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16. Abstract

Nonpoint source pollution is an environmental problem that is a concern among regulatory agencies and water quality professionals. A portion of this pollution is conveyed to receiving waters by stormwater drainage from highways, often via vegetated roadside shoulders, also called borrow ditches. The vegetated shoulders may act as filter strips, reducing the concentrations of pollutants in highway runoff.

Vegetated filter strips are recognized by many regulatory agencies as a Best Management Practice for the control and treatment of stormwater; however the relationship between performance and design parameters such as length, width, and vegetative cover are not well understood. Therefore, it is important to evaluate and document the extent to which these vegetated areas may reduce pollutant loads in runoff and mitigate the effects of discharging untreated highway runoff directly into receiving bodies of water.

The primary objective of this study is the documentation of the stormwater quality benefits of these vegetated sideslopes typical of common rural highway cross sections in Texas. The scope of this project included the selection of six sampling sites in the Austin and College Station areas that met a predetermined set of site criteria; the installation of 24 passive stormwater samplers and collection systems; monitoring of the sites and collection of runoff samples from storm events over a 14-month period; laboratory analyses of each of the runoff samples; compilation of the results into a database; statistical and graphical analyses of the results to determine differences between sites; and the evaluation of the performance of each of the vegetated filters and recommendations of site conditions conducive to maximum pollutant removal.

Results from this study indicate that significant removal of some pollutants occur over the width of vegetated filter strips, often within the first four meters of the edge of pavement. The results also indicate that vegetation density has a direct effect on the performance of vegetated filter strips. Dense vegetative cover within close proximity to the edge of pavement and vegetative cover of at least 90% are recommended to allow for maximum pollutant removal. The effects of a permeable friction course on the quality of runoff leaving the road surface were also examined. These results indicate that the porous surface appears to have a substantial impact on the quality of runoff leaving a road surface. These improvements in water quality are as great, if not greater, than the improvements gained from the vegetated filter.

Overall, the results from this study indicate that vegetated filter strips should be utilized by TxDOT as a best management practice for controlling and treating stormwater runoff from Texas highways. These filter strips demonstrate consistently high removal efficiencies for many of the pollutants of concern in stormwater runoff. In addition to providing water quality benefits, these vegetated areas are inexpensive and easy to implement, are easy to manage, and provide aesthetic benefits to the surrounding environment.

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Pollutant Removal on Vegetated Highway Shoulders

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Products

This report contains Products 1 and 2. Product 1, titled *Performance Characteristics of Grass Shoulders* can be found in Table 5.16 on page 77. Product 2 can be found in Appendix C on page 103.

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1. INTRODUCTION

1.1 Overview

Nonpoint source pollution is an environmental problem that is a concern among regulatory agencies and water quality professionals. A portion of this pollution is conveyed to receiving waters by stormwater drainage from highways, often via vegetated roadside shoulders, also referred to as borrow ditches. Vegetated filter strips are relatively smooth, moderately sloped, vegetated areas that accept stormwater runoff as overland sheet flow. The primary mechanisms for removal of pollutants are sedimentation, infiltration into the soil, and biological/chemical activity in the grass and soil media.

Vegetated filter strips are recognized by many regulatory agencies as a Best Management Practice for the control and treatment of stormwater; however the relationship between pollutant removal and design parameters such as length, width, and vegetative cover are not well understood. Therefore it is important to evaluate and document the extent to which these vegetated areas reduce pollutant loads in runoff and mitigate the effects of discharging untreated highway runoff directly into receiving bodies of water. The primary objective of this study is the documentation of the stormwater quality benefits of these vegetated sideslopes typical of common rural highway cross sections in Texas.

1.2 Regulatory Framework

Stormwater quality in the state of Texas is under the jurisdiction of the United States Environmental Protection Agency (USEPA) and the Texas Commission on Environmental Quality (TCEQ). The USEPA's Clean Water Act of 1972 was amended in 1987 to include stormwater discharges. The Act requires states to evaluate the condition of the surface waters within the state boundaries and to assess whether or not the water quality is supportive of designated beneficial uses. Stream segments that are deemed to not be supportive of the beneficial uses are designated as impaired and are placed on what is known as the 303(d) list. The 303(d) list is reviewed and updated every four years.

A total maximum daily load (TMDL) for the constituents contributing to the impairment must be developed for each of the listed waterbody segments. A TMDL is the maximum pollutant load that can be assimilated by the waterbody without impairing beneficial uses. The TMDL process involves quantifying all of the discharges of the specific pollutant of concern to a water body and identifying the parties responsible for the discharges. A system of wasteload allocations is developed that, if implemented, will allow the beneficial uses to be realized. All parties responsible for discharges to the water body are required to take measures to reduce their pollutant discharges in order to achieve their individual wasteload allocations.

Reductions in pollutant discharges for point sources are relatively straightforward and easy to achieve; however, quantifying and controlling the nonpoint sources is a much greater challenge. The measures implemented to reduce the discharge of pollutants are known as best management practices (BMPs). In Texas, the Texas Department of Transportation (TxDOT) is the party responsible for implementing BMPs to control and mitigate the potential negative effects of highway stormwater runoff on receiving bodies.

The number of water segments designated as impaired is expected to grow, especially in areas where development is occurring. As the trends of increased urbanization continue, new roadways are being constructed to accommodate the growing population. Increases in road surface area, among other things, will decrease the permeable ground cover where infiltration of rainwater and runoff can occur. A decrease in pervious ground cover increases the impact of runoff on receiving water bodies. These trends in development highlight the need to assess the contribution of pollutants in runoff from roadways and to mitigate their potential effects.

Available BMPs include structural and non-structural systems. Vegetated filter strips are an example of a non-structural BMP that can be used to mitigate and control stormwater pollutants from highways. This BMP is not as widely accepted as many other types of facilities. Regulatory agencies generally have a lack of understanding and confidence in vegetated filters; therefore, they tend to recommend them only as a pre-treatment option for runoff. However, there is a body of research that supports the use of vegetated filters as a primary pollution control method. A more precise understanding of the preferred design characteristics and benefits of this BMP can be developed by regulatory agencies through further research in this area. The documentation of these benefits can also be used to design systems that result in stormwater quality that meets specific requirements.

1.3 Objective

The primary objective of this project was the documentation of the stormwater quality benefits of vegetated shoulders that are typical of common rural highway cross sections. The effects of vegetation cover and slope on pollutant concentrations were assessed. Two geographic areas in Texas (Austin and College Station) were selected to assess the effect of different vegetation assemblages and slopes on pollutant reduction. Multiple sites within each geographic area were evaluated to increase the confidence in observed pollutant reductions. The scope of this project included:

- Selection of three sampling sites in the Austin area and three in the College Station area that met a predetermined list of site criteria.
- Installation of 4 passive stormwater samplers and collection systems at each selected site, for a total of 24 samplers.
- Monitoring of sites and collection of runoff samples from storm events over a 14-month period.
- Laboratory analyses of each of the runoff samples.
- Compilation of results into a database.
- Statistical and graphical analyses of results to determine differences between sites and different conditions
- Evaluation of the performance of each of the vegetated filters and recommendations of site conditions conducive to maximum pollutant removal.

2. LITERATURE REVIEW

2.1 Introduction

Increased development and urbanization will occur as populations continue to grow. The proliferation of roadways and other impervious surfaces are part of these development activities. Such surfaces and the stormwater runoff that they produce can have a large impact on receiving water bodies. Studies of runoff from multilane highways with more than 100,000 vehicles per day have shown that up to 25% of the samples can be classified as toxic whereas only 1% of normal urban stormwater samples can be classified the same way (Ellis, 1999a). Folkeson (1994) also indicated that highways can account for up to 50% of the suspended particles and 35-75% of metal influxes to urban watercourses although they only occupy 5-8% of urban drainage areas. Some roadway runoff is collected and treated by BMPs or other urban drainage systems; however, much of the runoff from highways is neither collected nor treated before entering the receiving body. Numerous studies over the last 25 years have focused on characterizing highway runoff and gaining a better understanding of pollutant transport processes. A proliferation of research also has been reported for vegetative controls for highway runoff including grassy swales and vegetated filter strips.

