \equiv g_{j,l} / 2^{j/2} \]

are the MODWT wavelet and scaling filters, respectively. If there is a signal \( X \) containing \( N \) values, the Multiresolution analysis (MRA) of the time series is given by [62]:

\[ X = \sum_{j=1}^{J_0} \tilde{D}_j + \tilde{S}_{j_0} \]

Where,

\[ \tilde{D}_{j,t} = \sum_{l=0}^{N-1} \tilde{h}_{j,l} \tilde{W}_{j,l \mod N} \]

\[ \tilde{S}_{j,t} = \sum_{l=0}^{N-1} \tilde{g}_{j,l} \tilde{V}_{j,l \mod N} \]

Where \( \tilde{D}_{j,t} \) and \( \tilde{S}_{j,t} \) are \( t \)th elements of scale \( j \), a set of coefficients are obtained with the same number of samples (\( N \)) as in the original signal (\( X \)). These are called wavelet details as they capture local fluctuations over the whole period of a time series at each scale. The set of values \( S_{j_0} \) provides a “smooth” or overall “trend” of the original signal. Adding \( D_j \) to \( S_{j_0} \), for \( j = 1, 2, \ldots, J_0 \), gives an increasingly more accurate approximation of the original signal.
3.4.2 Wavelet Variance

In calculating the wavelet variance, the methodology suggested by [62] was incorporated. Energy is conserved when MODWT is performed [63]:

\[ \|X\|^2 = \sum_{j=1}^{J_N} \|\tilde{W}_j\|^2 + \|\tilde{V}_{J_N}\|^2 \]

According to the required scale, an analysis of variance (ANOVA) can be derived from [62]:

\[ \hat{\sigma}_X^2 = \|X\|^2 - \overline{X}^2 = \sum_{j=1}^{J_N} \|\tilde{W}_j\|^2 + \|\tilde{V}_{J_N}\|^2 - \overline{X}^2 \]

A biased estimator of variance \( \nu_X^2 \) was used [63]. In the analysis reflection boundary coefficients were used, which included all 2N wavelet coefficients, obtained from down sampling after MODWT was used. This was applied to the reflected series \( \left\{X'_t\right\} \). The biased estimator was given by:

\[ \hat{\nu}_{X,b}^2(\tau_j) = \frac{1}{2N} \sum_{t=0}^{2N-1} \tilde{W}_{j,t}^2 \]

The wavelet variance allowed estimation of the contribution of each scale to the total variance of the original signal.
3.4.3 Power Spectral Density (PSD)

In calculating the PSD, the methodology suggested by [63] was incorporated. In MODWT transform, the $j$th level wavelet variance was approximately equal to twice the integral of the PSD, $S_X(f)$ [63]:

$$v^2_X(\tau_j) \approx 2\int_{\nu/(2^{j+1}\Delta t)}^{\nu/(2^j\Delta t)} S_X(f)df$$

If $C_j$ is the average value of $S_X(f)$ over the integral $\frac{1}{2^{j+1}\Delta t} < f \leq \frac{1}{2^j\Delta t}$

$$C_j = 2^j\Delta t\int_{\nu/(2^j\Delta t)}^{\nu/(2^{j+1}\Delta t)} S_X(f)df$$

An estimator to calculate the average PSD from the wavelet variance can be used:

$$\hat{C}_j = 2^jv^2_X(\tau_j)\Delta t$$

The PSD of the signal describes the distribution of power in a signal.

3.4.4 Wavelet Correlation

For a bivariate signal, the wavelet correlation can be calculated by [64].

$$\rho_{x,y}(\lambda_j) = \frac{\gamma_{x,y}(\lambda_j)}{\sigma_1(\lambda_j)\sigma_2(\lambda_j)}$$
\( \sigma_j^2(\lambda_j) \) and \( \sigma_j^2(\lambda_j) \) are wavelet variances for \( X_{1,t} \) and \( X_{2,t} \) associated with scale \( \lambda_j \). Wavelet correlation gives correlation between two parameters for selected time frequency scales.

3.4.5 Wavelet Cross Correlation

In calculating the wavelet variance, the methodology suggested by [64] was adopted. The wavelet cross correlation of a bivariate series can be calculated from wavelet cross covariance. The estimator for the cross covariance is given by [64]

\[
\overline{\gamma}_{\tau, X,Y}(\lambda_j) \equiv \frac{1}{N_j} \sum_{l=L_j-1}^{N_j-1} W_{j,l}^{(X)} \tilde{W}_{j,l+\tau}^{(Y)} \quad \tau = 0, \ldots, N_j - 1
\]

\[
\overline{\gamma}_{\tau, X,Y}(\lambda_j) \equiv \frac{1}{N_j} \sum_{l=L_j-1}^{N_j-1} W_{j,l}^{(X)} \tilde{W}_{j,l+\tau}^{(Y)} \quad \tau = -1, \ldots, -\left( N_j - 1 \right)
\]

\[
\overline{\gamma}_{\tau, X,Y}(\lambda_j) \equiv 0 \quad \text{Otherwise}
\]

Wavelet Cross Correlation is given by [64]

\[
\rho_{X,Y}(\lambda_j) = \frac{\gamma_{X,Y}(\lambda_j)}{\sqrt{\sigma_X(\lambda_j) \sigma_Y(\lambda_j)}}
\]

Wavelet cross correlation is used to find the lead – lag relationship in for two parameters.
3.5 RESULTS AND DISCUSSION

As anticipated, the data demonstrated seasonal variation of temperature, with dissolved oxygen showing an inverse relationship with the temperature (Figure 9). The temperature in the three construction phases varied between 5-28°C. The dissolved oxygen in the stream varied between 4 and 14 mg/L. pH of the stream varied between 6.5-8.5. Although, several spikes in data set for pH were observed during the active construction phase at the immediate downstream location. Turbidity recorded in the stream was generally low except during perturbation events due to precipitation or construction activity. Descriptive statistics for the four measured water quality parameters included the mean value with error bar (1 standard deviation) of each water quality parameter for all the five monitoring locations during each period of construction (Figure 10). Plots from left to right show different stages of construction, while plots from top to bottom show the values for the different water quality parameters. The mean values of temperature appeared to be elevated for the active construction phase; however, the values were higher due to the seasonal behavior of temperature. The mean value of dissolved oxygen did not change significantly; however, variation was higher for the post construction period. Mean pH values appeared higher for downstream locations D1 and D2 during the active construction phase, while mean turbidity values for all the locations during the three phases of construction were approximately similar, although variances were slightly higher before and after construction phase.
Figure 9. The water quality time series data collected during the three stages of construction of the culvert which were used for analysis. Four parameters - temperature, dissolved oxygen, pH and turbidity were measured from April through November, 2007.
Figure 10. Mean values of the water quality parameters plotted for the five different sampling locations. The subplots from left to right show three different phases of construction of the culvert; each subplot represents wavelet variances for all the five locations monitored.
3.5.1 Multiresolution Analysis

The Multiresolution analysis plots for temperature at location 1 during the pre-construction phase (original signal plotted at the top) are given in Figure 11. Following the original signal, frequency components were plotted from highest to lowest (moving from top to bottom of the figure). X represents the original signal, S9 is the approximation of the original signal at decomposition level 9, while D1 through D9 are details of the signal at levels of decomposition from 1 through 9. The decompositions represent the following time blocks: D1 = 30 minutes – 1 hour; D2 = 1-2 hours; D3 = 2-4 hours; D4 = 4-8 hours; D5 = 8-16 hours; D6 = 16-32 hours; D7 = 32-64 hours; D8 = 64-128 hours; and D9 = 128-256 hours. It can be observed that the variation observed in the temperature is maximum at the D6 level. This represents the daily scale in the temperature behavior of the stream.
Figure 11. Reconstructed MRA plots obtained from wavelet coefficients of the temperature time series for the period before construction. X represents the original signal. S9 is the approximation of the original signal at decomposition level 9 while D1 through D9 are details of the signal at levels of decomposition from 1 through 9.
3.5.2 Wavelet Variance

The wavelet variance for the water quality parameters, plotted against different levels of signal decomposition, is given with the subplots from left to right showing the three different phases of construction of the culvert and the different water quality parameters plotted from top to bottom (Figure 12). Each subplot represents wavelet variances for all five locations monitored. The wavelet variance for the water quality parameters plotted against different stages and locations of construction are also given, with each subplot representing wavelet variances for all nine levels of decomposition (Figure 13).
Figure 12 Wavelet variance for the water quality parameters as plotted against different levels of signal decomposition, with the subplots from left to right showing the three different phases of construction of the culvert. Each subplot represents wavelet variances for all the five locations monitored.
Figure 13 The wavelet variance for the water quality parameters plotted as a function of stages of construction (subplots from left to right show the five different locations which were monitored). Each subplot represents wavelet variances for all the nine levels of decomposition.

Diurnal variations were not evident in Figure 9 for the temperature time series; however, when the signal was decomposed using multiresolution analysis, diurnal variations in the temperature signal were observed (Figure 11). For example, level D5 (8 hrs – 16 hours) clearly demonstrated the diurnal behavior of the temperature data. The details revealed that the sub-daily variations (D1, D2, D3) were less prominent than the
daily (D6) variations. Additionally, the variations became less significant at scales longer than the daily scale.

The wavelet variance revealed the intensity of variation between the scales of the water quality time series, with the wavelet variance plots demonstrating the variance contribution of an individual scale to the total variance (Figure 12). Temperature, dissolved oxygen, and pH wavelet variance plots indicated that variation in the time series increased progressively until the sixth level D6 (16 – 32 hrs), where a maximum was achieved. This showed that diurnal variation in those three parameters contributed primarily to the total variance. Variance in turbidity did not show any particular trend. Also, variance at all the locations during the three stages of construction was comparable, with all three locations reaching a maximum at the sixth level.

Examination of the variance during the three different periods (before, during, and after construction) demonstrated that the variance in temperature increased at sub-daily scales during construction in all five sampled locations (Figure 13). At the sixth level D6 (16-32 hrs), variance remained consistent, which demonstrated an increased variance in temperature at smaller scales during the construction as compared to higher scales. Reduction in variance was observed for higher levels during the construction for temperature. Similar trends were observed for dissolved oxygen and pH, and the variance contribution by various scales remained consistent. Interestingly, it was observed that reduced variance in turbidity was observed for the period during construction (Figure 13).

3.5.3 Power Spectral Density

The Power Spectral Density plot demonstrated that for temperature, dissolved oxygen, and pH, there was a decrease in the distributed power for levels D1 (30 min – 1
hr), D2 (1-2 hrs), and D3 (2-4 hrs), with a similar linear decrease in the distributed power observed for levels greater than level D4 (Figure 14). At level D4 (4-8 hrs), a peak was observed which corresponded to a frequency of $10^3$. The same trend was observed in these three parameters for all the stages of construction, which demonstrated that lower scales contributed to the power of the signal. Power spectral density for turbidity showed a consistent decrease in the power for successive increase in levels. This trend was observed at the five locations for all three phases of construction.

Figure 14 Power spectral density of the water quality parameters plotted as a function of frequency. The subplots from left to right show the three different stages of construction.
3.5.4 Wavelet Correlation

Figure 15 depicts the wavelet correlation at increasing temporal scales for the three phases of construction for the parameters pH-Turbidity (top row), Dissolved Oxygen – Turbidity (Middle Row) and Temperature Turbidity (Bottom Row). For pH – Turbidity wavelet correlation a negative correlation was observed for the period before construction. Also, the correlation was negligible for lower levels (8 hours). For the period during construction a positive correlation was observed for lower scales (8 hours) in the three downstream locations, which indicated that the concrete pours impacted the pH of the receiving stream. Negative correlation was observed for upstream locations for the same scales. For the period after construction a negative correlation was observed at all the scales. The dissolved Oxygen – Turbidity relationship was weakly correlated. This suggested that dissolved oxygen did not vary in the stream, even with an increase in turbidity due to concrete pours or rain events. Correlation between Temperature and Turbidity was observed to be negligible at various temporal scales. Some positive correlation between the two parameters was observed for lower levels for the period during construction. This indicated an increase was observed in the temperature of the stream for smaller time scales (4 hours) due to an increase in turbidity.
Figure 15 Wavelet Correlation Plots are shown here for pH – turbidity (Top Row), DO – turbidity (middle row) and temperature – turbidity (bottom row) for the three phases of construction. Each subplot depicts the wavelet correlation between the two parameters for 9 levels.

Figure 16 depicts the wavelet correlation at increasing temporal scales for the three phases of construction for the parameters dissolved oxygen - pH (top row), temperature- pH (middle row) and temperature – dissolved oxygen (bottom row). The correlation between dissolved oxygen gradually increased from level D1 (30 min) to level D6. The correlation between the two parameters peaked at level D6. There was a positive correlation between the two parameters for all the levels except level D9 (128 hours).
where a negligible negative correlation was observed. A similar pattern was observed for correlation between temperature and pH except the fact that negative correlations were higher for levels D8 and D9 for the period during and after construction. Temperature and dissolved oxygen correlation was negligible for levels D1 through D4 (4 hours) for the period before construction. After that a negative correlation was observed. The two parameters had the strongest negative correlation for level D9 (128 hours). Similar trends were observed for the locations for the period during and after construction. Although the positive correlation between the two parameters peaked at level D5 (8 hours) instead of level D4.

Figure 16. Wavelet Correlation Plots are shown here for dissolved oxygen - pH (top row), temperature – pH (middle row) and temperature – dissolved oxygen (bottom row) for the
three phases of construction. Each subplot depicts the wavelet correlation between the two parameters for 9 levels.

3.5.5 Wavelet Cross Correlation

Wavelet Cross Correlation helps identify a lead-lag relationship in the bivariate series, which indicates which in frequencies a particular parameter is able to impart a greater change in the other parameter. Wavelet Cross Correlation results have been plotted for Dissolved Oxygen and Temperature for the D6 level (16 hours) for the period before construction (Figure 17). A periodic cycle of approximately 24 hours can be observed from the figure. For the D3 location, there is a lag of ~ 4 hours with a strong correlation of 0.93. This lag is comparable to the lag for the other locations which is ~ 5 hours.
Figure 17 Wavelet cross correlation plot is shown here for dissolved oxygen – temperature for the 6th level before construction.

Consequently, it can be said that for the period before construction, it takes approximately five hours for the changes in Dissolved Oxygen to be observed. Also, this shows that lower frequencies contribute to the shifts. This is not observed for the higher frequency data which is plotted in Figure 18. Figure 11 shows the wavelet cross correlation for the D3 level for the period before construction. It can be clearly observed that the lag is negligible in this case. This shows that the effect of temperature on the dissolved oxygen content of the stream is prominent for lower frequencies or higher levels.
Figure 18. Wavelet cross correlation plot is shown here for dissolved oxygen – 
temperature for the 3rd level before construction.