2.2 Vegetative Controls for Highway Runoff

Vegetative controls are common management tools for highway runoff pollution management. Various types of vegetative controls exist, but the two most important types are grassy swales and buffer/filter strips. Vegetated filter strips conventionally have slopes less than 5%, have permeable natural subsoils, and are most effective when treating runoff from relatively small catchment as the strips are unable to effectively treat at high runoff velocities associated with large impervious surfaces (Young et al., 1996). Results from a study in California indicate that vegetated buffer strips help to reduce the velocity of runoff, stabilize the slope, and stabilize accumulated sediment in the root zone of plants (Caltrans, 2003a). A minimum of 65% vegetative cover is required to achieve reduction in constituent concentrations and performance falls off rapidly as vegetative cover drops below 80% (Caltrans, 2003a; Barrett et al., 2004).

Kaighn et al. (1996) reported that the average removal rates in buffer strips were found to be 63.9% for TSS, 59.3% for COD, -21.2% for total phosphorus (indicating an increase over the strip), and 87.6% for Zn. Pollutants that are associated with larger particles are more easily removed by the vegetated buffer strip. The results of other studies confirmed this trend. Similar results were reported by Walsh et al. (1997). Walsh et al. reported that vegetated strips between seven and nine meters in length can be effective, but increased water depths and velocities are believed to have a negative effect on removal efficiencies.

Average reductions in TSS of 72% were reported for three buffer strip test plots with differing soil conditions (containing a biosolids compost, on-site native soil, and topsoil from off-site) (Yonge et al., 2000). Negative reductions were observed only infrequently. On average, edge of pavement and test plot effluent TSS levels were 41 milligrams per liter (mg/L) and 6.7mg/L, respectively. The runoff from the test plot with the compost contained an average COD concentration of 29.6mg/L compared to 6.7mg/L and 9.4mg/L from the other plots (Yonge et al., 2000). Average phosphorus concentrations were higher for the compost plot than for the edge of pavement or the other two test plots. The compost plot had the highest permeability and no measurable surface flow was observed.

The ability of vegetated slopes adjacent to freeways to remove contaminants from stormwater also was evaluated in a two-year water quality monitoring project undertaken in California. Eight sites were studied, each consisting of concrete V-shaped ditches placed parallel to the road at various distances from the edge of pavement. Sites had varying slopes and vegetative covers. The relationship between length of filter strip and resulting constituent concentrations was found to be nonlinear: concentrations were found to change very quickly between the edge of pavement and 1.1m and then level off. Results were compared with pilot studies conducted as part of the Caltrans BMP Retrofit Study (Caltrans, 2003b) Five of the eight sites were not significantly different from these pilot sites, indicating that existing vegetated areas along the highways perform similarly to systems engineered specifically for water quality improvements (Caltrans, 2003a; Barrett et al., 2004).

Overall, the Caltrans (2003a) study found concentration reductions to exist for TSS and total metals, and frequently for dissolved metals. Concentration increases, however, were observed for dissolved solids and occasionally for organic carbon. Nutrient concentrations generally remained unchanged. Substantial load reductions were observed for all constituents due to infiltration (even for constituents with no changes in concentration). The median of average effluent concentrations for constituents that decreased at all sites except one were found to be: 25mg/L for TSS, 8.6 micrograms per liter (μg/L) for Cu, 3.0μg/L for Pb, 25μg/L for Zn, 5.2μg/L for dissolved Cu, 1.3μg/L for dissolved Pb, and 12μg/L for dissolved Zn (Caltrans, 2003a; Barrett et al., 2004).

The California study also found vegetation species and height had no effect on performance of the filter strips, while vegetation density did. At sites with greater than 80% vegetation coverage, buffer lengths to achieve irreducible minimum concentrations for constituents whose concentrations decreased were found to be 4.2m for slopes < 10%, 4.6m for slopes between 10% and 35%, and 9.2m for slopes between 35% and 50%. At sites with less than 80% coverage, the critical buffer length for slopes greater than 10% was found to be 10m. Overall, minimum concentrations varied by site and could not be shown to be a precise function of buffer length, highway width, vegetation cover, hydraulic residence time, vegetation type, or slope (Caltrans, 2003a; Barrett et al., 2004).

In summary, studies of vegetated buffer strips adjacent to highways have provided mixed results, although general trends in performance have emerged. A range of runoff pollutant reductions (or increases) compiled from the results of various studies are presented below:

- TSS: 50-87%
- COD: 59-69%
- Total P: -21.2-45%
- Nitrate: 23-50%
- TKN: 33-54%
- Pb: 17-41%
- Zn: 75-91%

Differences in reductions of pollutants can be explained by a number of factors. Site characteristics play a crucial role in the effectiveness of a vegetated area at removing pollutants from stormwater runoff. Higher vegetation densities have a direct correlation with the ability of a buffer to remove pollutants. Similarly, lower slopes and increased retention times also have been shown to increase the pollutant removal rates. Differences in traffic volumes and other road conditions also play a role in the quality of runoff leaving the road surfaces at each site. In situations where compost or mulch layers are used on top of the vegetation, higher nutrient and COD levels have been observed in the runoff. Variations in site performance also occur on a storm by storm basis; therefore long study periods can be helpful for determining average site performance trends.

Additional work is needed in order to assess the expected performance of vegetated BMPs in different regions of the country since precipitation patterns, soil structures, and road cross-sections vary by region and often by state. The 2002 TxDOT Summary reports 79,361 centerline miles of state maintained roadways and highways of which more than 70% have rural type cross sections with vegetated sideslopes (CAMPO, 2002). Highway shoulder borrow ditches with different soil conditions, vegetation assemblages and densities, and shoulder slopes are all expected to result in different pollutant removal efficiencies of vegetated buffer areas. State regulatory and transportation agencies are therefore interested in gaining a better understanding of their performance in Texas. The benefits of vegetated buffer strips in the State must be documented so that the roadsides can be used as part of the design for meeting stormwater quality requirements.

2.3 Permeable Friction Course

Porous asphalt is an alternative to traditional asphalt and is produced by eliminating the fine aggregate from the asphalt mix. A layer of porous asphalt approximately 50 mm thick is placed as an overlay on top of an existing road base. The overlay typically is referred to as Permeable Friction Courses (PFC), Open Graded Friction Courses (OGFC), Porous European Mixtures (PEM), or plant mix seal coats. The void space in a porous asphalt overlay layer generally is 18-22% (Asphalt Pavement Alliance, 2003). Rain that falls on the friction course drains through the porous layer to the original impervious road surface at which point the water drains along the boundary between the surfaces until the runoff emerges at the edge of the pavement. The volume of surface runoff and the amount of spray generated during rain events are reduced to a large extent as a result of the permeable nature of this surface. This suppression of spray improves visibility and increases the level of safety for motorists. The porous asphalt also provides a reduction in the noise level produced by vehicles on the road (Stotz and Krauth, 1994).

Permeable asphalt overlays are used increasingly by many state DOTs, including those in Georgia, Texas, California, and Utah. Advancements in the design and installation of PFCs are leading to longer life spans and applicability in dense traffic and high speed traffic areas. The improved PFC mixes are expected to last at least 10 years (Asphalt Pavement Alliance, 2003).

The impact of PFC on stormwater runoff quality has been evaluated in few scientific studies; however, there are several reasons to think that improved water quality may result from the installation of this material. PFC might be expected to reduce the generation of pollutants, retain a portion of generated pollutants within the porous matrix, and impede the transport of pollutants to the edge of the pavement.

Irish et al. (1998) reported that the concentrations of selected constituents in highway runoff were affected by the number of vehicles passing the site during a storm event. These constituents included oil/grease, copper, and lead. Spray generated from tires was assumed to wash pollutants from the engine compartments and bottoms of vehicles. It is reasonable to expect that the amount of material washed off vehicles while driving in the rain will be reduced since PFC reduces splash and spray. This reduction in the amount of material washed from vehicles is expected to decrease the loading of pollutants washed off the road surface; therefore, the concentrations of these pollutants in the runoff generated from roads paved with PFC will be decreased.

The porous structure of PFC also may act as a filter of the stormwater. Runoff enters the pores in the overlay surface and is diverted towards the shoulder by the underlying conventional pavement. Pollutants in the runoff can be filtered out as the water flows through the pores, especially suspended solids and other pollutants associated with solid particles. Pollutants also may become attached to the PFC matrix by straining, collision, and other processes. Material that accumulates in the pore spaces of PFC is difficult to transport and may be trapped permanently in the pore spaces. On the surface of a conventionally paved road, splashing created by tires moving through standing water easily can transport even larger particulate material rapidly to the edge of pavement. However, water velocities within the pore spaces of the PFC are low and likely could only transport the smallest particulate material.