In Figure 12, Wavelet cross correlation of turbidity and pH is plotted for level D6
for the period during construction. It can be observed that although there is a small lag of
~ 2 hours between the two parameters for the upstream locations but the correlation is
very weak ~ -0.25. Also, for the downstream locations there is a significant lag as
compared to the upstream locations but the correlation is negligible. This suggests that
for lower frequencies (level D6), turbidity has a negligible effect on the pH.
Figure 19. Wavelet cross correlation plot is shown here for turbidity - pH for the 6th level during construction.

Additionally, the cross correlation between the turbidity and pH has a higher correlation but a negligible lag of less than 1 hour (Figure 20). This suggests that any change in the turbidity of the stream changes the pH of the stream at higher frequencies (lower levels) as compared to lower frequencies.
Figure 20. Wavelet cross correlation plot is shown here for turbidity - pH for the 3rd level during construction.
3.5.6 Effect of Perturbation Events during Construction Activity

The wavelet coefficients were compared with the precipitation events and construction activity during the construction phase for the four parameters for location D3. This was done to compare the behavior of water quality indicators at different temporal scales. The decomposed wavelet levels for temperature is plotted in Figure 21. The red bars indicate precipitation events during this period, whereas grey bands indicate construction activity. The larger grey band also includes a period of low flow in the stream. It can be observed that approximate temperature matches well with the original signal when higher frequency levels are removed from the signal. A gradual increase in temperature is observed due to summer. It can be observed that perturbation due to precipitation or concrete pours does not have a major impact due to the absence of spikes in the levels D1,D2,D3 and D4 barring one event on 18th July. Diurnal variation dominates the trend for temperature in the stream.
Figure 21. Reconstructed wavelet coefficients for temperature compared with precipitation events and construction activity.
In the case of pH (Figure 22) significant changes can be observed for smaller scales D1, D2, D3 and D4 during concrete pours and rainfall events. More impact can be observed due to the events involving concrete pours indicating spikes for shorter scales. This indicates concrete pours can have acute impact on the stream water pH for smaller scales. However, for higher scales D5, D6 it is observed that for the period during low flow in the stream the contribution from higher scales is more and dominates the trend of pH in the stream.
Figure 22. Reconstructed wavelet coefficients for pH compared with precipitation events and construction activity.
For dissolved oxygen (Figure 23) it can be observed that contribution of smaller scales affects the original signal during precipitation events. Also impact of concrete pours can be observed. A significant drop in dissolved oxygen is observed around 10\textsuperscript{th} August. Here it can be observed that contribution at the smaller scale is more than what is observed at higher scales. This shows acute change in dissolved oxygen dominates the general trend of dissolved oxygen.
Figure 23. Reconstructed wavelet coefficients for dissolved oxygen compared with precipitation events and construction activity.
For turbidity (Figure 24), it can be observed that precipitation is major contributor to the change in original turbidity series as compared to concrete pours, but concrete pours have an impact on the general trend nevertheless. The impact of concrete pours can be related to changes in pH as well during concrete pour events. The approximate signal is low generally except during perturbation events. Infact, contribution of both smaller and higher scales to the total turbidity trend is similar indicating that contribution to the original signal is consistent at all temporal scales.
Figure 24. Reconstructed wavelet coefficients for turbidity compared with precipitation events and construction Activity
3.6 CONCLUSIONS

This study has analyzed high-resolution water quality data collected during a construction event using a statistical wavelet analysis technique (MODWT). As compared to conventional static statistical analysis, which considers the data set to be a stationary signal, the current technique is useful for transient signals as in the case of stormwater monitoring data. It gives insight into the behavior of parameters at several temporal scales. For example, the diurnal behavior of parameters is clearly evident in the results. Also, the transient events which affect the quality of water can be easily determined using this technique as the monitoring data can be broken into several temporal scales. For example, the effect of short term events such as concrete pours and storm events was observed. This can be used to determine the contribution and dominant scale in the original trend. Also, Bivariate wavelet analysis like wavelet correlation and wavelet cross correlation can be used to gain further insight into the effect of one parameter on the other at several frequencies. Consequently, the use of dynamic statistical analysis techniques is a step forward in the direction of environmental monitoring, giving engineers more insight into the dynamic processes occurring on a construction site, including monitoring stormwater runoff from highways, stream and BMP monitoring, or monitoring the effect of anthropogenic activities like construction on water systems. Since concrete pours affect dissolved oxygen acutely, engineers must create temporary BMPs before streams receive streams that can handle intense as opposed to long term cumulative loadings.
CHAPTER 4. ASSESSMENT OF THE SAND FILTER PERFORMANCE

4.1 INTRODUCTION

Amongst the different forms of treatments, one of the most popular BMP that finds widespread use for mitigating the impact of stormwater to streams is the sand filter. Sand filters primarily remove constituents of the stormwater through the physical process of filtration \[17\]. This enables sand filters to perform relatively well for suspended solids and associated pollutants’ removal but poorly for dissolved solids that may pass to receiving streams unabated. In order to evaluate the efficacy of sand filters in the Piedmont geology, it is imperative to understand the consequences of using sand filters as the sole mitigation strategy before discharging incoming stormwater runoff into receiving waters.

One of the major questions required to assess the efficiency of any BMP in attaining water quality goals \[65\] is how the degree of pollution control or effluent quality performance provided by the BMP vary from pollutant to pollutant. Stormwater runoff contains a variety of pollutants that can affect the quality of receiving waters and some parameters may even be site specific \[65\]. However, pollutants may be divided into three basic categories which are useful to assess the efficacy of BMP structures- 1) physical characteristics like temperature, pH, etc., 2) presence of heavy metals like lead, copper etc. that impact biological lifeforms and 3) nutrient loadings like nitrates, nitrogen etc. which impact aquatic life.
The primary objectives of this study were 1) to assess the performance of sand filter as a BMP for treating typical suspended as well as dissolved pollutants found in highway stormwater runoff; 2) assess efficacy of sand filter for the specific pollutants that were monitored at a field site and 3) provide design criteria for sand filters that are efficient in treating various pollutants.

4.2 SITE AND DATA DESCRIPTION

4.2.1 Pre-existing data

The data for evaluating the competency of sand filters in mitigating typical pollutants found in stormwater runoff (objective 1) was obtained from the International Stormwater BMP Database [66]. The original objective of the database was to enable long-term scientific research regarding the factors affecting BMP performance. It was developed using a combination of literature review, of studies conducted prior to 1999, along with ongoing data entry from various agencies and independent researchers. The influent and effluent pollutant data specific to sand filters (Table 8) was extracted from the database for the purpose of this analysis. The pollutants selected to assess the sand filter were pH, turbidity, temperature, total suspended solids (TSS), total dissolved solids (TDS), dissolved and total heavy metals namely, lead (Pb), zinc (Zn), copper (Cu), dissolved and total phosphorus (P), nitrogen and oxides of nitrogen.
Table 8. Design Details of Sand Filters Used in the Analysis [66]

<table>
<thead>
<tr>
<th>BMP Name</th>
<th>Permanent Pool Volume</th>
<th>Permanent Pool's Surface Area</th>
<th>Permanent Pool's Length</th>
<th>Media Filter’s Surface Area</th>
<th>Type and Depth (or Thickness) of Each Filter Media Layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appleyard Drive Delaware Sand Filter</td>
<td>13.5 m³</td>
<td>0.0022 ha</td>
<td>24.38 m</td>
<td>0.0022 ha</td>
<td>20” layer of sand in concrete box</td>
</tr>
<tr>
<td>Foothill SF</td>
<td>216.6 m³</td>
<td>0.0102 ha</td>
<td>12.49 m</td>
<td>0.0039 ha</td>
<td>18 in. sand; geotextile layer; 6 in. gravel</td>
</tr>
<tr>
<td>La Costa PR</td>
<td>285.7 m³</td>
<td>0.0179 ha</td>
<td>14.93 m</td>
<td>0.0072 ha</td>
<td>18 in. sand; geotextile layer; 6 in. gravel</td>
</tr>
<tr>
<td>Eastern SF</td>
<td>115.5327 m³</td>
<td>0.0053 ha</td>
<td>8.99 m</td>
<td>0.0026 ha</td>
<td>18 in. sand; geotextile layer; 6 in. gravel</td>
</tr>
<tr>
<td>Delaware Sand Filter</td>
<td>3.7 m³</td>
<td>71 ft²</td>
<td>7 ft</td>
<td>71 ha</td>
<td>2” DE #57 stone; 1.5” sand ASTM C-33; Geotextile Fabric</td>
</tr>
<tr>
<td>7/8</td>
<td>105.6218 m³</td>
<td>0.0056 ha</td>
<td>7.92 m</td>
<td>0.0031 ha</td>
<td>18 in. sand; geotextile layer; 6 in. gravel</td>
</tr>
<tr>
<td>Shasta Maintenance Station Full Sedimentation Austin Sand Filter</td>
<td>370 m³</td>
<td>518 m²</td>
<td>37 m</td>
<td>280 m²</td>
<td>450 mm sand</td>
</tr>
<tr>
<td>Mountain Gate Sand Filter</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>108 m²</td>
<td>460 mm sand</td>
</tr>
<tr>
<td>Termination</td>
<td>222.3 m³</td>
<td>0.011 ha</td>
<td>11.9 m</td>
<td>0.006 ha</td>
<td>18 in. sand; geotextile layer; 6 in. gravel</td>
</tr>
<tr>
<td>SE Landfill Sand Filter</td>
<td>118.8 m³</td>
<td>0.144 ha</td>
<td>0.8 m</td>
<td>0.144 ha</td>
<td>The sand filter is constructed in a basin and consist of 0.6 meter of sand over a 0.225 meter bed of graded # 8910 stone. 12 inches of ASSHTO C-33 type sand (d50-0.85mm) underlain by a 12 inch deep fine gravel layer that is drained by a perforated pipe. The coefficient of uniformity is 5.0.</td>
</tr>
<tr>
<td>Lakewood Sand Filter (95)</td>
<td>9.2 m³</td>
<td>0.001 ha</td>
<td>8.2 m</td>
<td>0.0015 ha</td>
<td>12 in. sand; geotextile layer; 6 in. Gravel</td>
</tr>
<tr>
<td>Escondido</td>
<td>12.2 m³</td>
<td>0.002 ha</td>
<td>24.9 m</td>
<td>0.0027 ha</td>
<td>1. Graded sand to a depth of 0.76 m; 2. Filter fabric; 3. 0.91 m dolomite limestone under drain. 17.4 in. The filter media was sand, specified to meet the requirements of ASTM C-33 concrete sand. Sieve analyses in the supply sand yielded the following results:</td>
</tr>
<tr>
<td>Megginis Ck. Sand Filter</td>
<td>163001.5 m³</td>
<td>8.150 ha</td>
<td>1 m</td>
<td>1.7993 ha</td>
<td>- Effective Size: 0.125 mm - Uniformity Coefficient: 7.8</td>
</tr>
<tr>
<td>Airpark Sand Filter</td>
<td>11.8 m³</td>
<td>0.0024 ha</td>
<td>28.8 m</td>
<td>0.0022 ha</td>
<td>Sand - 2.8 ft deep</td>
</tr>
<tr>
<td>Parkrose SF</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.0014 ha</td>
<td></td>
</tr>
</tbody>
</table>
4.2.2 Study Site and Data Description

The site selected for monitoring stormwater runoff for objective 2 was located in the City of Canton, Cherokee County, Georgia (Figure 1) on the I-575 at SR-20. I-575 is a 50 km long interstate spur located in north Georgia (Inset 1a), which connects the Atlanta metropolitan area with the north Georgia mountains. Motivation for the construction of the Canton sand filter was to limit roadway runoff to the habitat of the Cherokee darter fish, which is a threatened species endemic to the Etowah river system in North Georgia. The sand filter was constructed under an agreement between GDOT and the U.S. Fish and Wildlife Service.

4.3 BMP DESCRIPTION AND MONITORING PROGRAM

BMP description and stormwater monitoring program for this site has been previously described in detail in chapter 3.

4.4 METHODOLOGY

The efficiency of typical sand filters for treating individual pollutants was assessed using the pre-existing data in 3 ways. The efficiency of the various sand filters was evaluated per rainfall event for each pollutant using scatter plots. A statistical analysis for the competency of sand filters for mitigating the different pollutants was conducted by computing the box-plots and probability plots of the influent and effluent concentrations.
The efficiency of sand filters to mitigate the various categories of pollutants (namely metals, and total solids) simultaneously was evaluated using the k-means [67] clustering algorithm. The kmeans clustering algorithm partitions a dataset \([X_1, X_2, X_3, \ldots, X_p]\) with each ‘X’ being n dimensional into a pre-specified number \(k<n\), of clusters, \(S = [S_1, S_2, S_3, \ldots, S_k]\) such that each cluster is statistically different from each other.

\[
\arg\min_S \sum_{i=1}^{k} \sum_{x \in S_i} ||X - \mu_i||
\]

\(\mu_i\) = mean of \(S_i\)

The \(X_i\) dataset was 3 dimensional comprising of the cleaning efficiency of the total metals (Copper, Lead and Zinc) and 2 dimensional when comprising total solids. The kmeans clustering algorithm then clustered the sand filters in accordance with the ability to mitigate all metals together as well as for the removal of total solids. The design parameters of each cluster were then evaluated to assess the performance of sand filters in mitigating various pollutants simultaneously.

\[
C = \left( \frac{P_i - P_o}{P_i} \right)
\]

\(C\) = Cleaning efficiency of a pollutant

\(P_i\) = influent concentration of the pollutant

\(P_o\) = effluent concentration of the pollutant
4.5 RESULTS AND DISCUSSION

4.5.1 Typical Highway Runoff Characteristics

Since the dominant treatment mechanism of sand filters is filtration, they are typically used for removal of suspended solids. However, when combined with the use of sedimentation basins they may also assist in attenuation of runoff and settlement of floatables and other heavy suspended solids. The first part of this study involved evaluating the efficiency of the sand filter for mitigating thermal, physical and chemical pollution. The statistical characteristics of the pollutants obtained from International Stormwater Database are given in Figure 25, Figure 26 Figure 27 and Figure 28. The distribution of most incoming pollutants follows a log normal distribution implying that the occurrence of extreme loadings is less probable. The mean and standard deviation of the concentration of the total dissolved solids is higher than that of total suspended solids implying that treatment of dissolved solids in stormwater runoff is an important component (Figure 25). The mean pH value of stormwater runoff is slightly acidic (pH = 6.94) and based on the distribution is typically acidic (pH <7) rather than basic (pH >7). The mean temperature of stormwater runoff is 9.24 °C while the lognormally distributed turbidity values have a mean of 47.79 NTU.
Figure 25. Distribution of total suspended and dissolved solids observed at inlet of sand filters.