Several studies have been conducted to examine the distribution of solids and associated pollutants on road surfaces. These studies generally indicate that the majority of pollutants are located within 3 feet of the curb (Laxen and Harrison, 1977; Little and Wiffen, 1978). The pollutants are transported to the area of the curb by wind turbulence generated by vehicles traveling along the roadway. These materials accumulate in the gutter and are transported easily by rainfall runoff to the storm drain system. Roadways with a PFC surface accumulate particulate material and the associated pollutants within the pores of the structure and the solids are not blown to the side of the road. In fact, air pressure in the vicinity of tires likely forces particles further into the void spaces of the PFC.

Berbee et al. (1999) studied the runoff generated from both porous and non-porous road surfaces in the Netherlands. The porous pavement site had an average daily traffic count of 83,000 and was paved with a 55 millimeter layer of pervious asphalt on top of an impervious base. The pervious asphalt surface was three years old at the time of the study. The second highway site had an average daily traffic count of 53,000 and was paved with conventional impervious asphalt. Runoff samples were collected over one week periods to provide an average profile of the concentrations of the constituents in the runoff. Lower concentrations of pollutants were observed in runoff sampled from the porous asphalt than from impervious asphalt for many of the constituents monitored. Specifically, total suspended solids (TSS) concentrations were 91% lower, total Kjeldahl nitrogen (TKN) 84% lower, chemical oxygen demand (COD) 88% lower, and total copper (Cu), lead (Pb), and zinc (Zn) ranged from 67-92% lower than in runoff from the conventional asphalt pavement (Berbee et al., 1999). The dissolved fractions of copper and zinc were higher in the runoff from porous asphalt overlay. Solids, as well as some of the metals, were believed to be trapped in the porous asphalt overlay.

The effects of settling and filtration on the quality of runoff produced by both porous and non-porous asphalt surfaces also was evaluated by Berbee et al. (1999). Laboratory-scale experiments were performed to assess the removal efficiencies of both runoff treatment methods. Results indicate that pollutant removal efficiencies were lower for both settling and filtration processes when treating the runoff from the porous asphalt surface than from the impervious road surface, raising a question as to the need for such treatment methods in combination with porous asphalt road surfaces. The observed reduced efficiency was believed to be the result of the inherently cleaner nature of the runoff produced by the porous surface.

Research by Stotz and Krauth (1994) quantified the differences in the quality of runoff generated from a porous asphalt overlay and an impervious road surface in Germany. The results indicated that the load of filterable solids in runoff from the porous surface were 60% lower than runoff from an impervious surface, indicating that the overlay surface acts as a filter and detains the particles. Similarly, the load of total copper and total lead in runoff from the porous surface was 31% and 55% less than in runoff from conventional asphalt pavement.

3. STATE OF THE PRACTICE IN TRANSPORTATION

3.1 Introduction

In order to understand and assess the state of the practice of using vegetated buffer strips as non-structural BMPs, a survey was conducted of other state departments of transportation (DOTs). The purpose of this survey was to provide documentation and evaluation of the degree to which vegetated roadsides reduce the adverse impacts that might be caused by discharging untreated runoff directly to the receiving waters. This process involved selecting DOTs which have a strong erosion control program and consider vegetated roadside slopes or grassed embankments as a strategy to improve stormwater runoff quality. The summary of the survey provides documentation of the water quality benefits of the vegetated roadsides typical of common rural highway cross sections. The information was collected from telephone surveys and the questions asked of each DOT were the following:

- Does your agency consider or cite the vegetated roadsides as part of the strategy to control non-point source pollutants in your National Pollutant Discharge Elimination System (NPDES) permits?
- If yes,
    - What are the dominant vegetated species on your roadsides?
    - Which type of treatment do the vegetated species on your state roadsides provide?
    - What are the benchmark constituents your department expects to be trapped by the roadside slopes?

Additional questions evolved based on the initial responses and those questions included the following:

- Is the project carried out in test plots, is it a real-time project, or is it conducted in order to satisfy the state laws?

- Have you had projects that documented the efficiency of the vegetated roadsides in trapping pollutants?

The DOTs selected for this survey include:

- Florida Department of Transportation (FDOT)
- Maryland Department of Transportation (MDOT)
- Minnesota Department of Transportation (MNDOT)
- New York Department of Transportation (NYDOT)
- Utah Department of Transportation (UDOT)
- Virginia Department of Transportation (VDOT)
- Washington State Department of Transportation (WSDOT)

3.2 Summary of Survey Findings

In general, all surveyed DOTs have a positive view about vegetated roadsides in treating highway stormwater runoff.

3.2.1 FLORIDA DOT

FDOT has identified the benefits of vegetated roadsides with respect to erosion control and is looking forward to analyzing the water quality benefits. The department did not cite any specific research or reference publications as the basis for including vegetated roadsides as a storm water quality practice. The researcher, Jeff Caster, says that the roadsides are covered with grass species (turf grass) in order to minimize the bare soil area thereby reducing the impact of rain drops and anchoring the soil. Maintenance activities include mowing at appropriate intervals maintaining a minimum height of 0.15m (6 in). No preliminary results are available.

3.2.2 MARYLAND DOT

MDOT has recognized vegetated roadsides as part of the strategy to control non-point source pollutants. The department did not cite any specific research or reference publications as the basis for including vegetated roadsides as a storm water quality practice at the time of the survey. The researcher, Raja Veeramachaneni, says that vegetated roadsides are considered as a part of the road design. The department has recognized the utility of vegetated roadsides to be two-fold: roadsides filtering various constituents as the runoff flows through the swales (sheet flow), and grassy channels offering pretreatment, filtering most of the pollutant load, before the runoff enters the structural runoff control.

The grassy channels in Maryland have an average side slope of 1-3%. The department is experimenting with different slopes by altering the existing channels to study the influence of slopes on the filtration offered by the grassy channels. Constituents such as suspended solids, coarse particles, heavy metals, and phosphorus are expected to be trapped. The benchmark pollutants of the state are total suspended solids (TSS) and total phosphorus (TP). The results indicate that 80% of the TSS has been trapped and the percentage of TP trapped is fluctuating (usually around 40%). Mr. Veeramachaneni feels that the vegetated roadsides are efficient in removing coarse particles but inefficient in terms of dissolved solids. According to him, increasing the retention time by constructing ponds could facilitate infiltration causing the water-soluble nutrients and pesticides to enter the soil profile in the area. These chemicals are either taken up by the vegetation or broken down by a combination of biological and chemical processes. This approach enhances the efficiency of the vegetation roadsides.

3.2.3 MINNESOTA DOT

MN/DOT has also identified vegetated roadsides along with bio-swales, bio-retention ditches, and infiltration ditches as an effective means of water quality enhancement. The researcher, Dwayne Stenlund, says that the department considers plants as an intricate part of the design process. The design process consists of determining the soil recipe in terms of its organic matter content and the soil's infiltration capability. Lakes in Minnesota have high phosphorus content and additional monitoring revealed that switch grass (*Panicum virgatum*) has been found to be extremely efficient with respect to phosphorus removal. A design objective in Minnesota is to create soil with a certain amount of activated carbon content which is capable of sequestering certain types of heavy metals. The tie up of metals in the soil could be estimated based on the cation exchange capacity. Also, past studies conducted by the department indicate that compost and peat, when blended with the soil appropriately, can have affinity to certain metals.

The objective is to create the soil bed with equal parts of silt, clay, and compost, and develop tree species that can detoxify hydrocarbons, thereby increasing water quality. In the design of the vegetation matrix, soil type and the resulting infiltration rate are important engineering variables. Grade and water volume are the other parameters in the design specifications for vegetated swales.

The researcher referred to the hydraulic engineering center manual (HEC-11, 2000) mentioning the retardance classes (A-E, where "A" stands for un-mowed tall grass and "E" stands for mowed short turf grass). The theory is that tall plant species offer more retardance to the runoff causing increased settling of solids and vice versa. Mixed species (four types of grass and two types of flowers) were observed to provide better treatment than a monoculture. The department uses both grass species and broad leaved plants on the vegetated matrix and observed better performance than a single type of species. The department has yet to document this in a roadside manual but is likely to publish one in the coming fall. Maintenance activities include mowing at appropriate intervals but are limited by practical wildlife concerns such as nesting and snake hills and hence shoulder cutting and spot mowing are performed in order to prevent weeds. On the whole, the researcher suggests that the impact of soil chemistry on constituent removal could be better understood by considering the vegetation matrix along with the soil recipe.