Figure 26. Distribution of pH, temperature and turbidity observed at inlet of sand filters.
Figure 27. Distribution of total nitrogen, NO\textsubscript{X}, copper, lead, phosphorus and zinc observed at inlet of sand filter.
Figure 28. Distribution of dissolved copper, lead, phosphorus and zinc observed at inlet of sand filter.

The total concentrations (suspended + dissolved) of nutrients as well as heavy metals and the dissolved concentrations of the pollutants are provided in Figure 27 and Figure 28 respectively. The log normal form of distribution for the pollutants implies that the frequency of events wherein the concentration of pollutants is extremely high is less. Based on the concentrations of heavy metals, zinc (Zn) is the most abundant (mean 126.75 μg/L), followed by copper (Cu) and lead (Pb). The ratio (R) of mean dissolved to mean total concentration of the pollutants (Zn = 0.61, Cu = 0.38, Pb = 0.12, P = 0.56) suggests that mitigating the pollution caused by different pollutants would require treatment of both suspended and dissolved solids. Mitigation of Zn and P (R > 0.5) would
require treatment of dissolved pollutants, whereas most of Cu and Pb could be treated by
treating for suspended solids.

4.5.2 Efficiency of Sand Filters for Typical Pollutants

The efficiency of sand filters in treating suspended and dissolved pollutants is
described using 3 types of plots. The first type is scatter plots which describe the
respective effluent concentrations of different pollutants given the influent concentrations
for different storm events. The second are box plots to describe the distribution of
influent and effluent concentrations of different pollutants and the third are the
probability plots of the influent and effluent concentrations which statistically explain the
efficiency of sand filters in treating pollutants based on different influent concentrations.

Following scatter plots delineates the effluent concentrations corresponding to
influent concentrations for different storm events. Results of the monitoring site in
Georgia are highlighted in red. The scatter plot for the total suspended and dissolved
solids (Figure 29) reveals the high efficacy of sand filters (data points below the 1:1 line)
in treating suspended solids but not dissolved solids. This follows from the typical
understanding of sand filter treating solids through the process of filtration. The absence
of a correlation between the influent and effluent concentration of suspended solids
signifies that regardless of the input suspended solid concentration, the sand filter
performs well in pollutant removal.

The pH of the effluent is typically a little higher (Figure 30) than the influent
concentration and is highly correlated implying that the effect on pH treatment by the
sand filter is dependent on the input pH. The temperature of the effluent concentration of
the stormwater is similar to the influent temperature except for when the temperature of the influent concentrations is relatively higher (~20°C). This could potentially be attributed to detention basins which allow time for the cooling of incoming water or diffusion in the filter media thus indicating filter media acts as a sink. Similar to results for suspended solids, the turbidity of effluent is also not correlated to influent concentrations and is treated relatively well within the sand filter. This occurs because most of the turbidity is caused as a result of suspended solids.

The scatter plots for the nutrient concentrations (Figure 31) reveal that a majority of the total phosphorus is mitigated by the sand filter, but neither dissolved phosphorus, total NOₓ or nitrogen is mitigated. On the contrary, the amounts of NOₓ compounds tend to increase slightly in the effluent. NOₓ represents the quantity of nitrite and nitrate together. The increase in effluent concentration of NOₓ could potentially be due to oxidation of nitrogen in the stormwater runoff before reaching the BMP outlet. The results for metals show that total and dissolved copper is not mitigated well by the sand filter whereas zinc and lead (total and dissolved) is mitigated relatively well Figure 32.
Figure 29. Scatter plot of influent v/s effluent concentration of total suspended and dissolved solids in stormwater runoff.

Figure 30. Scatter plot of influent v/s effluent concentration of total pH, temperature and turbidity in stormwater runoff.
Figure 31. Scatter plot of influent v/s effluent concentration of total and dissolved phosphorus, total NO$_X$ and Nitrogen in stormwater runoff.
Figure 32 Scatter plot of influent v/s effluent concentration of total and dissolved metals in stormwater runoff.
Kruskal-Wallis test (or the non-parametric equivalent of ANOVA) was employed to assess a statistically significant difference in median values of influent and effluent concentrations of the various pollutants. The p-values for the test are provided in Table 9 while the corresponding box plots are provided in Figure 33, Figure 34, Figure 35, and Figure 36. It was found that a statistically significant difference (p-values <0.05) in median concentrations was found in all parameters but temperature, total nitrogen, dissolved phosphorus and dissolved copper.

The median concentration of total suspended solids decreased whereas the median concentration of total dissolved solids increased slightly in the effluent (Figure 33). This implies the effectiveness of the sand filters in treating suspended solids but not dissolved solids. The increase in effluent concentration of dissolved solids could potentially occur because of the dissolution of some solids trapped either within the sand filter or detention basins during the transit of the influent stormwater to the BMP outlet. The pH (Figure 34) values increased slightly in the effluent whereas the turbidity became lower. The decrease in turbidity follows the effective removal of suspended solids by the BMP. The increase of pH on the other hand implies some reduction occurring in the system either during the transit between inlet and outlet or in the detention basin.
Table 9. p-values of the Kruskal-Wallis Test for Influent v/s Effluent Concentrations

<table>
<thead>
<tr>
<th>Parameter</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>TDS</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>pH</td>
<td>0.007</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.917</td>
</tr>
<tr>
<td>Turbidity</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total Nitrogen</td>
<td>0.156</td>
</tr>
<tr>
<td>Total NO\text{X}</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total Phosphorus</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dissolved Copper</td>
<td>0.113</td>
</tr>
<tr>
<td>Total Copper</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dissolved Copper</td>
<td>0.113</td>
</tr>
<tr>
<td>Total Zinc</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dissolved Zinc</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Total Lead</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>Dissolved Lead</td>
<td>0.0153</td>
</tr>
</tbody>
</table>

The total copper concentration decreased whereas there was no significant difference between the dissolved and total copper concentration. The concentration of the other two metals decreased significantly in the total as well as dissolved form. Total phosphorus and nitrogen decreased slightly in the effluent whereas there were no statistically significant differences between the NO\text{X} and dissolved phosphorus concentrations.
Figure 33. Box plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.

Figure 34. Box plot of influent and effluent concentration of total pH, temperature and turbidity in stormwater runoff.
Figure 35. Box plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.
Figure 36. Box plot of influent and effluent concentration of total and dissolved phosphorus, total NOX and nitrogen in stormwater runoff.

The probability plots (Figure 37, Figure 38, Figure 39, Figure 40) describes the fraction (y-axis) of times a value less than the corresponding concentration (x-axis) was observed. Distinct influent and effluent probability curves reflect differences between the influent and effluent concentrations whereas overlapping curves reflect no differences. For example, if the 0.95 (y-axis) values correspond to 100 mg/L on the influent probability curve, it implies that 95% of the times, the influent concentration remain less than 100 mg/L. If the effluent curve lies to the left of the influent curve, it represents effective mitigation. Figure 37 shows that the total suspended solids are effectively
mitigated (effluent curve to the left of the influent probability curve) whereas the total dissolved solids are not. In fact, statistically, the effluent concentration of the total dissolved solids remains higher than the influent (curve lying to the right of the influent curve). Total turbidity is also effectively mitigated (Figure 38) whereas the probability curves for temperature are almost identical overlapping, implying no effect of sand filters on the thermal pollution. The sand filter does little to alter the pH of the stormwater runoff. It was also observed that the pH of the influent is greater than ~7 over 25% of the times whereas the pH is higher than 7 in the effluent for more events than is the influent. This implies the influent is more acidic than the effluent.

The total concentration of metals (Figure 39) reflects some level of mitigation of metals coming in stormwater runoff through separation between the probability curves for the influent and effluent. The dissolved concentration of zinc also shows distinct mitigation as a result of the sand filter. However, there is no change in the concentration probability curves of dissolved copper and lead, implying the ineffectiveness of the sand filter for the two metals statistically.

The sand filter performs variably with respect to nutrients (Figure 40). The total concentration of phosphorus is effectively mitigated through the sand filter whereas the dissolved phosphorus is not. On the other hand, the concentration of NOX is statistically higher in the effluent than in the influent. The concentration of total nitrogen as N on the other hand is unaffected by the presence of the sand filter.
Figure 37. Probability plot of influent and effluent concentration of total and dissolved solids in stormwater runoff.
Figure 38. Probability plot of influent and effluent concentration of total pH, temperature and turbidity in stormwater runoff.
Figure 39. Probability plot of influent and effluent concentration of total and dissolved metals in stormwater runoff.
Figure 40. Probability plot of influent and effluent concentration of total and dissolved phosphorus and total NOX and nitrogen in stormwater runoff.
4.5.3 Efficiency of Sand Filter at Canton Study Site

Nine storm events were monitored between the months of February 2011 through May 2011 during the course of this study, with varying antecedent dry periods, total rainfall, duration, and rainfall intensities (Table 10).

<table>
<thead>
<tr>
<th>Event</th>
<th>Date</th>
<th>Antecedent Dry Period (days)</th>
<th>Rainfall Depth (mm)</th>
<th>Rainfall Duration (hrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>2/25/2011</td>
<td>15</td>
<td>12.30</td>
<td>2.92</td>
</tr>
<tr>
<td>3</td>
<td>2/28/2011</td>
<td>3</td>
<td>18.03</td>
<td>2.92</td>
</tr>
<tr>
<td>4</td>
<td>3/5/2011</td>
<td>5</td>
<td>46.70</td>
<td>29.33</td>
</tr>
<tr>
<td>5</td>
<td>3/9/2011</td>
<td>3</td>
<td>81.50</td>
<td>15.58</td>
</tr>
<tr>
<td>6</td>
<td>3/15/2011</td>
<td>5</td>
<td>28.10</td>
<td>7.00</td>
</tr>
<tr>
<td>7</td>
<td>3/26/2011</td>
<td>2</td>
<td>40.10</td>
<td>15.17</td>
</tr>
<tr>
<td>8</td>
<td>4/4/2011</td>
<td>3</td>
<td>40.30</td>
<td>3.50</td>
</tr>
<tr>
<td>9</td>
<td>4/11/2011</td>
<td>6</td>
<td>10.60</td>
<td>2.67</td>
</tr>
<tr>
<td>10</td>
<td>4/15/2011</td>
<td>3</td>
<td>57.40</td>
<td>8.58</td>
</tr>
</tbody>
</table>

The performance of the sand filter in reducing pollutant concentrations was evaluated by analyzing the quality of water at the inlet to the sedimentation basin (referred to as inlet), inlet to the sand filter (referred to as intermediate) and outlet of the sand filter (referred to as outlet).

In-situ conductivity (Figure 41) was consistently highest at the outlet, while pH (Figure 41) across the site tended to be in the slightly basic range, likely due to runoff flowing over Portland cement concrete surfaces. This is in contrast to the pH of runoff observed in other sand filter locations where the influent stormwater was slightly acidic. However, in line with the effect of sand filter, the pH of effluent stormwater is higher
than the influent pH. Average temperature (Figure 41) measured at the three inlet locations showed a reasonably consistent drop between the inlet and outlet. The majority of the drop in temperature took place at the sand filter, suggesting that during the summer, the sand filter will likely act as a heat sink, preventing high temperature runoff from reaching Canton Creek. A consistent reduction in suspended solids and turbidity was observed between the inlet and outlet locations. Despite the short retention time observed from the hydrographs (Figure 3), the large reduction in TSS and turbidity between the inlet and the intermediate location suggests that there is sufficient time for a large amount of settlement and particle removal to take place. As observed in-situ, although conductivity decreased from the inlet to the intermediate location, the conductivity observed at the outlet was consistently the highest measured value. Results from measurements of total and dissolved lead, copper, and zinc measured were mixed in terms of treatment efficiency. While the total zinc underwent a consistent decrease from the inlet to the outlet, elevated levels of copper were consistently measured at the outlet, compared to the inlet. Lead performance was mixed, with only one half of the events measured from late March through April experiencing a decrease in the total lead from inlet to outlet. Measured dissolved heavy metals were significantly lower than the total heavy metals, and in many cases were below detection limits, which suggest that the bulk of heavy metals measured at the site were associated with suspended solids. Total nitrogen, nitrites + nitrates (NOx), and total phosphorus were measured throughout March and April. Total nitrogen and NOx were removed between the outlet for three out of four measured events. In the case of total nitrogen, a significant portion of the removal appears to be occurring in the detention pond. Measured concentrations of total
phosphorus were lower than total nitrogen and NOx, and decreased across the site from inlet to outlet during all but one observed event.

Figure 41. Bar plot representing influent v/s effluent concentrations of physical characteristics measured for different storm events.
Figure 42 Bar plot representing influent v/s effluent concentrations of nutrients measured for different storm events.

Figure 43. Bar plot representing influent v/s effluent concentrations of metals measured for different storm event.
4.5.4 Design parameters

The previous analysis focuses on analysing the impact of sand filters on each pollutant individually. In order to evaluate the efficiency of the sand filter to simultaneously mitigate various pollutants, a k-means cluster analysis was set up for the cleaning efficiency of sand filter for total metals (copper, lead and zinc). The clusters were iteratively computed till a cluster was formed for sand filters effectively mitigating all three metals. The design parameters of the sand filters comprising of this cluster were then evaluated to provide an appropriate design criteria for sand filters that conforms to the cleaning efficiency represented by the cluster. The design parameters of the sand filters as well as the cluster locations are shown in Figure 44.

Figure 44. Clusters of cleaning efficiency of sand filters for total metals and design parameters of the sand filters for each cluster.
The median of the removal efficiency in different clusters is provided in Table 11. Cluster 2 delineates the sand filters that perform relatively better than the others in mitigating metal pollutants.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Copper</td>
<td>0.47</td>
<td><strong>0.62</strong></td>
<td>-0.02</td>
<td>0.59</td>
</tr>
<tr>
<td>Lead</td>
<td>0.81</td>
<td><strong>0.87</strong></td>
<td>0.84</td>
<td>0</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.2</td>
<td><strong>0.91</strong></td>
<td>0.87</td>
<td>0.90</td>
</tr>
</tbody>
</table>

The median values of the design parameters of the sand filters comprising different clusters are provided in Table 12. The results indicate that a single design parameter cannot be outlined as controlling the removal efficiency of the sand filter. For example, cluster 2 and 4 have similar pool area and depth, yet because of differences in the pool area and depth, the cleaning efficiency of the 2 clusters is different. The best combination of design parameters based on the data analysed is highlighted in Table 12.

<table>
<thead>
<tr>
<th>Design parameter</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter Area (m²)</td>
<td>32</td>
<td><strong>280</strong></td>
<td>57</td>
<td>280</td>
</tr>
<tr>
<td>Filter depth (cm)</td>
<td>46</td>
<td><strong>46</strong></td>
<td>46</td>
<td>46</td>
</tr>
<tr>
<td>Pool area (m³)</td>
<td>56</td>
<td><strong>102</strong></td>
<td>102</td>
<td>518</td>
</tr>
<tr>
<td>Pool depth (m)</td>
<td>12</td>
<td><strong>8</strong></td>
<td>12</td>
<td>2</td>
</tr>
</tbody>
</table>
A similar cluster analysis (Figure 45) was computed for the total suspended and dissolved solids.