3.2.4 New York DOT

Currently, NYSDOT has established vegetated roadsides as part of the road design to satisfy the New York state regulations (NYSDOT, 1995; NYSDOT, 1999). However, a researcher at NYSDOT, Nancy Alexander, believes that vegetated roadsides (vegetation ditches) could treat the storm water runoff before flowing into the receiving water body. Constituents like sediments, heavy metals, and nutrients are expected to be trapped. NYSDOT had not documented their review at the time of the survey.

3.2.5 Utah DOT

UDOT assumes vegetated roadsides to be an effective strategy for treating stormwater runoff. The researcher, Ira Bickford, says that the department is yet to analyze the benefits of vegetated roadsides and hence no preliminary results are available. The department has established vegetated roadsides (or vegetated ditches) using 10-20 different combinations of seed mixes. Constituents such as sediments and heavy metals are believed to be trapped by the vegetation matrix. The department did not cite any specific research or reference publications as the basis for including vegetated roadsides as a stormwater quality practice at the time of the survey.

3.2.6 WASHINGTON DOT

WSDOT is exploring the water quality benefits of vegetated roadsides in test plots. The department has updated the roadside manual with additional information on using compost as a soil amendment (WSDOT, 2004; WSDOT, 2005). The researcher, Mark Maurer, believes that the addition of compost should augment the growth of the vegetated species thereby increasing the vegetation density.

Washington State has eight different physical geographic divisions. The type of species used to establish the vegetated areas varies by geographic region; the most predominant type of species is Hemlock grass (*Tsuga*). According to Mark Maurer, the short grass species provide better treatment than the broad leafed plants as the sheet of runoff (overland flow) flows through the vegetation matrix. The dense fibrous roots hold the soil and form numerous root channels that result in increased infiltration. They help reduce the volume of runoff reaching retention ponds or other water bodies. The high stem count contributes to the denser cover thereby resulting in better filtration. As the sheet of water flows through the vegetative roadside, the primary treatment is provided by the grass species followed by the secondary treatment by the coniferous trees. Furthermore, the grass cover increases the residence time, which in turn reduces the velocity of the flow. Thus the energy in the runoff is blocked by the species and serves as a means for erosion control.

Future work includes determining parameters such as soil infiltration rate, soil type, and the concentration of various constituents in the runoff after passing through the roadside areas. The department is focusing on the removal of heavy metals and the collected samples are sent to a consultant lab for analysis. The maintenance manual includes instructions for appropriate mowing at certain intervals. The researcher referred to the manual called "Roadside Management Study" mentioning the roadside design factors.

3.3 Concluding Remarks

The information obtained from the survey gives a picture of the acceptance of vegetated roadsides by other DOTs. Vegetated roadsides have been identified as an effective means of improving stormwater quality. In summary, MN/DOT has conducted in-depth research with special emphasis on soil/plant matrix, while WSDOT is investigating various parameters such as infiltration rate, soil type, and rainfall intensity. On the other hand, NYSDOT and MDOT have established vegetated roadsides primarily to satisfy their respective state laws (grass-lined swales should maintain a minimum height of approximately four to six inches). UDOT has assumed roadside slopes to be beneficial and FDOT has identified the erosion resistant capabilities of vegetated roadsides.

Surveyed DOTs have different views on the design of vegetated roadsides for several reasons. Vegetated roadsides could be used as a primary treatment device or used in conjunction with other stormwater practices. Their assessments indicate that substantial labor and material cost savings could be gained in areas where vegetated slopes are used instead of traditional piping systems. Hence, all DOTs who participated in the survey value vegetated roadsides for their cost benefits.

In addition to stormwater quality benefits, DOTs also think that vegetated roadsides can not only address water quality concerns but also facilitate aesthetic enhancement. The DOTs believe that densely vegetated roadsides could be designed to add visual interest to a site or to screen unsightly views.

Some DOTs have assessed the water quality and erosion control benefits of vegetated roadsides. The pollution prevention benefits of vegetated roadsides, as identified by the DOTs include protecting soil from the impact of raindrops, slowing down stormwater runoff, anchoring soil in place, intercepting soil before it runs off, and increasing filtration rate of soil. Thus vegetated roadsides could be used as an environmentally sensitive alternative to the conventional storm water sewers.

Design of vegetated roadsides with special focus on the soil/vegetation matrix is going to pave the way for future research. Additionally, it will provide more insight into the process of treating stormwater runoff using roadsides. Moreover, this approach is believed to greatly influence the efficiency of filtration delivered by the roadsides. Though no published results are available at this point from the surveyed DOTs, it is reasonable to believe that vegetated roadsides can be effective in reducing the concentration of constituents in highway runoff.

4. MATERIALS AND METHODS

4.1 Site Selection Criteria

This study was conducted at six sampling sites, three in Austin and three in College Station, Texas. Several criteria were used to ensure that the selected sites were representative of these particular regions of the state. Area highways with rural type cross-sections were evaluated based on their slope, soil type, and vegetation characteristics. The site selection criteria include:

- Location: Vegetated shoulder areas adjacent to highways in Austin and College Station with rural cross sections
- Traffic Volume: High Average Daily Traffic (ADT) counts, preferably above 35,000
- Shoulder size and area: Vegetation width from paved shoulder to high water mark of borrow ditch of at least 8m, and vegetation length in direction of road of at least 40m to accommodate all sampling and collection systems
- Slope: Shoulder slopes in range of 1:6 to 1:8
- Vegetation: Vegetation density and type typical of each region
- Runoff source: Source of runoff to grassy shoulder areas from highway only and not other areas
- Direction of flow: Road surface should not be curved or super-elevated in front of or up-gradient of the site to ensure that runoff flows to and down the vegetated shoulder in a uniform and consistent pattern
- Safety of researchers: Highly visible sites with safe shoulder approaches and off-road parking facilities

4.2 Site Descriptions

4.2.1 AUSTIN SITES

Three sites on Loop 360 in Austin were selected for this study. A map indicating the locations of the three sites is presented in Figure 4.1. Loop 360 is a 14 mile state highway in the western part of Austin that extends from the Barton Creek/Mopac area on the south to Highway 183 on the north (TxDOT, 2003). The first research site is a plot of land adjacent to the southbound lanes of Loop 360 north of FM 2222. The second and third sites are located together on a plot of land adjacent to the northbound lanes of Loop 360 north of the Loop 360/Mopac interchange. All three sites met the criteria established for this study.

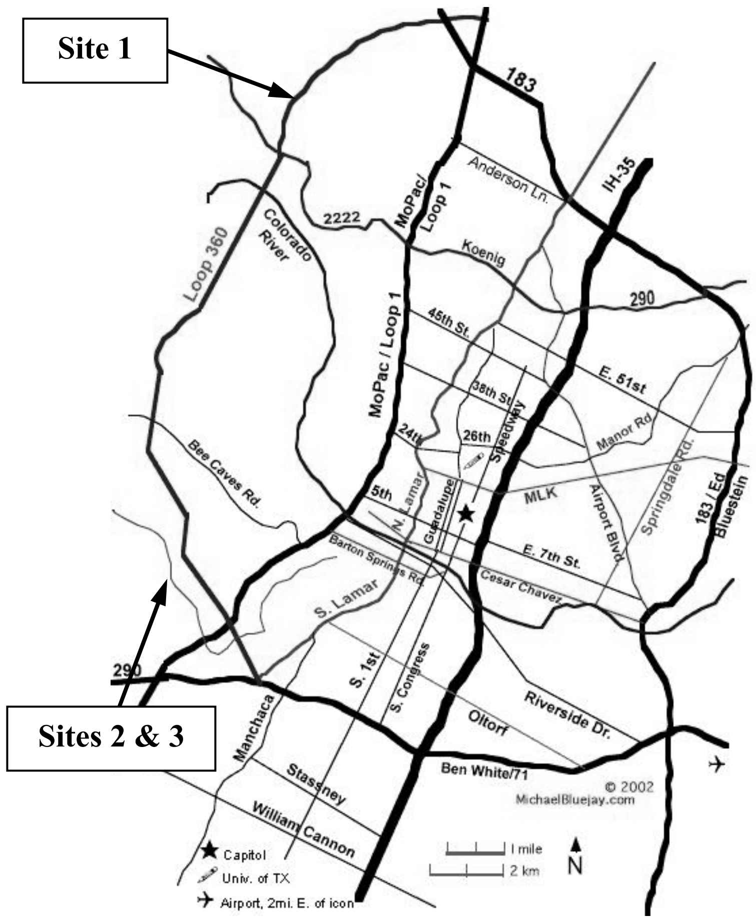

Figure 4.1 Map of Austin showing Loop 360 and location of 3 research sites

Austin Site 1 is located at 7600 North Loop 360 near the intersection with Lakewood Drive, north of FM 2222. The site is adjacent to the southbound lanes of the highway, is directly in front of a commercial office complex, and has a slope of about 1:8 (12%). The 2002 TxDOT estimate of the ADT for this stretch of highway, from Spicewood Springs Avenue on the north to FM 2222 on the south, was 43,000 (CAMPO, 2002). The soils in this area are part of the Volente Complex, which has a silty clay loam texture. These soils have been highly modified by construction of Loop 360 and there is a substantial amount of road base material incorporated in the shallow soil horizon, especially near the edge of pavement. These soils have moderate to low permeability and severe shrink swell potential.

A quantitative and qualitative vegetation survey was conducted by a research scientist from Texas A&M University in September 2004. The average vegetative cover calculated for Site 1 was 83%, with a range of 58% near the road edge to 94% near the bottom of the sloped shoulder. The vegetative cover is comprised almost exclusively of King Ranch Bluestem and Bermudagrass. In some areas significant patches of Buffalograss are present. Few other minor species were noted. Site 1 also provided the opportunity to study the performance of a vegetated buffer strip receiving highway runoff from two different surface types. In the summer and fall of 2004, TxDOT installed a PFC overlay on a section of Highway 360 that included Site 1. Aerial and site photographs of Site 1 are presented in Figure 4.2.

Austin Sites 2 and 3 are located at 1905 South Loop 360, about a mile and a half north of the Loop 360/Mopac interchange. The sites are adjacent to the northbound highway lanes and are located in front of a partially occupied commercial building with adequate room for safe parking. The shoulder area has an average slope of 1:5.5 (18%) and is large enough to accommodate both sets of collection pipes and all sampling equipment. The 2002 TxDOT estimate of the ADT for the section of highway which encompasses these sites, from FM 2244 on the north to Walsh Tarlton Drive on the south, was 35,000 (CAMPO, 2002). The underlying soils at these two sites are Speck stony clay loam. The soils have low permeability and rock fragments typically cover up to 50% of the land surface. Like Site 1, construction of the highway has substantially altered the original texture and highway base material is common in the surface layers, especially near the edge of pavement.

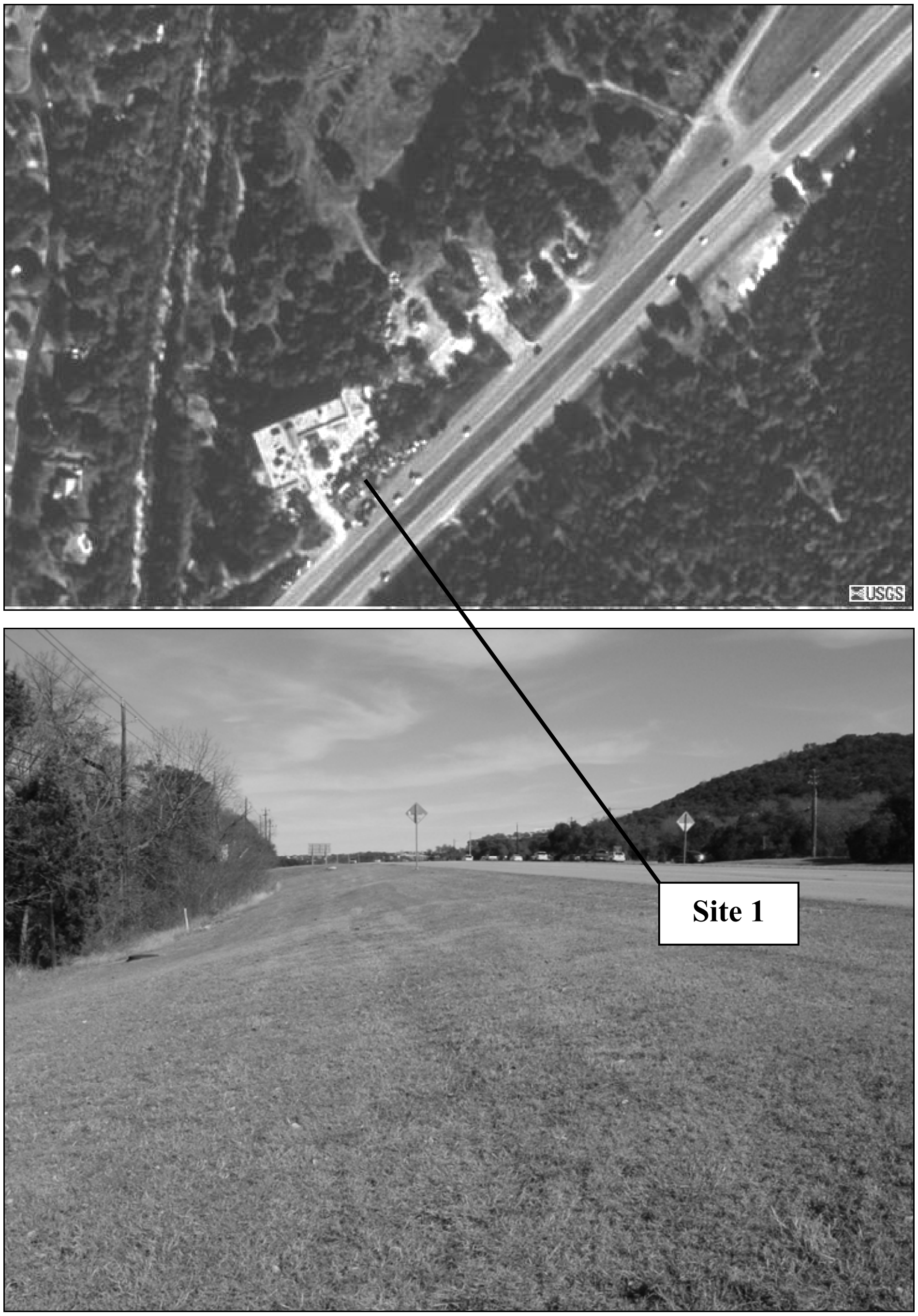

Figure 4.2 Aerial and site photographs of Austin Site 1 (Aerial photograph: USGS, 2004)

Sites 2 and 3 were purposely chosen to be adjacent to each other so that an additional site variable could be introduced, namely, the application of a one-inch compost layer at one of the two sites while holding all other site conditions constant (slope, ADT, vegetation types, storm volumes and frequency, etc.), This alteration to Site 3 was performed in order to evaluate the effect of a biosolids compost layer on runoff characteristics and the performance of the vegetated filter strip. September 2004 vegetation survey results for these sites resulted in an average vegetation density of 97% at Site 2 and 100% at Site 3. Detailed vegetation survey results for all research sites can be found in Appendix A. Similar to Site 1, the vegetated cover at both of these sites is comprised almost exclusively of King Ranch Bluestem and Bermudagrass, with a few significant patches of Buffalograss. Aerial and site photographs of Sites 2 and 3 are presented in Figure 4.3.

4.2.2 College Station Sites

All three sites in College Station are located consecutively on the south bound lane shoulder of State Highway (SH) 6 between University Drive and Harvey Road. The sites are adjacent to SH 6 and are directly exposed to the heavy traffic on the highway. All the sites have ample room to accommodate all the sampling equipment. The 2003 Bryan District TxDOT office estimate of the ADT for this stretch of highway was 76,000 vehicles per day. A map of the College Station study area is presented in Figure 4.4.

A quantitative and qualitative vegetation survey was conducted at each of the sites in August 2004 to examine the vegetated buffer. The vegetation coverage was conducted using a 1.22m x 1.22m (4ft x 4ft) quadrant grid placed at random locations at all College Station sites. The vegetation extent and plant identification for each of the sites was conducted using image processing software. The total pixels covered by the actual living grass were calculated as the percentage of vegetated cover. Detailed survey results are located in Appendix A.

Site 1 is the northernmost of the three research sites on SH 6 in College Station. It is located adjacent to the southbound lanes of the highway just south of University Drive and has adequate space to accommodate the sampling systems. The slope of the grassy shoulder at this site is in the range of 6-8%. An aerial photograph and site photograph of this site are presented in Figure 4.5 and Figure 4.6. The average vegetation cover at this site was found to be 99% and the dominant species were identified as King Ranch Bluestem, Bermudagrass, and Bahiagrass.