![Cluster analysis and design parameters of sand filters with respect to total solids.](image)

Figure 45. Cluster analysis and design parameters of sand filters with respect to total solids.

The median values of the removal efficiency and the design parameters of the corresponding clusters are provided in Table 13 and Table 14 respectively. It is seen that cluster 2 performs the best when assessing the cleaning efficiency of sand filters for total suspended and total dissolved solids simultaneously.

<table>
<thead>
<tr>
<th>Metal</th>
<th>Cluster 1</th>
<th>Cluster 2</th>
<th>Cluster 3</th>
<th>Cluster 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>0.19</td>
<td><strong>0.88</strong></td>
<td>0.91</td>
<td>0.92</td>
</tr>
<tr>
<td>TDS</td>
<td>-0.41</td>
<td><strong>0.26</strong></td>
<td>-0.85</td>
<td>-0.24</td>
</tr>
</tbody>
</table>

Table 13. Median Cleaning Efficiency of Clusters
In terms of median values of design parameters, the values of cluster 2 for total solids and cluster 4 for total metals are similar and vice-versa. Therefore, if we adopt the median values of cluster 2 (for total metals that corresponds to cluster 4 for total solids) as the design criteria for the sand filter, it may provide efficient cleaning of metals and high efficiency for removal of total suspended solids but not for total dissolved solids. In contrast, if design parameters corresponding to cluster 2 for total solids are used to design BMPs, an overall cleaning efficiency for total solids may be obtained but the sand filter will perform poorly for total metal concentrations in the stormwater runoff.
4.6 CONCLUSION

In summary, highway runoff characterization, sand filter performance, and design parameter assessment yielded the following results.

- The distribution of most incoming pollutants follows a log normal distribution implying that the occurrence of extreme loadings is less probable.
- Historical sand filter data reveals that among nutrients, a majority of the total phosphorus is mitigated by the sand filter whereas neither dissolved phosphorus, total NO$_X$ or nitrogen is mitigated. Among metals, zinc is mitigated by the sand filter but not copper and lead.
- Quantitative characterization of highway runoff at the Canton study site for selected parameters indicated that the parameters were well below state standards and other studies conducted elsewhere in the United States, with the exception of pH.
- Temperature of the stormwater is decreasing as water flows through the sand filter. Conductivity measured at the outlet is consistently higher than the conductivity at the inflow.
- Effluent dissolved concentrations of lead and zinc were below state standards in all but one instance, while effluent dissolved copper exceeded state standards in five events.
- An analysis of the design parameters of sand filters that can effectively mitigate total metals have a median pool area of 102 m$^2$, pool depth of 8 m, filter surface area of 280 m$^2$ and filter depth of 46 cm.
CHAPTER 5: THERMAL BEHAVIOR OF IRON OXIDE COATED SANDS

5.1 INTRODUCTION

An understanding of the thermal behavior of soils is important in engineering projects where heat transfer is involved – for example, nuclear waste disposal, high voltage buried power cables, underground heat storage, pavement performance in extreme climates, and heat generation in landfills. Thermal conductivity is the fundamental soil parameter which needs to be investigated to understand such heat transfer processes. While thermal conductivity measurements for soils have been performed for some time, little effort has focused an understanding of the influence of soil coatings on the thermal conductivity of a given system. In nature, such iron oxide coated soils are formed as a result of chemical weathering and exist as residual soils, primarily in hot and humid climates throughout the world. In the present study, laboratory thermal needle probe tests, based on transient line heat source method, were conducted to investigate the effect of iron oxide coatings on the thermal conductivity of laboratory prepared coated sands and to assess the possible role of iron oxide coated sands as engineered amendments in sand filter BMPs. Tests were conducted on uncoated, goethite coated and hematite coated ASTM 20-30 and ASTM 100-200 sands.
5.2 THERMAL CONDUCTIVITY OF GRANULAR MATERIALS

5.2.1 Mechanism of Heat Conduction

Thermal conductivities of various materials vary over several orders of magnitude. Figure 46 shows thermal conductivities for various states of matter at normal temperature and pressure. Natural soils can exhibit wide range of thermal conductivities. However, for pure sands the inclusion of water has a dominant impact on the thermal conductivity of the soil matrix.

![Figure 46. Range of thermal conductivities for various states of matter [68].](image)

Solids can be considered to be made up of free electrons and atoms bound in a periodic arrangement (lattice). Heat transfer in solids can be due to two effects: 1)
Migration of free electrons and lattice vibrational waves. Lattice vibration quanta are termed as phonons [68]. In pure metals electron contribution dominates, while in insulators and semi-conductors transfer through phonons is important. When electrons and phonons carry thermal energy that results in conduction, the total thermal conductivity is expressed as the sum of the two individual components.

Heat- transfer processes in soils can be represented in terms of Fourier’s law of heat conduction.

\[
q = -k \cdot \nabla T
\]

Where, \( q \) is heat flux (thermal energy per unit area), \( k \) is thermal conductivity, \( \nabla \) is the dimensional del operator and \( T (x, y, z) \) is the scalar temperature field. Hence, thermal conductivity of soil can be defined as the amount of heat passing in unit time through a unit cross-sectional area of the soil under a unit temperature gradient applied in the direction of heat flow. Since a soil is a porous media, it consists of two phases, i.e. a solid phase and a fluid phase (air or water), the heat transfer mechanisms for a soil matrix can be described as shown in Figure 47.

![Figure 47. Heat transfer in soils [69].](image-url)
Thermal conductivity of soil constituents varies across two orders of magnitude. $k_{\text{mineral}} \geq 3 \text{ W/m.K} > k_{\text{water}} = 0.56 \text{ W/m.K} > k_{\text{air}} = 0.026 \text{ W/m.K}$ [69]. This suggests that the most important heat transfer path in soils is through particle-particle contacts. Convection plays an important role when the mean particle size exceeds 6 mm (gravel) [70] because the increased particle size results in an increase in pore volume. As a result continuous flow channels are formed in the porous media where water can move freely due to temperature gradients within the soil. Radiative heat transfer is negligible for sand sized particles ($75 \mu m – 4.75 \text{ mm}$)[69]. Several theoretical models have been suggested in previous studies based on the thermal conductivity of individual soil constituents and their respective volume fraction in the soil matrix. $n$ is volume fraction of soils These relations have been summarized in Table 15.

Table 15. Theoretical Thermal Conductivity Models

<table>
<thead>
<tr>
<th>Model</th>
<th>Effective Thermal Conductivity, $k_e =$</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Series</td>
<td>$\sum (n/k_i)^{-1}$</td>
<td>[71]</td>
</tr>
<tr>
<td>Parallel</td>
<td>$\sum n_k_i$</td>
<td></td>
</tr>
<tr>
<td>Geometric Mean</td>
<td>$\prod k_i^{n_i}$</td>
<td>[72]</td>
</tr>
<tr>
<td>Log</td>
<td>$-a \ln(n) + p$</td>
<td>[73]</td>
</tr>
<tr>
<td></td>
<td>$[a = 0.291 \text{ W/mK}, \ p = 0.026 \text{ W/mK}]$</td>
<td></td>
</tr>
<tr>
<td>Volume Fraction</td>
<td>$\left[n k_{\text{air}}^{n} + (1-n) k_{\text{mineral}}^{n}\right]^{1/s}$</td>
<td>[69]</td>
</tr>
<tr>
<td></td>
<td>$[s = -0.25]$</td>
<td></td>
</tr>
<tr>
<td>Hashin and Shtrikman Bounds</td>
<td>$k_1 \left[1 + (3 n_2 (k_2 – k_1))/(3k_1 + n_1 (k_2 – k_1))\right]$</td>
<td>[74]</td>
</tr>
<tr>
<td></td>
<td>$[\text{Lower: 1-pore, 2-solid, Upper: 1-solid, 2-pore}]$</td>
<td></td>
</tr>
<tr>
<td>Cubic Cell</td>
<td>$(\beta -1)/(k_a \beta) + (\beta /(k_a (\beta ^2 - 1) + k_m))\beta = [1/(1-n)]^{1/3}$</td>
<td>[75]</td>
</tr>
</tbody>
</table>
Thermal conductivity of granular materials has been a topic of study for quite some time. It has been studied for several granular materials. Different models to estimate thermal conductivity have been suggested. Also, the effects of various parameters on the thermal conductivity of granular materials have been studied. A brief review of the same is presented here.

5.2.2 Studies on Thermal Properties of Granular Materials

Thermal properties of several granular materials have been studied. These include Ottawa 20-30 [69, 76, 77], F-110 sand [69], Blasting sand [69], crushed sand [69], quartz sand [78-83], Monterey sand [79], bentonite [84], Bangkok clay [85], clay [86], Leda clay [87], clay-sand mixture [82, 88], sand-clay mixture [89], clay-graphite [88], Cotton soil-sand [70], fly ash [81, 82, 90], silt [81, 83], gravel [81], granite [91], glass beads [78, 92, 93], sandy loam [94], clay loam [94], silty sand [82], leaf compost [95], Black cotton soil [96], steel spheres [97], lead shot [78], silicon nitride [98], hydrite bearing sediments [99].

5.2.3 Studies on Factors Affecting Thermal Conductivity of Granular Materials

Different factors affecting the thermal conductivity of materials have also been studied. These include – mineralogy[78, 91], particle size [82, 83, 93, 98], structure [100], applied pressure [69, 97], density [70, 78, 79, 84, 89, 101], water content [70, 79, 84, 101-103], presence of salts/ organic matter [92, 93, 104], peat content [105], temperature [76, 79, 89, 106-108], contact behavior [69, 102].
Various factors which affect the thermal conductivity of soils are porosity, dry density, mineralogical composition of soil, temperature and degree of saturation of the soil. Thermal conductivity of soils decreases linearly with the increase in the porosity of the soil [80]. The variation of thermal conductivity of sands with porosity has been plotted and the models shown in Table 15 have been checked for consistency in Figure 4. Series-Parallel and Hashin and Shtrikman provide upper and lower bounds of effective thermal conductivity for soils. It is observed that the log model agrees well with the experimental data from [69] and [109] while other models tend to over or under predict the effective thermal conductivity.

Figure 48. Variation of Thermal Conductivity of with Porosity.
Increase in the dry density of a soil results in a decrease in its thermal resistivity [79]. This effect can be easily understood by the increase in the number of contacts due to an increase in the coordination number between particles in soil in a soil matrix with greater density for a unit volume.

Water is more conductive when replacing air in the pore space of the soil, increases the thermal conductivity of soils, though the main mode of heat transfer is still conduction through particle contacts. It is evident from the plot of thermal conductivity of sand for increasing degree of saturation of the pore space from the experimental data of [109] that the rise in thermal conductivity is larger when the degree of saturation is low. This is due to the formation of pendular water Figure 47 that increases the area of contact between soil particles. Thus, during pendular stage heat transfer rises quickly. As the degree of saturation is increased further pore space is occupied by water and the subsequent rise in thermal conductivity decreases Figure 49.
Figure 49. Effect of degree of saturation on thermal conductivity of sands [109].

One of the major factors affecting the thermal conductivity of soils is due to the difference in mineralogical composition of soils. Minerals in a soil matrix usually have the maximum thermal conductivity, and air has the lowest as mentioned previously. Thermal conductivities of some of the constituents of soils are presented in Table 16. Most sands have unsaturated thermal conductivities less than 1 W/mK; hence, the importance of the minerals in heat transfer through sands is apparent.
Table 16. Thermal Conductivities of Some Constituents of Soil [110]

<table>
<thead>
<tr>
<th>Material</th>
<th>Thermal Conductivity (W/mK)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz (-)</td>
<td>12.66</td>
</tr>
<tr>
<td>Quartz (+)</td>
<td>6.71</td>
</tr>
<tr>
<td>Quartz (random)</td>
<td>9.09</td>
</tr>
<tr>
<td>Quartz glass</td>
<td>1.27</td>
</tr>
<tr>
<td>Granite</td>
<td>1.72 -3.84</td>
</tr>
<tr>
<td>CaCO₃ (+)</td>
<td>3.80</td>
</tr>
<tr>
<td>Marble</td>
<td>2.08 -2.94</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.22</td>
</tr>
<tr>
<td>Ice</td>
<td>2.22</td>
</tr>
<tr>
<td>Sandstone</td>
<td>2.00</td>
</tr>
<tr>
<td>Dolomite</td>
<td>1.72</td>
</tr>
<tr>
<td>Slate</td>
<td>1.49</td>
</tr>
<tr>
<td>Water</td>
<td>0.61</td>
</tr>
<tr>
<td>Mica (+)</td>
<td>0.59</td>
</tr>
<tr>
<td>Air</td>
<td>0.03</td>
</tr>
</tbody>
</table>

(+) Perpendicular to crystallographic axis
(-) Parallel to crystallographic axis

5.2.4 Development of Techniques to Measure Thermal Conductivity of Granular Materials

Several experimental techniques have been used to measure the thermal conductivity of granular materials. These include steady state method – guarded hot plate [111, 112], transient state methods – single needle probe [69, 77, 81, 94, 99, 113-116], dual needle probe [85, 94, 117-119], multifunctional probes [120], and TDR probes [104].
5.3 MATERIALS AND METHODOLOGY

The tests were conducted on ASTM 20-30 and ASTM 100-200, uncoated sand, hematite coated sand and goethite coated sand. The preparation of iron oxide coated sands is explained in detail [121]. The first step was the pretreatment of solution. Soil was first pretreated by soaking in 3% H$_2$O$_2$ for 24 hrs to remove organics attached to the surface. The sample was then washed with deionized water and dried in the oven for 24 hrs. The sample was then soaked in pH = 3 (HNO$_3$) for 24 hrs and stirred regularly. After 24 hrs, the sample was washed with deionized water and dried in the oven for 24 hrs. The second step was coating of the iron particles via a heterogenous suspension reaction [121, 122]. Preparation of heterogenous suspension included making a solution which contained: $V_{\text{Water}} = 353$ ml, mass of iron oxide, $M_{\text{FeOX}} = 5$g, mass of NaNO$_3$, $M_{\text{NaNO}_3} = 0.3$ g, volume of nitric acid (2N), and $V_{\text{HNO}_3} = 237.1$ μL in a volumetric flask. The above solution was mixed for 24 hours using a magnetic stirrer. The target pH was 3 and ionic strength were 0.01. The final step was mixing sand with the solution. 125 gram of sand was added to the prepared solution in a shaking bottle. The mixture was shaken in a twist shaker for 24 hrs. The pH of the supernatant after 24 hrs was checked and adjusted to 3. After the pH of the solution became stable, the shaker was stopped and the coated sand was washed with deionized water until the supernatant was clear. The sample was then dried in the oven.
The properties of the prepared sand samples are presented in Table 17.