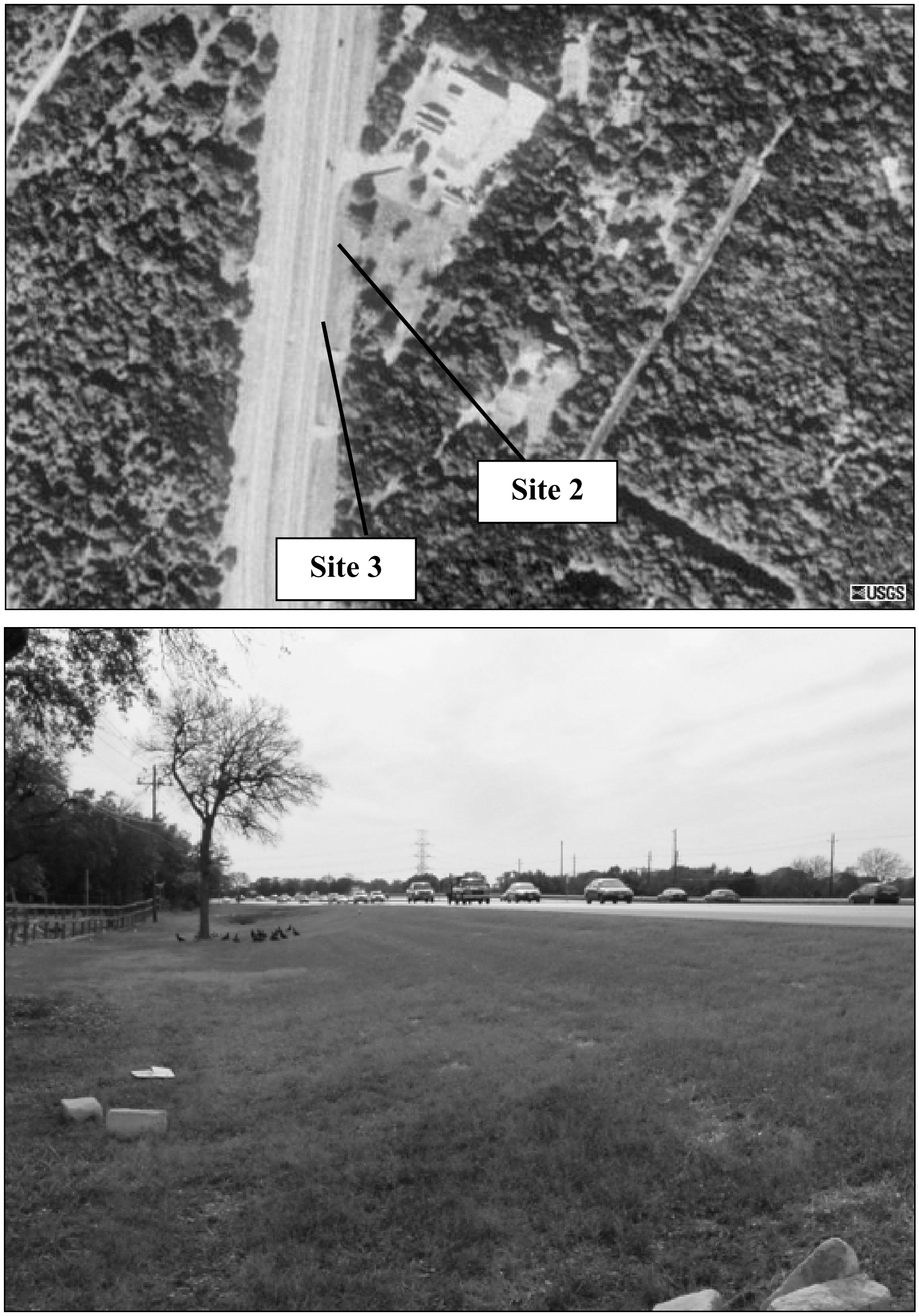

Figure 4.3 Photographs of Austin Sites 2 and 3 (Aerial photograph: USGS, 2004)

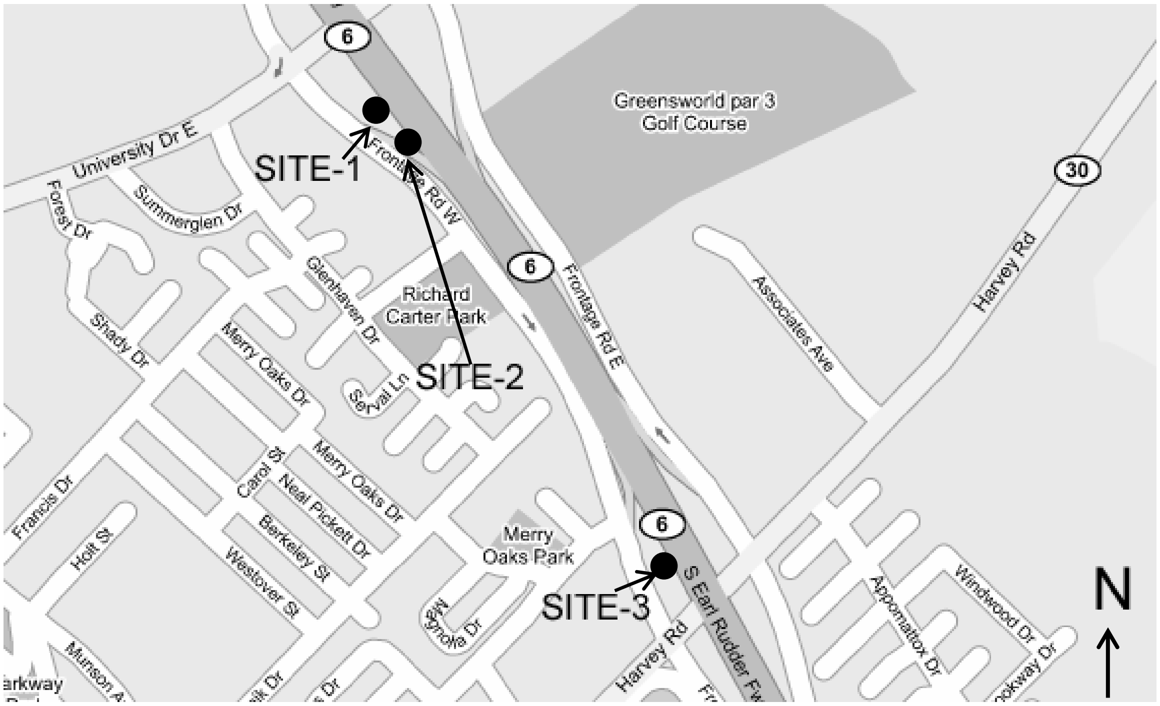

Figure 4.4 Map of College Station Site

Figure 4.5 Aerial View of Site 1 in College Station
(Aerial Photograph: Google Maps, 2005)

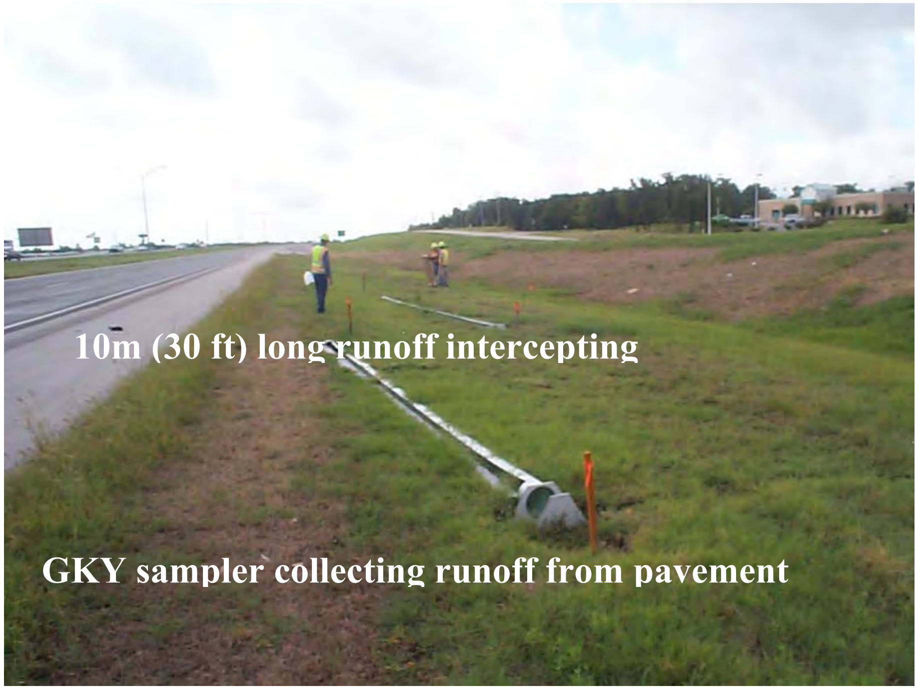

Figure 4.6 Photograph of College Station Site 1

College Station Site 2 is also located adjacent to the southbound lanes of SH 6, and is just south of Site 1. This site has a slope of 18-20%. Site and aerial photographs of this site are presented in Figure 4.7 and Figure 4.8. The results of the vegetation survey indicate that the site has an average vegetation cover of 97% and is comprised almost exclusively of Bermudagrass.

Site 3 is the southernmost of the research sites on SH 6 in College Station. It is located just north of Harvey Road and is adjacent to the southbound lanes of the highway. The slope of College Station is in the range of 14 - 15%. The average vegetation density across this site is 98% and the vegetation is comprised almost exclusively of Bermudagrass. Figure 4.9 and Figure 4.10 show an aerial photograph and a site photograph.

Figure 4.7 Aerial View of Site 2 in College Station (Aerial Photograph: Google Maps, 2005)

Figure 4.8 Site photograph of College Station Site 2

Figure 4.9 Aerial View of College Station Site 3 (Aerial Photograph: Google Maps, 2005)

Figure 4.10 Photograph of College Station Site 3

Textural analysis of the soils at the three College Station sites were not performed; however, soil samples from Site 3 were analyzed by the Soil, Water and Forage testing laboratory at the Heep Center in College Station, Texas to determine the soil chemical properties. This analysis was done at the various locations (0m, 2m, 4m, and 8m) of Site 3. The soil analysis report indicates high heavy metal content and phosphorus in the soil.

Tables 4.1, 4.2, 4.3, and 4.4 show the results of the soil analysis report. The normal range of constituent concentrations in the soil was obtained from the soil analysis report (Soil Analysis Report, 2004).

Table 4.1 Soil Content Analysis at Site 3 – 0m

Analysis	**Results (ppm)**	**Normal Range(ppm)**	**Comment**
Nitrate-N	6	NA	Very Low
Phosphorus	14	30-50	Moderate
Zinc	15.18	0.20-0.27	Excessive
Copper	1.47	0.11-0.15	Excessive

Table 4.2 Soil Content Analysis at Site 3 – 2m

Analysis	**Results (ppm)**	**Normal Range(ppm)**	**Comment**
Nitrate-N	4	NA	Very Low
Phosphorus	23	30-50	Very High
Zinc	13.47	0.20-0.27	Excessive
Copper	1.76	0.11-0.15	Excessive

Table 4.3 Soil Content Analysis at Site 3 – 4m

Analysis	**Results (ppm)**	**Normal Range(ppm)**	**Comment**
Nitrate-N	4	NA	Very Low
Phosphorus	8	30-50	Low
Zinc	2.43	0.20-0.27	Very High
Copper	0.45	0.11-0.15	Very High

Table 4.4 Soil Content Analysis at Site 3 – 0m

Analysis	**Results (ppm)**	**Normal Range(ppm)**	**Comment**
Nitrate-N	4	NA	Very Low
Phosphorus	9	30-50	Low
Zinc	3.33	0.20-0.27	Very High
Copper	0.32	0.11-0.15	Very High

4.2.3 Summary of Site and Sampling Conditions

Research sites were selected for this study based upon certain physical criteria including slope, traffic volume, vegetation density, and vegetation type. To the extent possible, sites were selected that met the criteria but which also differed from one another so that differences in performance might be attributed to particular characteristics. A summary of the important characteristics at each of the six research sites are presented in Table 4.1.

Table 4.5 Summary of Physical Site Characteristics

Location	Site	ADT	Slope	Vegetation Density	Vegetation Type
Austin	1	43,000	12%	83%	King Ranch Bluestem, Bermudagrass
	2	35,000	18%	97%	King Ranch Bluestem, Bermudagrass
	3	35,000	18%	100%	King Ranch Bluestem, Bermudagrass
College Station	1	76,000	8%	99%	Bermudagrass, King Ranch Bluestem, Bahiagrass
	2	76,000	20%	97%	Bermudagrass
	3	76,000	15%	98%	Bermudagrass

4.3 Site Setup

Each site was photographed and measured prior to installation of the collection and sampling systems. A series of runoff collection and sampling systems were installed at each site in January and early February 2004 in the manner shown in Figure 4.11. The collection systems consisted of 10m lengths of standard 8-inch PVC pipes. A length-wise section of each pipe was removed and a strip of galvanized metal flashing was attached along one of the edges to create a lip to better direct runoff into the pipe. Shallow trenches were dug parallel to the highways at 2m, 4m, and 8m distances from the edge of pavement at each site to accommodate the collection pipes. Collection pipes were situated such that the metal flashing was flush with ground level. The pipes were placed slightly askew rather than exactly parallel to the road edge to ensure that runoff would easily flow to one end of the collection pipe. A photograph of a collection pipe is shown in Figure 4.12. The 1-inch layer of biosolids compost was applied to Site 3 in Austin by researchers shortly after the installation of the collection and sampling systems. Volumetric rain gauges also were installed at each research site in Austin.

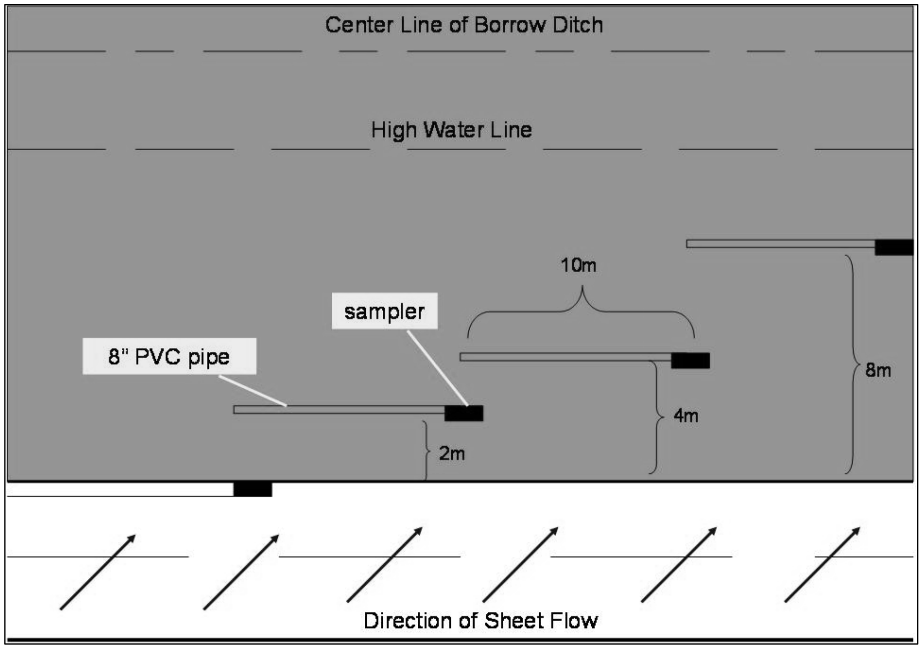

Figure 4.11 Schematic diagram of site layout (not to scale)

Figure 4.12 Photograph of installed collection pipe at Austin Site 2

GKY FirstFlush Samplers were installed to collect the runoff at the gravity-fed collection end of each pipe. GKY FirstFlush Samplers are passive stormwater samplers that can hold up to 5 liters (L) of water. The lid of each sampler is constructed with 5 sampling ports, each of which can be plugged to better control the rate at which collected runoff enters the sampler. Plastic flaps on the underside of each port function as closing mechanisms, preventing additional water from entering the sampler once it has reached its capacity. Each sampler is fitted with a 5L, removable plastic container and lid to allow for easy transport. Figure 4.13 shows a diagram of the GKY sampler and its components

Samplers also were installed at each site at the edge of pavement in order to collect runoff directly from the highway surface. Holes were dug and the samplers placed in the holes so that their top surface was just below the road surface and held in place by concrete. Photographs of an installed sampler at the edge of pavement are shown in Figure 4.14.

Zero meter flow strips, also referred to as gutter strips (visible in Figure 4.14) were laid at all of the research sites to help direct runoff to the sampler at the edge of the pavement. The flow strips were D-shaped gaskets, 25mm (1 inch) high, with the flat surface placed on the pavement and affixed with adhesive. The gutter strips were removed mid-study from all sites due to concern about their effect upon the collected runoff.