### Table 17. Properties of Uncoated and Coated Sands Used in the Tests.

<table>
<thead>
<tr>
<th>Properties</th>
<th>ASTM 20/30*</th>
<th></th>
<th>ASTM 100-200**</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Uncoated Goethite</td>
<td>Hematite</td>
<td>Uncoated Goethite</td>
<td>Hematite</td>
</tr>
<tr>
<td>d50 (mm)</td>
<td>0.11</td>
<td>0.11</td>
<td>0.72</td>
<td>0.72</td>
</tr>
<tr>
<td>Gs</td>
<td>2.65</td>
<td>2.66</td>
<td>2.65</td>
<td>2.66</td>
</tr>
<tr>
<td>$\varepsilon_{\text{max}}$</td>
<td>0.848</td>
<td>0.88</td>
<td>0.739</td>
<td>0.746</td>
</tr>
<tr>
<td>$\varepsilon_{\text{min}}$</td>
<td>0.535</td>
<td>0.53</td>
<td>0.519</td>
<td>0.526</td>
</tr>
<tr>
<td>Iron Content (mg Fe/g sand)</td>
<td>0</td>
<td>0.62</td>
<td>0</td>
<td>0.13</td>
</tr>
</tbody>
</table>

*data from [123], **data from [124]

Figure 50. From left to right - Image of a) Uncoated 20-30 sand b) Goethite Coated 20-30 Sand and c) Hematite Coated 20-30 Sand.
The tests were conducted on dry uncoated and coated soils based on the infinite line heat source theory as described in [125]. The test setup consists of a dual thermal needle probe (KD2Pro) which is used to supply a constant amount of heat per unit length of the needle. The temperature rise in a homogenous isotropic medium for radial heat flow is given by the equation

$$\frac{\partial T}{\partial t} = D \left[ \frac{\partial^2 T}{\partial r^2} + \frac{1}{r} \left( \frac{\partial T}{\partial r} \right) \right]$$

Where, \( r \) is the radial distance from the center of needle at which temperature is measured, \( t \) is time, \( T \) is temperature and \( D \) is the thermal diffusivity. For the test using a dual needle probe, heat is applied for a time (th) and temperature is measured in the monitoring needle, 6mm apart during the heating and cooling period. The collected data is fit to the following equations using a non-linear least squares procedure.

For the heating phase:

$$T^* = b_0 t + b_1 Ei \left( \frac{b_2}{t} \right)$$

For the cooling phase:

$$T^* = b_0 t + b_1 \left\{ Ei \left( \frac{b_2}{t} \right) - Ei \left[ \frac{b_2}{t - t_h} \right] \right\}$$

Where,

$$T^* = \frac{4\pi (T - T_0)}{q}$$

\( Ei \) is exponential integral and \( b_0, b_1 \) and \( b_2 \) are fitting constants.
$T_0$ is the temperature at the start of the test and $q$ is the heat input. Thermal conductivity is obtained from

$$k = \frac{1}{b_1}$$

The tests were conducted in a modified oedometer cell to observe the effect of vertical stress on the thermal conductivity of test specimens. For the loading part of the curve, measurements were conducted starting at an initial stress of 1 kPa and increased incrementally until a maximum stress of 438 kPa. The measurements were then conducted for unloading part of the curve. The setup is shown in Figure 51.

![Figure 51. Test setup for thermal conductivity measurements.](image)
5.4 RESULTS AND DISCUSSION

5.4.1 Thermal Conductivity Behavior Under Applied Vertical Stress

A nonlinear increase in the thermal conductivity for all samples with an increase in applied vertical stress was observed. A trend of this behavior is shown for ASTM 20-30 uncoated, ASTM goethite coated and ASTM hematite coated sands in Figure 52 Figure 53 and Figure 54. The loading and unloading curves for thermal conductivity did not follow the same path and a hysteresis was observed, with thermal conductivities of the specimen during the unloading portion being higher when compared to the loading portion. This was due to particle rearrangement under applied vertical stress. The increase in thermal conductivity at the highest applied vertical stress as compared to the initial state was roughly 25% for test specimens. Tests were conducted for relative densities of 30%, 50% and 70%. Successively higher thermal conductivities during the loading and the unloading part of the curves was observed for the specimens with increasing relative density. Denser specimens have more particle to particle contacts hence improving the particle-particle conduction.
Figure 52. Thermal conductivity evolution in uncoated ASTM 20-30 under applied vertical stress.
Figure 53. Thermal conductivity evolution in goethite coated ASTM 20-30 under applied vertical stress.
Figure 54. Thermal conductivity evolution in hematite coated ASTM 20-30 under applied vertical stress.

5.4.2 Thermal Conductivity Behavior with Porosity

Results of behavior in thermal conductivity for uncoated and coated ASTM 20-30 and ASTM 100-20 sands is plotted in Figure 55 and Figure 56 respectively. Examination of the results indicates that a linear increase in thermal conductivity is observed with reduced porosities. This is due to possible increase in the number of contacts per volume resulting in increased conduction efficiency[69]. The thermal conductivity of uncoated ASTM 20-30 specimens varied from 0.24 W/mK to 0.34 W/mK. Goethite coated ASTM 20-30 specimens showed similar thermal conductivity ranges as compared to the
uncoated ASTM 20-30 samples for different relative densities. This indicates, even with
an increase in the number of contacts per volume, goethite coatings do not have an effect
on the thermal conductivity. This is due to low iron content present on the surface of
goethite coated sands. However, ASTM 20-30 hematite coated samples for loose and
dense condition were higher as compared to the uncoated and goethite coated samples.
This can be due to two reasons. First, with increased particle contacts there is a
possibility of heat conduction between iron-iron nanoparticle contacts, sorbed on the
surface of the sand particle for loose conditions. For dense specimens in addition to iron-
iron nanoparticle contacts there is a possibility of heat conduction through hematite-sand
particle contacts. Second, the iron content on the surface of sand particle is higher as
compared to goethite coated sand hence the possibility of iron-iron nanoparticle contact
and iron-sand contact is more for hematite coated particles. In the case of ASTM 100-200
specimens, observed thermal conductivities are lower as compared to ASTM 20-30
uncoated and coated samples. This may be due to mean small grain size of the ASTM
100-200 specimens as there is a correlation between grain size and thermal conductivity
observed [83]. The comparable thermal conductivities observed for hematite coated,
goethite coated and uncoated ASTM 100-200 samples indicate the for smaller grain size
the iron coating does not seem to have an impact on enhanced thermal conductivity. The
thermal conductivity range observed for hematite coated ASTM 100-200 sand was
between 0.25 -0.3 W/mK as compared to 0.26 – 0.36 W/mK in the case of uncoated
ASTM 20-30 sand.
Figure 55. Behavior of thermal conductivity for uncoated and coated ASTM 20-30 specimens with change in porosity.
Figure 56. Behavior of thermal conductivity for uncoated and coated ASTM 100-200 specimens with change in porosity.

5.4.3 Thermal Conductivity Behavior with Dry Density

Results of the thermal conductivity behavior plots with dry density are shown in Figure 57 and Figure 58. Examination of results indicated that the thermal conductivities of all the specimens increased linearly with the increase in dry density. This is explained by the fact that air which has a very low thermal conductivity is replaced by mineral with a higher thermal conductivity. It was observed that thermal conductivity for goethite coated and uncoated ASTM sands was similar. This indicates no effect of iron oxide
coatings on the thermal conductivity of the sand particles. However, hematite coated sands exhibit higher thermal conductivities as compared to uncoated and goethite coated ASTM 20-30 samples. In the case of ASTM 100-200 uncoated, goethite coated and hematite coated samples, an insignificant change in the thermal conductivity values was observed.

Figure 57. Behavior of thermal conductivity for uncoated and coated ASTM 20-30 specimens with change in dry density.
Figure 58. Behavior of thermal conductivity for uncoated and coated ASTM 100-200 specimens with change in dry density.

5.4.4 Comparison of Thermal Conductivity Results with Literature and Models

There are several theoretical models for estimating effective thermal conductivity of soils as discussed previously in the review. Theoretical models do not perform very well for dry or soils as soils have very due to low thermal conductivities of air as exhibited earlier except the log model. Hence, it is difficult to compare results of thermal conductivity with theoretical models; consequently, empirical models are compared here
with the results of this study. The empirical models are shown in Table 18. The comparison of thermal conductivity results with existing model is shown in Figure 59.

Table 18. Empirical and Semi-Empirical Models for Thermal Conductivity of Soils [123]

<table>
<thead>
<tr>
<th>Reference</th>
<th>Equation*</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>[126]</td>
<td>( k_t(dry) = \frac{0.135 \cdot \gamma_d + 64.7}{2700 - 0.947 \cdot \gamma_d} \pm 20% )</td>
<td>Natural Soils ( \gamma_d \text{ in kg/m}^3 )</td>
</tr>
<tr>
<td>[126]</td>
<td>( k_t(dry) = 0.039 \cdot n^{-2.2} \pm 25% )</td>
<td>Crushed Rocks</td>
</tr>
<tr>
<td>[127]</td>
<td>( k_t(dry) = 0.025 + 0.238 \cdot \gamma_d - 0.193 \cdot \gamma_d^2 + 0.114 \cdot \gamma_d^3 )</td>
<td>Mineral and Organic Soils ( \gamma_d \text{ in g/cc} ) ( \alpha: 1.7 &amp; \beta: 1.8 ) (Crushed Rocks) ( \alpha: 0.75 &amp; \beta: 1.2 ) (Natural Soils) ( \alpha: 0.3 &amp; \beta: 0.87 ) (Organic Soils)</td>
</tr>
<tr>
<td>[100]</td>
<td>( k_t(dry) = \alpha \cdot 10^{-\beta \cdot n} )</td>
<td></td>
</tr>
<tr>
<td>[128]</td>
<td>( k_t(dry) = -0.56 \cdot n + 0.51 )</td>
<td>0.2 (&lt; \ n \ &lt; 0.6 )</td>
</tr>
</tbody>
</table>

\( K_t(dry) \): thermal conductivity of soil in W/mK; \( \gamma_d \): dry density; \( n \): porosity

Comparison of thermal conductivity results for uncoated and iron oxide coated ASTM 20-30 and ASTM 100-200 sands is plotted in Figure 59. It is observed that natural soils exhibit a wide range of thermal conductivities with respect to dependence on dry
density. This is intuitive as natural soils are more complex in particle size and shape, mineralogy etc. However, results for thermal conductivity of pure sands are comparatively higher than natural sand results [69]. The results of thermal conductivity measurements in this study agree well with the pure sand results. The empirical model under predicts the thermal conductivity results for pure sands and the thermal conductivity results from the current study. However, most of the data from the current study lie within the upper bound of the trendline. This under prediction is a result of the trend line generated from mainly natural soils. However, clean sands tend to exhibit higher thermal conductivities.

Figure 59. Comparison of thermal conductivity test results with an existing empirical model for dry density and existing thermal conductivity data for pure sand and natural soil [123, 126]. Previous dataset includes pure sand [69, 123], natural soil [126, 129], trend line fit [126].
Figure 60. Comparison of thermal conductivity test results with porosity from existing literature[123]. Dataset includes pure sand [69], natural soil [126, 129].

The thermal conductivity results from this study were also compared with the behavior of pure sands and natural soils with porosity (Figure 60). Uncoated and coated sand results agree well with pure sands.
5.5 CONCLUSION

In conclusion,

- Thermal conductivity tests were conducted on dry uncoated, goethite coated and hematite coated sands iron oxide coated sands with applied vertical stress.
- It was observed that thermal conductivity evolution for samples was non-linear during the loading and unloading phase and hysteresis was observed.
- Thermal conductivity results for uncoated and coated samples increased linearly with a decrease in porosity.
- A linear increase in thermal conductivity with an increase in dry density was observed.
- The thermal conductivity of ASTM 20-30 hematite coated sand particles was observed to be higher as compared to the goethite coated samples and uncoated particles. Thus, 20-30 hematite coated sands have the possibility of being used as amendments where enhanced heat dissipation is required as in cases of sand filters at sites where thermal pollution is a concern.
CHAPTER 6. METAL ADSORPTION BY IRON OXIDE COATED SANDS

6.1 INTRODUCTION

Highway runoff is rich in concentrations of dissolved heavy metals that are typically generated from multiple building material and vehicular sources. Three metals that are of significant interest are copper, zinc and lead. Specifically, the primary sources for copper in highway runoff are roofing material and brake lining, zinc is sourced from brake linings, galvanized steel and tire wear, while lead is primarily an outcome of the breakdown of brake linings [130]. The presence of metals in highway runoff poses the most serious threat to aquatic ecosystems of receiving streams.

In the past, roadside contaminant treatment facilities were passive and based primarily on attenuation of peak flows and avoidance of flooding. Recently, more attention has recently been directed to construct facilities that also remove pollutants. The majority of stormwater controls that are being used to treat roadway stormwater runoff before it is discharged to water systems include treatment based on detention (stormwater ponds, trenches, bioretention etc.) and filtration. A limitation of detention systems is that dissolved metals and colloids cannot be removed effectively via settling [130, 131]. Therefore, some sort of a treatment system needs to be designed to trap the dissolved metals, and application of filtration systems where sorption is used to contain the dissolved heavy metals is promising [130, 132].
One method of highway runoff pollutant mitigation for the state of Georgia is the sand filter. Even though this method of treatment is financially viable and performs well with respect to total solid (pollutant) removal, it does not perform well for treating dissolved metal pollution. An innovative engineering solution to this problem has been the introduction of engineered materials like coated sands, which can adsorb metal concentrations from the passing stormwater and hence mitigate the quantity of metals that reach the receiving streams. Due to the present abundance and conditions that favor the formation of iron oxide coated sands [121], there is interest in the potential use of these sands as sorbents in these applications.

The removal of dissolved pollutants from stormwater requires a sand filter medium that can sorb the pollutants out of the runoff as it filters through. The sorptive capabilities of a soil depend on a number of factors- 1) properties of the soil material and chemical nature of the pollutant, 2) total available surface area on which the pollutant can sorb, and 3) distribution of the surface area, i.e. how fast the runoff travels through the soil and comes in contact with soil particle surfaces.

In this study, the utility of the two stable forms of iron oxide coated sands (hematite and goethite) coated sands were compared against uncoated sands as a sand filter medium. Some studies [130] on the sorption of heavy metals on different forms of coated sands have been conducted before, and the use of iron oxide coated sands as sorbates for the removal of heavy metals has been encouraging [133], but it was also observed [130] that iron oxide coated sands perform moderately in the removal of certain heavy metals. However, practical engineering applications also necessitate the need to evaluate the impact of variables, such as co-existing metals in the runoff, on the performance of
coated sands. This work focuses on evaluating the utility of removal of three heavy metals (copper, zinc and lead) by using the iron oxide coated sands. In addition to the different forms of iron oxide coatings on the sand that affect its surface area [121], the effect of varying soil gradation on sorptive removal of these heavy metals was also studied.

6.2 MATERIALS AND METHODS

6.2.1 Sorbents

Six different sorbents were used in this analysis: uncoated ASTM graded sand, ASTM 100/200, hematite coated sand, and goethite coated sand (graded and ASTM 100/200) soils were prepared in the laboratory to be used as sorbents in the study. The particle size distributions of the two soil types ensure different void ratios (Table 19) and particle sizes of the soil. The D$_{50}$ grain size of ASTM 100/200 is smaller than that of the graded soils (Table 19). Thus, the surface area of the ASTM 100-200 soils is larger than that of the graded soils. However, the iron oxide coating content on the graded soils is higher for the graded soils. Therefore, comparison between the performance of the ASTM 100-200 sand and the graded sand, shows that the larger surface area of the ASTM 100-200 soils can be mitigated by the higher iron oxide coating of the graded sand.
### Table 19. Material Properties

<table>
<thead>
<tr>
<th>Properties</th>
<th>ASTM graded</th>
<th></th>
<th></th>
<th>AST 100/200**</th>
</tr>
</thead>
<tbody>
<tr>
<td>D$_{50}$ (mm)</td>
<td>0.365</td>
<td>0.365</td>
<td>0.365</td>
<td>0.11</td>
</tr>
<tr>
<td>Specific Gravity</td>
<td>2.65</td>
<td>2.67</td>
<td>2.66</td>
<td>2.65</td>
</tr>
<tr>
<td>Iron Content (mg Fe/g sand)</td>
<td>-</td>
<td>1.22</td>
<td>0.23</td>
<td>-</td>
</tr>
</tbody>
</table>

*D$_{50}$: median grain size; Hem.: hematite coated sand; Goe.: Goethite coated sand; **: data from [134]

### 6.2.2 Heavy Metal Concentrations

Stormwater consists of a complex mixture of pollutants, such as dissolved and total metals, organics, nutrients, and salts. In order to simulate stormwater samples and evaluate sorption of different metals together, 12 batches of artificial stormwater with different concentrations of copper (Cu), zinc (Zn) and lead (Pb) (Table 20) were synthetically prepared. These concentrations were determined based on the study done by [130] while honoring the ratios between different pollutant concentrations measured at the field site in Canton, Georgia. The pollutant concentrations also represent a wide range of expected concentrations of the different pollutants found in stormwater [4].
Table 20. Constitution of Synthetic Stormwater.

<table>
<thead>
<tr>
<th>Batch</th>
<th>Cu (µg/L)</th>
<th>Zn (µg/L)</th>
<th>Pb (µg/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.6</td>
<td>8.4</td>
<td>2</td>
</tr>
<tr>
<td>2</td>
<td>7.6</td>
<td>24</td>
<td>2.4</td>
</tr>
<tr>
<td>3</td>
<td>36</td>
<td>117</td>
<td>7</td>
</tr>
<tr>
<td>4</td>
<td>246</td>
<td>795</td>
<td>48</td>
</tr>
<tr>
<td>5</td>
<td>585</td>
<td>1905</td>
<td>115</td>
</tr>
<tr>
<td>6</td>
<td>1250</td>
<td>4050</td>
<td>245</td>
</tr>
<tr>
<td>7</td>
<td>246</td>
<td>795</td>
<td>48</td>
</tr>
<tr>
<td>8</td>
<td>585</td>
<td>1905</td>
<td>115</td>
</tr>
<tr>
<td>9</td>
<td>1250</td>
<td>4050</td>
<td>245</td>
</tr>
<tr>
<td>10</td>
<td>2500</td>
<td>8040</td>
<td>490</td>
</tr>
<tr>
<td>11</td>
<td>7500</td>
<td>24300</td>
<td>1470</td>
</tr>
<tr>
<td>12</td>
<td>15000</td>
<td>48240</td>
<td>2940</td>
</tr>
</tbody>
</table>

6.2.3 Batch Testing

Each soil sample was oven-dried at 105°C prior to testing for sorption. The samples were prepared by mixing the required amount of 1000 ppm stock solutions of copper, zinc, and lead and then diluting with deionized water. Batch tests were conducted to determine the amount of sorption of different pollutants onto the different types of soil. A 50 ml sample from each batch of stormwater was sorbed to 1 g soil samples to attain a sorbent per solution concentration of 20 g/L. The soil samples were then shaken for 24 hours in a rotating shaker to provide sufficient contact time to the pollutants to each soil particle. After 24 hours of shaking the sample supernatant was extracted with the help of a syringe filter. Samples were then prepared to test by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES), 13.95 ml of the synthetic stormwater
supernatant and mixed with 1.07 ml of 5% HNO₃ and 15µL of Yttrium, which which was used as an internal standard for the ICP-OES system. This concentration was assumed to represent the equilibrium concentration or the concentration of the stormwater pollutants after the competitive sorption was completed. The sorptive behavior of each pollutant onto the different sands was evaluated separately by fitting the Freundlich isotherm to the sorption results.

6.2.4 Freundlich Isotherm

The synthetic stormwater is a mixture of 3 different pollutants and thus, creates competitive sorption of the pollutants on the available sorption sites. Competitive sorption assumes that each sorption site is equivalent, each sorption site can accommodate only one pollutant at a time, and that there is no interaction between molecules on adjacent sites. The solid phase heavy metal concentrations of copper, lead, and zinc adsorbed on each soil type was computed assuming the following:

\[ q_e = \frac{C_0 - C_e}{X} \]

Where,

\( q_e \) = solid phase heavy metal concentration (µg/g)

\( C_0 \) = initial heavy metal concentration in stormwater samples (µg/L)

\( C_e \) = final concentration of supernatant (µg/L)

\( X \) = sorbent dosage in g/L

The solid phase heavy metal concentrations computed from the test results can be modelled using the Freundlich isotherm [130] as described below.
\[ \log q_e = \log K + \frac{1}{n} \log C_e \]

Where,

\( K \) = correlation constant (L/μg)

\( n \) = Freundlich isotherm constant

\( n \) values determine linearity of the sorptive behavior of the sorbents while \( K \) is the sorption coefficient which represents slope of the sorbed pollutant versus equilibrium concentration. In order to evaluate the overall efficiency of each soil, sorption coefficients, \( K_d \) were determined by

\[ K_d = \frac{q_e}{C_e} \]

Higher values of \( K_d \) imply higher sorption capacity.

6.3 RESULTS AND DISCUSSION

Sorption of sorbates depends primarily on 3 factors – 1) (physical or chemical) affinity of sorbate for sorbents, 2) surface area of sorbents available for sorption and 3) contact time available to sorbents to interact with sorbates. In this study, the sorption results are discussed with respect to the first two factors since an equal amount of time was given to all sorbents (coated and uncoated graded soils and ASTM 100/200) to adsorb the pollutants.
Table 21 represents the mean of the values of all the sorbed metal concentrations on the different soil samples obtained for the 12 batches of stormwater. A clear pattern of heavy metal adsorption for ASTM 100/200 and ASTM graded uncoated soils was not observed even though ASTM 100/200 consists of smaller soil particles than the graded soils (D50 = 0.11 as compared to D50 = 0.365 of the graded soils), which creates larger surface area in the ASTM 100/200 for sorption. A comparison of the coated and uncoated soils reveals that the sorption of metals on the hematite coated soils is higher as compared to uncoated and goethite coated soils, indicating the potential use of iron oxide coated sands in treating stormwater runoff for dissolved metals in sand filters. The increased sorption occurs because the presence of iron coatings on the sand alters the sorption capacity of the sand particles. Past research [130, 133] has shown that sorption of heavy metals tends to increase with iron content. The iron content per gram of coated sand is higher in the ASTM 100/200 than the graded soil (Table 19). Iron content on the hematite coated sands is larger than the goethite coated sands Table 19, hence the amount of iron oxide coating impacts the sorptive behavior for coated sands.

Table 21. Mean of the Sorbed Solids on Different Soil Samples

<table>
<thead>
<tr>
<th>Samples</th>
<th>qe Cu mg/g</th>
<th>qe Zn mg/g</th>
<th>qe Pb mg/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-200 Uncoated</td>
<td>0.038</td>
<td>0.081</td>
<td>0.011</td>
</tr>
<tr>
<td>100-200 Goethite</td>
<td>0.036</td>
<td>0.079</td>
<td>0.011</td>
</tr>
<tr>
<td>100-200 Hematite</td>
<td>0.048</td>
<td>0.092</td>
<td>0.012</td>
</tr>
<tr>
<td>Graded Uncoated</td>
<td>0.036</td>
<td>0.081</td>
<td>0.016</td>
</tr>
<tr>
<td>Graded Goethite</td>
<td>0.041</td>
<td>0.084</td>
<td>0.015</td>
</tr>
<tr>
<td>Graded Hematite</td>
<td>0.038</td>
<td>0.088</td>
<td>0.017</td>
</tr>
</tbody>
</table>
Goethite is an oxyhydroxide of ferric (FeO(OH)) while hematite is an oxide of ferric (Fe$_2$O$_3$). It was found that hematite coating typically enabled better sorption of metals coated sands. However in other studies, higher sorption of metals (specifically arsenic) was also observed on goethite as compared to hematite [135]. Copper, zinc, and lead carry a positive charge in dissolved form. This occurs because goethite has OH$^-$ ion which has greater affinity for positively charged dissolved metal ions as opposed to the oxide that comprises hematite comprises [135]. It should be noted that this occurs in a relatively acidic stormwater environment. In a more basic environment, the dominant mechanism of removal is typically precipitation of dissolved metals because of the presence of excess OH$^-$ ions.

6.3.1 Experimental Results

The plots of equilibrium concentrations and sorbed solid concentrations are shown in Figure 61 through Figure 66.
Figure 61. Copper removal using uncoated and coated ASTM 100-200 sands.
Figure 62. Copper removal using uncoated and coated ASTM graded sands.

The sorption of copper on ASTM 100-200 is larger than on the graded soils except 100-200 goethite coated sand. The concentration on uncoated soils becomes smaller at higher equilibrium concentrations whereas is lower or comparable to coated soils at lower concentrations. This indicates that the coated soils will be adsorb pollutants with a higher efficiency is the pollutant loading is high.
Figure 63. Zinc removal using uncoated and coated ASTM 100-200 sands.
For the same initial concentration, the adsorbed zinc concentrations are slightly higher than copper. The plots for zinc Figure 63 and Figure 64 also reveal that the sorbed solid concentration on hematite coated soils is consistently higher than the uncoated soils at increasing equilibrium concentrations in general. There were some outliers (batch 3) observed in the zinc dataset which may be an error. The analysis indicates better removal of zinc by hematite coated soils at all equilibrium concentrations.
Figure 65. Lead removal using uncoated and coated ASTM 100-200 sands.
Figure 66. Lead removal using uncoated and coated ASTM graded sands.

Lead has a more distinct sorption signature in terms of the sorbed quantities of metals (Figure 65 and Figure 66) versus equilibrium concentrations as the curves are distinct. The results for lead are similar to those of copper, which show better sorption on hematite coated soils for higher pollutant loading. It is also observed that sorption of lead is highest while the lowest sorption is for copper indicating better removal for lead as compared to copper in case of competitive sorption.
6.3.2 Freundlich Isotherm

As observed in chapter 4, copper and lead require treatment for dissolved solids as opposed to zinc, which can be mitigated by treating for suspended solids. Freundlich isotherms were thus fit to the experimental isotherms (Figure 62 through Figure 66) of copper and lead for our dataset. The parameters derived using graphical solution of the isotherm are given in Table 22.

The parameters for the Freundlich isotherm were determined by fitting Freundlich equation to the obtained test results. $R^2$ were used to determine the goodness of fit of the isotherm. The isotherm fit for all soils fit well except for hematite coated sand in the case of lead (low $R^2$). The n value indicates the degree of linearity between sorbate and adsorption. An ‘n’ value of 1 indicates linear adsorption. Both soils demonstrated close to linear behavior for copper and zinc sorption. However, for lead the n values were consistently higher than 2 in case of all soil samples indicating a non-linear behavior of sorption.
Table 22. Parameters for Graphical Solution of Freundlich Isotherm

<table>
<thead>
<tr>
<th>Soils</th>
<th>n Cu</th>
<th>n Zn</th>
<th>n Pb</th>
<th>K Cu</th>
<th>K Zn</th>
<th>K Pb</th>
<th>RSQ Cu</th>
<th>RSQ Zn</th>
<th>RSQ Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-200 Uncoated</td>
<td>1.006</td>
<td>0.885</td>
<td>2.310</td>
<td>0.018</td>
<td>0.007</td>
<td>0.017</td>
<td>0.95</td>
<td>0.88</td>
<td>0.96</td>
</tr>
<tr>
<td>100-200 Goethite</td>
<td>1.008</td>
<td>0.914</td>
<td>3.260</td>
<td>0.019</td>
<td>0.007</td>
<td>0.016</td>
<td>0.95</td>
<td>0.92</td>
<td>0.93</td>
</tr>
<tr>
<td>100-200 Hematite</td>
<td>1.065</td>
<td>0.900</td>
<td>3.094</td>
<td>0.020</td>
<td>0.008</td>
<td>0.016</td>
<td>0.88</td>
<td>0.91</td>
<td>0.90</td>
</tr>
<tr>
<td>Graded Uncoated</td>
<td>1.062</td>
<td>0.823</td>
<td>2.587</td>
<td>0.017</td>
<td>0.006</td>
<td>0.026</td>
<td>0.92</td>
<td>0.93</td>
<td>0.93</td>
</tr>
<tr>
<td>Graded Goethite</td>
<td>0.855</td>
<td>0.857</td>
<td>2.355</td>
<td>0.019</td>
<td>0.007</td>
<td>0.023</td>
<td>0.94</td>
<td>0.95</td>
<td>0.93</td>
</tr>
<tr>
<td>Graded Hematite</td>
<td>0.931</td>
<td>0.865</td>
<td>2.504</td>
<td>0.020</td>
<td>0.007</td>
<td>0.028</td>
<td>0.94</td>
<td>0.95</td>
<td>0.78</td>
</tr>
</tbody>
</table>

RSQ: R-square for fitted Freundlich isotherm

n values for lead are comparatively higher indicating more non-linear behavior for lead and implying that the behavior of sand particles is pollutant specific.

K is an indicator of adsorption capacity. The adsorption capacity for hematite coated ASTM 100-200 sands is highest indicating its maximum utility as a sand filter medium for mitigating dissolved metals. K_d determines the amount of solid sorbed onto the soils per unit of equilibrium concentration of solute. It is also known as the partitioning coefficient and is slope of a linear isotherm approximation. Overall, hematite coated ASTM 100-200 and ASTM graded had highest partitioning coefficients (Table 23) for copper and zinc as compared to the uncoated and goethite coated soils.
Table 23. Sorption Coefficients, $K_d$ of Different Soils for Copper, Zinc and Lead

<table>
<thead>
<tr>
<th>Sample</th>
<th>Cu $K_d$ L/g</th>
<th>Zn $K_d$ L/g</th>
<th>Pb $K_d$ L/g</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-200 Uncoated</td>
<td>0.021</td>
<td>0.010</td>
<td>0.095</td>
</tr>
<tr>
<td>100-200 Goethite</td>
<td>0.021</td>
<td>0.009</td>
<td>0.346</td>
</tr>
<tr>
<td>100-200 Hematite</td>
<td>0.022</td>
<td>0.011</td>
<td>0.371</td>
</tr>
<tr>
<td>Graded Uncoated</td>
<td>0.023</td>
<td>0.009</td>
<td>0.293</td>
</tr>
<tr>
<td>Graded Goethite</td>
<td>0.020</td>
<td>0.010</td>
<td>0.167</td>
</tr>
<tr>
<td>Graded Hematite</td>
<td>0.022</td>
<td>0.010</td>
<td>0.372</td>
</tr>
</tbody>
</table>

6.4 CONCLUSIONS

In this study, the sorption characteristics of dissolved metal pollutants in stormwater on (hematite and goethite) coated and uncoated ASTM 100-200 and graded soils were studied. Stormwater runoff from impervious or low permeability road surfaces is a major contributor of pollutants to the environment. It has the potential to affect the quality of receiving water bodies and other water conveyance systems. Stormwater runoff, especially road runoff, is rich in heavy metals that, unlike organic pollutants, are not degradable in the environment. [1, 130, 136]. The major sources of heavy metals in stormwater runoff from the traffic-related sources are brake linings (Cu, Ni, Cr, Zn, Pb), tire wear (Zn), and autocatalysts (Pt, Pd, Rh) [130, 137]. Also, these metals are either dissolved in water or attached to the particulates [138].

It was observed that hematite coated ASTM 100-200 and ASTM graded soils were better in sorbing metal pollutants as compared to uncoated and goethite coated soils. Hence hematite coated soils are better sand filter amendment for constructing sand filters.
with respect to sorption. This study is valid for slightly acidic stormwater conditions (which is also the typical case as found in chapter 4). The engineering recommendation would be to use hematite coated soils as a sand filter amendment.

This study is based on equilibrium conditions and the effect of varying contact time of the stormwater and sand as a result of varying porosity of different types of soils has not been done. Before implementation of such a sand filter in the field, a non-equilibrium study taking into consideration the flow characteristics and its effect on sorption by varying soils should be conducted.
CHAPTER 7. CONCLUSIONS

7.1 OVERALL CONCLUSIONS

The overall conclusions of this work is that it is important to monitor non-point source runoff for different sites to assess the scope of pollution from runoff to receiving waters so that effective and economical solutions can be found. This monitoring needs to be conducted both during the active construction phase (acute pollution) and post construction phase. Which stormwater control needs to be installed at a particular location requires site specific data so that pollutants of concern can be specifically targeted. Apart from conventional stormwater monitoring procedures, it is important to assess the water quality indicators across different time scales because pollutants vary temporally, and in order to target them efficiently and economically it is important to understand their mechanism and co-behavior across times scales. Apart from event mean concentrations measured in the field, frequently sampled pollutographs, with the help of in-situ monitoring probes, give insight about the complex physico-chemical processes which can be hidden when studying only mean values. It can help an engineer in eliminating multiple pollutant measurement when surrogates can be used, assuming parameters are correlated. This can be helpful in water quality modeling applications for stormwater BMPs and receiving systems. In order to target mitigation of different pollutants, an engineer should design a BMP depending on the time scale important for different key pollutants that are flowing into the basin.
In summary, highway runoff characterization, sand filter performance, and temporal analysis yielded the following results.

- Quantitative characterization of highway runoff at the site for selected parameters indicated that the parameters were well below state standards and other studies conducted elsewhere in the United States, with the exception of pH.

- No correlation between pollutants and antecedent dry period was observed; however, pollutants had correlations with rainfall intensity. Combination of antecedent dry period and rainfall resulted in improved correlations.

- The levels of dissolved metals (copper, lead, zinc) coming from the roadway were low, with only copper exceeding state standards in two storm events.

- Effluent dissolved concentrations of lead and zinc were below state standards in all but one instance, while effluent dissolved copper exceeded state standards in five events.

- Variance of temperature pH, conductivity and flow depth increases with increasing time periods indicating contribution to total variance of the original signal is more at higher time scales and fluctuations are low in comparison at lower time scales. Temperature and pH indicate a dominant scale at a period of 15 minutes so when we design a sand filter this time scale needs to be taken into account.

- Temperature, pH and conductivity exhibit correlation with flow depth with increasing period indicating that the interaction between water quality indicators is higher for greater time periods. Also, correlation between parameters across
time indicate higher correlation during initial part of the event. From results it can be concluded that monitoring initial part of the storm at a frequency of higher than a sample every 15 minutes to understand the behavior of highway runoff is critical. Also higher correlations indicate that during initial part of the storm we can expect other parameters to behave similarly if we have to reduce the number of parameters being monitored.

This study has analyzed high-resolution water quality data collected during a construction event using a statistical wavelet analysis technique (MODWT).

- As compared to conventional static statistical analysis, which considers the data set to be a stationary signal, the current technique is useful for transient signals as in the case of stormwater monitoring data.
- It gives insight into the behavior of parameters at several temporal scales. For example, the diurnal behavior of parameters is clearly evident in the results.
- Also, the transient events which affect the quality of water can be easily determined using this technique as the monitoring data can be broken into several temporal scales. For example, the effect of short-term events such as concrete pours and storm events was observed.
- This can be used to determine the contribution and dominant scale in the original trend. Also, bivariate wavelet analysis like wavelet correlation and wavelet cross correlation can be used to gain further insight into the effect of one parameter on the other at several frequencies.
Consequently, the use of dynamic statistical analysis techniques is a step forward in the direction of environmental monitoring, giving engineers more insight into the dynamic processes occurring on a construction site, including monitoring stormwater runoff from highways, stream and BMP monitoring, or monitoring the effect of anthropogenic activities like construction on water systems.

In summary sand filter performance, and design parameter assessment yielded the following results.

- The distribution of most incoming pollutants follows a log normal distribution implying that the occurrence of extreme loadings is less probable.
- Historical sand filter data reveals that among nutrients, a majority of the total phosphorus is mitigated by the sand filter whereas neither dissolved phosphorus, total NO\textsubscript{X} or nitrogen is mitigated. Among metals, zinc is mitigated by the sand filter but not copper and lead.
- Quantitative characterization of highway runoff at the Canton study site for selected parameters indicated that the parameters were well below state standards and other studies conducted elsewhere in the United States, with the exception of pH.
- Temperature of the stormwater is decreasing as water flows through the sand filter. Conductivity measured at the outlet is consistently higher than the conductivity at the inflow.
• Effluent dissolved concentrations of lead and zinc were below state standards in all but one instance, while effluent dissolved copper exceeded state standards in five events.

• An analysis of the design parameters of sand filters that can effectively mitigate total metals indicates a median pool area of 102 m$^2$, pool depth of 8 m, filter surface area of 280 m$^2$ and filter depth of 46 cm. The results of this study can be used in conjunction with standard design procedures as guidance for the design engineer.

In conclusion results on thermal conductivity of sands include,

• Thermal conductivity tests were conducted on dry uncoated, goethite coated and hematite coated sands iron oxide coated sands with applied vertical stress.

• It was observed that thermal conductivity evolution for samples was non-linear during the loading and unloading phase and hysteresis was observed.

• Thermal conductivity results for uncoated and coated samples increased linearly with a decrease in porosity.

• A linear increase in thermal conductivity with an increase in dry density was observed.

• The thermal conductivity of ASTM 20-30 hematite coated sand particles was observed to be higher as compared to the goethite coated samples and uncoated particles. Thus 20-30 hematite coated sands have the possibility of being used as amendments where enhanced heat dissipation is required as in cases of sand filters at sites where thermal pollution is a concern.
In this study, the sorption characteristics of dissolved metal pollutants in stormwater on (hematite and goethite) coated and uncoated ASTM 100-200 and graded soils were studied.

- It was observed that hematite coated ASTM 100-200 and ASTM graded soils were better in sorbing metal pollutants as compared to uncoated and goethite coated soils. Hence hematite coated soils are better sand filter amendment for constructing sand filters with respect to sorption. This study is valid for slightly acidic stormwater conditions (which is also the typical case as found in chapter 4). The engineering recommendation would be to use hematite coated soils as a sand filter amendment.

- This study is based on equilibrium conditions and the effect of varying contact time of the stormwater and sand as a result of varying porosity of different types of soils has not been done. Before implementation of such a sand filter in the field, a non-equilibrium study taking into consideration the flow characteristics and its effect on sorption by varying soils should be conducted.
7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

To gain further insight into highway runoff, performance of stormwater BMPs and role of iron oxide coated sands as engineered amendments following recommendations can form a starting point for future research.

7.2.1 Highway Runoff Characterization

- To begin with, more post-construction sites in Georgia can be monitored for highway runoff quality originating from pavement surfaces in Georgia to generate a database. Sites can be selected for varying catchment sizes, catchment types, surrounding land use and annual average daily traffic to assess the type and quantity of primary pollutants originating from such surfaces. This can be used to check the repeatability of results found in the current study or variations due to change in site characteristics.

- Frequently sampled pollutographs for water quality parameters like metals and nutrients, especially during the initial part of the storm can be helpful in assessing acute pollutant loads and relating catchment response with the contaminant loads.

- Sampling of solids can be conducted for individual precipitation events to characterize the solids and pollutants associated with the solids phase associated with a particular site.

- Long term monitoring at a site is suggested to gain further insight into seasonal behavior of pollutants originating from highways. Also, impact of environmental variables like antecedent dry period, rainfall intensity can be further explored.
7.2.2 Receiving Water Quality

- Results of temporal analysis can be used to model response behavior of receiving waters at varying scales which can be useful in prediction of receiving water quality behavior.
- Portability of results can be checked by conducting temporal analysis at other receiving water sites.
- The scope of temporal analysis can be expanded from water quality indicators like temperature, pH, turbidity and conductivity to include parameters which are easy to monitor and critical for a particular site.
- Long term behavior of streams can be assessed to observe change in water quality patterns at varying temporal scales if data set is available or if a receiving water is monitored for multiple years.

7.2.3 BMP Performance

- To create a database of sand filter performances for Georgia, more sand filters with varying design parameters can be monitored.
- Primary pollutants can be sampled frequently to generate pollutographs. This will be helpful in assessing time dependent behavior of sand filter BMPs. Also, site specific or general BMP model can be created using pollutographs in conjunction with inlet and outlet hydrographs to predict effluent water quality.
- A lifecycle assessment of sand filter BMPs would be helpful in assessing the feasibility of sand filters as compared with other post-construction BMPs.
- Assessing long term performance of sand filters is essential to determine the deterioration or change in performance over extended periods of time.
7.2.4 Iron Oxide Coated Sands as Engineering Amendments

- Thermal conductivity study on iron oxide coated sands with the introduction of water can be conducted to assess how the behavior of the matrix changes with the inclusion of water in the matrix.
- Thermal conductivity tests can be conducted on natural iron oxide rich soils to assess how laboratory prepared iron oxide sands vary in thermal behavior as compared to iron oxide rich residual soils.
- Further insight can be gained by performing tests by subjecting the uncoated and coated specimens to cyclic thermal loading to assess the change in behavior.
- For adsorption tests, to better simulate the field conditions primary pollutants observed at specific sites can be used to create synthetic stormwater.
- Desorption tests can be conducted to study the detachment behavior of primary pollutants.
- To further explore the behavior of competitive adsorption of primary pollutants column tests or field scale tests can be conducted so that the results can be upscaled for actual field conditions.
APPENDIX A. TEMPORAL ANALYSIS OF WATER QUALITY INDICATORS IN A SAND FILTER

For the In-situ water quality indicators (temperature, conductivity and pH) collected at the inlet and the outlet of the sand filter a temporal analysis using wavelets was conducted by calculating the global wavelet spectrum and variance of the water quality indicators from it. Also, correlation between selected parameters was assessed as a function of time. The data analyzed is from two events (E4 and E5). Global wavelet spectrum for temperature, conductivity and pH is plotted for events E4 and E5 in Figure 67. A few observations can be made from the results – First, there is an increase in the variance of parameters with increasing time scales. It is minimum for a 4 min period and maximum at an hourly scale. This indicates that fluctuations in the water quality indicators at lower scales are low as compared to the water quality indicator fluctuations at higher time scales. Second, observation that can be made is that in general variances observed at the inlet of the sand filter are higher as compared to the outlet of the sand filter except two cases. Lower variances indicate a compact distribution at the outlet of the sand filter. For event 5, temperature variance is slightly higher at the outlet of the sand filter. Also, in event 4 pH variance is higher at the outlet at a period of 4mins. This behavior between the two locations is explored further by plotting the ratio of variances of water quality indicators between the inlet and the outlet.
Figure 67. Global wavelet spectrum for three water quality indicators (temperature, conductivity and pH) for events E4 and E5 measured at the inlet and the outlet of the sand filter.
The ratio of the variances of water quality indicators between inlet and outlet is presented in Figure 68. A few observations can be made - first it gives a clear picture of the behavior of the variances between the inlet and the outlet concentration mentioned previously which indicate higher inlet variance. For temperature and pH a drop in ratio of variance is observed at smaller period of 4 mins. Thereafter, it increases and stabilizes for higher periods. The trend of fluctuation in variances across the time periods is similar for both temperature indicating a pattern in the sand filter. For conductivity it can be observed that the comparative behavior of inlet with respect to outlet variance is stable for lower time periods. Thereafter, it fluctuates indicating a pattern similar to pH. This pattern although present in temperature is not significant. Sudden changes in the ratio of variances at a period of 50 min are attributed to end effects during the wavelet variance computations. From the global wavelet variance trends it can be said that the sand filter is stabilizing the temperature, pH fluctuations and conductivity fluctuations regardless of change in mean values of the measured water quality indicators. Also, a pattern is of fluctuation in comparative variance is observed which points us to inherent process occurring inside the sand filter. The behavior between the parameters is further assessed by calculating the correlation between the selected water quality parameters for increasing time periods.
Figure 68. Ratio of inlet and outlet global wavelet spectrum for three water quality indicators (temperature, conductivity and pH) for events E4 and E5 measured at the inlet and the outlet of the sand filter.
Correlation between Temperature and Conductivity, Temperature and pH and pH and conductivity are presented in Figure 69. For temperature-conductivity, correlation between the two indicators are observed to be consistently low with an \( R^2 \) of between 0.18 and 0.42 with increasing periods. On the other hand, for outlet an increase in correlation is observed for periods higher than 8 minutes. Maximum correlation for event 4 is observed at a period of 30 minutes with a \( R^2 \) of 0.78. For event 5 maximum correlation is observed to be increasing even after a period of 64 minutes with an \( R^2 \) of above 0.9, but it includes edge effects close to the 64 minute period. From this behavior we can say that the two parameters don’t affect each other at the inlet location but at the outlet the two parameters are increasingly correlated with increasing time period. An increase in correlation between temperature-pH and pH-conductivity is observed at the outlet with a peak correlation at a period of 30 minutes with an average \( R^2 \) between 0.6 and 0.7. Inlet correlation between temperature-pH and pH-conductivity are observed to exhibit a similar behavior in Event 4 and Event 5. In event 4, the correlation between the two events peak at same period as the inlet with an \( R^2 \) of 0.6-0.7. On the other hand for event 5 the two correlations have comparatively low \( R^2 \) values at a period of 30 minutes. In general, the behavior of the three parameters indicates that 30 minute is an important time scale in which the correlations between the parameters dominate indicating increased interaction between the parameters due to physico chemical mechanisms in the sand filter. This result seems to agree with the variance results we observed previously where a fluctuating pattern was observed at a period of roughly 30 minutes. An outcome of this result is that monitoring at this site should be conducted with a sampling rate of less than 30 minutes to get a better understanding of the sand filter processes.
Figure 69. Correlation between three water quality indicators (temperature, conductivity and pH) for events E4 and E5 measured at the inlet and the outlet of the sand filter.
APPENDIX B. SELECTION OF STORMWATER BMPs

B.1 Introduction

In an effort to attenuate or treat polluted stormwater runoff a variety of stormwater BMPs are being used by throughout United States for attenuation and treatment of highway runoff. Since each BMP has its own specific characteristics and usage, it may not be applicable to all locations and conditions, which complicates the selection of the best BMP for a given site. The current practice is to use selection matrices suggested in various state department of transportation manuals to facilitate the selection of an adequate BMP for a particular application. Using these selection matrices can become a cumbersome process to come up with a BMP for a specific site because the user has to compare several BMP alternatives on the basis of several site specific criteria. Hence, using multi-criteria decision analysis (MCDA) provides a method to eliminate this difficulty and it has attracted the attention of decision makers for a long time. This is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information [139]. In this short study an attempt was made to come up with a suitable selection criteria for BMPs for different sites located in Georgia.
Generally, the MCDA problem expressed as follows:

\[
X = \begin{pmatrix}
A_1 & A_2 & \cdots & A_m \\
\begin{pmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\
x_{21} & x_{22} & \cdots & x_{2n} \\
\vdots & \vdots & \ddots & \vdots \\
x_{m1} & x_{m2} & \cdots & x_{mn} \end{pmatrix}
\end{pmatrix}
\]

Where,

\( x_{ij} \) is the performance of \( j \)-th criteria of \( i \)-th alternative, \( w_j \) is the weight of criteria \( j \), \( n \) is the number of criteria and \( m \) is the number of alternatives available. There are several MCDA methods available today. One such method is the Analytical Hierarchy Process (AHP), which was developed by [140, 141]. It is a hierarchical technique for organizing and analyzing complex decisions.

B.2 Methodology

The AHP is a four-step process (Figure 70), which can be described as follows –


The first step in performing the AHP is to identify all possible stormwater BMP alternatives from which a single alternative is to be selected. A list of general application stormwater controls is presented in Table 24.
Table 24. List of General Application BMPs

<table>
<thead>
<tr>
<th>S.No.</th>
<th>BMPs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wet Pond</td>
</tr>
<tr>
<td>2</td>
<td>Wet ED Pond</td>
</tr>
<tr>
<td>3</td>
<td>Micro pool ED Pond</td>
</tr>
<tr>
<td>4</td>
<td>Multiple Ponds</td>
</tr>
<tr>
<td>5</td>
<td>Shallow Wetland</td>
</tr>
<tr>
<td>6</td>
<td>Shallow ED Wetland</td>
</tr>
<tr>
<td>7</td>
<td>Pond/Wetland</td>
</tr>
<tr>
<td>8</td>
<td>Pocket Wetland</td>
</tr>
<tr>
<td>9</td>
<td>Bioretention Areas</td>
</tr>
<tr>
<td>10</td>
<td>Surface Sand Filter</td>
</tr>
<tr>
<td>11</td>
<td>Perimeter Sand Filter</td>
</tr>
<tr>
<td>12</td>
<td>Infiltration Trench</td>
</tr>
<tr>
<td>13</td>
<td>Dry Swale</td>
</tr>
<tr>
<td>14</td>
<td>Wet Swale</td>
</tr>
</tbody>
</table>

The next step is to identify a list of criteria influencing the selection of a single alternative from the list of feasible alternatives. Relevant criteria pertaining to the selection include:

Stormwater treatment suitability – water quality, channel protection, overbank flood protection, extreme flood protection, rate control and volume reduction.

Water quality – percent removal of total suspended solids, heavy metals, nutrients and fecal coliform.
Site Applicability – drainage area, space required for the BMP, site slope, minimum head required, depth to water table and type of soils available at the site.

Implementation Considerations – pretreatment, community acceptance and wildlife habitat.

Some selection criteria are either not quantifiable or the units of measurement are different; consequently, a relative scale of importance is implemented as an alternative [140] (Table 25).

Table 25. Scale of Relative Importance [140]

<table>
<thead>
<tr>
<th>Intensity of Importance</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The alternatives being compared contribute equally to the defined objective</td>
</tr>
<tr>
<td>3</td>
<td>One alternative is favored slightly over the other in terms of achieving the defined objective</td>
</tr>
<tr>
<td>5</td>
<td>One alternative is favored strongly over the other in terms of achieving the defined objective</td>
</tr>
<tr>
<td>7</td>
<td>One alternative is favored very strongly over the other in terms of achieving the defined objective</td>
</tr>
<tr>
<td>9</td>
<td>The evidence favoring one alternative over the other is absolute in terms of achieving the defined objective</td>
</tr>
<tr>
<td>2, 4, 6, 8</td>
<td>Intermediate values available to express user-defined comparisons</td>
</tr>
</tbody>
</table>

This table can be used to make pairwise comparisons among different alternatives for a particular selection criteria and a weight can be assigned to that alternative. This comparison between the selected alternatives is done for each criterion. Finally, criteria are also compared and ranked against each other. Hence for a total number of M alternatives, for each criterion we get a M x M matrix. This is called as BMP comparison.
matrix. For N criterions, after pairwise comparing each criterion we get an N x N matrix. This is known as the criteria judgment matrix.

Step 2. Extraction of Priority Vectors.
After creating the various BMP comparison matrices as well as the criteria judgment matrix, the relative importance of each matrix is calculated by finding the right principal eigenvector of each judgment matrix.

Step 3. Ranking of Competing Alternatives.
The final step is the construction of the BMP decision matrix. Column entries in the BMP decision matrix are made by entering the priority vectors obtained from each individual BMP comparison matrix. The decision matrix is of dimensions M x N. M representing the number of BMP alternatives being considered and N indicating the total number of influential criteria for which BMP comparison matrices were constructed.
After the decision matrix and criteria priority vector is obtained by finding the right principal eigenvector of the BMP comparison matrix and the criteria judgment matrix, a matrix of the form as shown in the general expression results. Using the decision matrix we can calculate the ranks by pairwise calculating weighted products. Weighted product can be calculated by using the following relation –

\[ P\left( \frac{A_k}{A_l} \right) = \prod_{j=1}^{n} \left( \frac{a_{Kj}}{a_{Lj}} \right)^{w_j} \]

For \( K, L = 1, 2, 3, \ldots m \)

If

\[ P\left( \frac{A_k}{A_l} \right) \geq 1 \]
Then alternative $A_k$ is better than $A_l$. The best alternative is the one which is better than or at least equal to all other alternatives. Hence, using this method, we can come up with a stormwater BMP which is best suited for a particular site (Table 26).

Table 26. Example of a Decision Matrix

<table>
<thead>
<tr>
<th>#</th>
<th>BMP</th>
<th>Weights $\rightarrow$</th>
<th>0.288</th>
<th>0.288</th>
<th>0.288</th>
<th>0.093</th>
<th>0.043</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Dry Pond</td>
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<td>0.012</td>
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<td>0.088</td>
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<td>0.088</td>
<td>0.046</td>
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<td>0.096</td>
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<td>9</td>
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<td>0.039</td>
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<td>11</td>
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<tr>
<td>12</td>
<td>Propreitary</td>
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<td>0.011</td>
<td>0.01</td>
<td>0.093</td>
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</table>
C.1 Canton Creek Background Sampling

Background samples at Canton Creek were collected on 26th August 2010 at 7 locations (Figure 71) to assess the affect of commercial center runoff on the Canton Creek water quality. The results for conventional and metal contaminants have been presented in Table 1.

Figure 71. Canton creek background sample locations.
Table 27. Background Sampling Results

<table>
<thead>
<tr>
<th>Sample #</th>
<th>Canton Creek Background</th>
<th>Tributary 1</th>
<th>Canton Creek @ Tributary 2</th>
<th>Tributary 2</th>
<th>Canton Creek U/S of Tributary3</th>
<th>Tributary 3</th>
<th>Canton Creek D/S of Tributary3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>34°13.824' N, 84° 27.630'W</td>
<td>34°13.812' N, 84° 27.645'W</td>
<td>34°13.893' N, 84° 27.813'W</td>
<td>34°13.897' N, 84° 27.816'W</td>
<td>34°14.048' N, 84° 27.921'W</td>
<td>34°14.054' N, 84° 27.913'W</td>
<td>34°14.046' N, 84° 27.932'W</td>
</tr>
<tr>
<td>pH</td>
<td>7.1</td>
<td>6.7</td>
<td>6.8</td>
<td>6.9</td>
<td>6.8</td>
<td>6.8</td>
<td>6.9</td>
</tr>
<tr>
<td>Conductivity (μS/cm)</td>
<td>86.66</td>
<td>116.4</td>
<td>90.01</td>
<td>83.17</td>
<td>87.21</td>
<td>77.95</td>
<td>84.29</td>
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<tr>
<td>Turbidity (NTU)</td>
<td>4.65</td>
<td>1.98</td>
<td>5.01</td>
<td>6.45</td>
<td>4.06</td>
<td>1.32</td>
<td>3.73</td>
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<tr>
<td>Temperature (C)</td>
<td>23</td>
<td>21.5</td>
<td>23</td>
<td>20</td>
<td>22</td>
<td>22</td>
<td>23</td>
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<tr>
<td>Cu (mg/L)</td>
<td>0.02244</td>
<td>0.01218</td>
<td>0.01947</td>
<td>0.03804</td>
<td>0.02324</td>
<td>0.02033</td>
<td>0.01254</td>
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<tr>
<td>Pb (mg/L)</td>
<td>0.00316</td>
<td>0.00154</td>
<td>0.00747</td>
<td>0.00646</td>
<td>0.0043</td>
<td>0.00546</td>
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<tr>
<td>Zn (mg/L)</td>
<td>0.00142</td>
<td>0.00786</td>
<td>0.00395</td>
<td>0.00285</td>
<td>0.00253</td>
<td>0.00322</td>
<td>0.00299</td>
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<tr>
<td>Ni (mg/L)</td>
<td>0.01291</td>
<td>0.01217</td>
<td>0.01314</td>
<td>0.01206</td>
<td>0.0127</td>
<td>0.01272</td>
<td>0.01295</td>
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<tr>
<td>Cd (mg/L)</td>
<td>0.14574</td>
<td>0.14583</td>
<td>0.14567</td>
<td>0.14565</td>
<td>0.14568</td>
<td>0.14562</td>
<td>0.1457</td>
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<tr>
<td>Cr (mg/L)</td>
<td>0.0433</td>
<td>0.04258</td>
<td>0.04366</td>
<td>0.04107</td>
<td>0.04313</td>
<td>0.04345</td>
<td>0.04362</td>
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<tr>
<td>Fe (mg/L)</td>
<td>0.32008</td>
<td>0.1315</td>
<td>0.18372</td>
<td>0.17863</td>
<td>0.24022</td>
<td>0.03012</td>
<td>0.25897</td>
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<tr>
<td>Al (mg/L)</td>
<td>0.01126</td>
<td>0.00331</td>
<td>0.00517</td>
<td>0.00492</td>
<td>0.011</td>
<td>0.01025</td>
<td>0.00517</td>
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<tr>
<td>Mn(mg/L)</td>
<td>0.04363</td>
<td>0.65996</td>
<td>0.05905</td>
<td>1.5588</td>
<td>0.05591</td>
<td>0.00681</td>
<td>0.05422</td>
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</table>
The results (Table 27) show that there is only a small variation in the temperature values at the sampling locations in the Canton Creek. Tributary temperatures are slightly lower than the creek temperatures due to the canopy which blocks the sunlight and thus tributaries are not exposed to direct sunlight. pH values both for the creek and the tributaries vary between 6.7 and 7.1 and hence there is not a lot of variation their values. Turbidity values for the creek remained between 3.73 and 5.01 NTU’s. It was observed that the turbidity of the 2nd tributary was significantly higher than the other two tributaries. Higher value of turbidity for the 2nd and 1st tributary can be attributed to the discharge the two tributaries receive from the shopping center. On the other hand the turbidity value in the 3rd tributary was much lower. This indicates that the runoff from the ramps which contributes to the 3rd tributary is has lower suspended solids. Conductivity values for the creek varied between 84.29 and 90.01 μS/cm. The conductivity value for the 1st tributary was significantly higher than the other two tributaries. Similarly, metal contaminants showed similar behavior.

Comparison of Background Results with In-stream Monitoring Data

Temperature values collected during background sampling (Figure 72) were similar to the temperature values monitored at the 5 different locations during the construction event except Tributary 2 and 3 which exhibited lower temperatures. This could be because of the canopy temperatures affecting the results combined with lower ambient temperature during the day. Although Canton creek temperature values observed at the 5 locations during 2007 were higher compared to the values measured at the same
location in 2006. This is due to the difference between higher ambient daily temperatures in 2007.

Figure 72. Comparison of background results with in-stream monitoring data.
REFERENCES


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VITA

ADITYA BHATT

Aditya Bhatt was born in Lucknow, India. He earned his B.E., Civil Engineering, from Punjab Engineering College, Chandigarh, India in 2008, after which he began his studies in the Geosystems program group in the School of Civil and Environmental Engineering at Georgia Tech. His research interests include Geoenvironmental systems, Stormwater management and sustainability, environmental pollution, mitigation, laws and policies. When he is not at work he likes to read history, listen to music and play cricket or tennis.