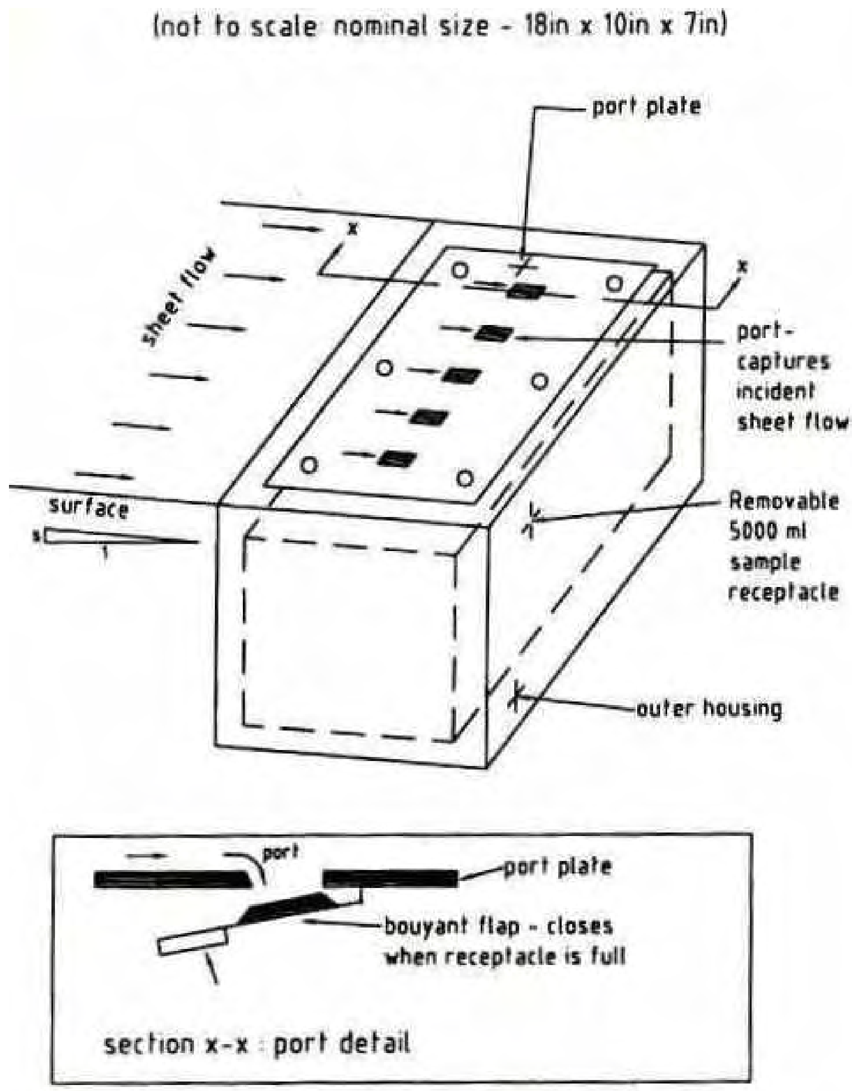

Figure 4.13 GKY First Flush Sampler (GKY, 2005)

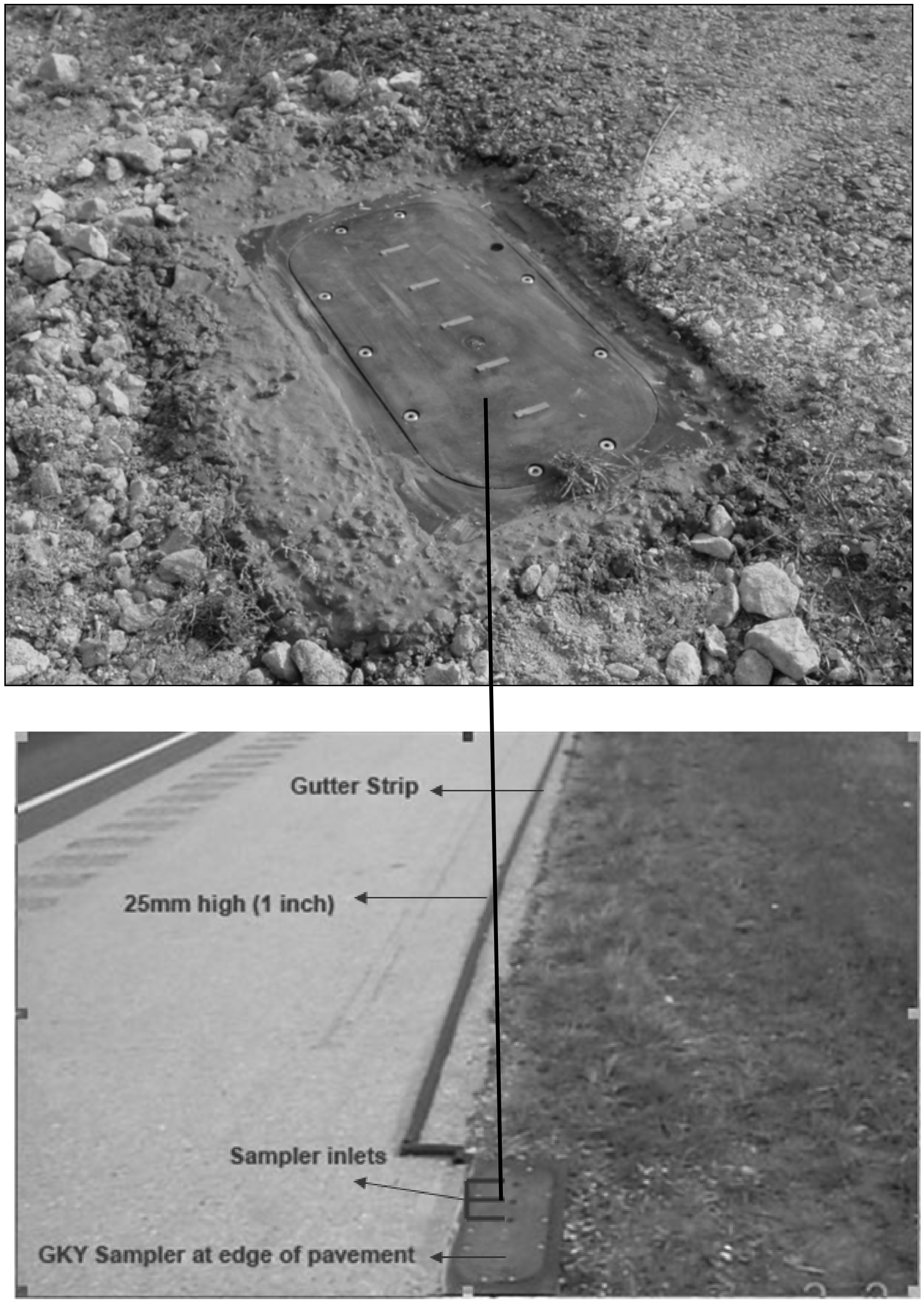

Figure 4.14 Photograph of installed sampler at the edge of pavement

4.4 Pre-Sampling and Maintenance

A large quantity of dirt and grass was dug up and disturbed during the installation at all three sites. These conditions would not have resulted in runoff samples representative of normal site functioning, therefore sampling activities did not begin immediately after installation was complete. A few large storms were allowed to pass unsampled so that excess loose dirt could be washed away and disturbed vegetation could begin to re-establish itself.

Periodic mowing of the sites was conducted by TxDOT contracted mowing crews at the Austin sites and by Texas Transportation Institute (TTI) crews at the College Station sites. Mowing occurred three to four times a year at each site, mostly during the wet summer months, but also occasionally during the drier months. During the study period, the Austin sites were mowed in early May, July, September, and late December 2004. The College Station sites were mowed in mid-April, July, and November 2004. Standard mowing practices for highway shoulders are limited to cutting only and do not include collection of grass clippings, therefore large amounts of loose grass and weeds were present at each site after mowing was completed, especially directly in front of the collection pipes. Sampling was not performed at any of the sites immediately after they were mowed. The majority of the loose clippings were manually raked away from the collection and sampling areas by researchers and at least one storm was allowed to elapse before sampling activities were resumed. This delay in sampling helped ensure that runoff conditions from each storm sampled were not a function of loose grass and dirt in the path of the runoff.

Other maintenance activities were performed at each site as needed between rain events. Such activities included trash and debris collection, treatment of fire ant mounds, and repairs to the collection pipes, galvanized flashing, and sampler holders. Fire ant mounds were a frequent, recurring problem at all of the research sites, especially around the perimeter of the collection pipes. This is believed to be due to the soil and vegetation in those areas already being somewhat disturbed and loosened, thereby making a convenient and efficient place for the ants to build their mounds. Treatment of the mounds was performed on an as needed basis at each site by using the commercially available insecticide, AMDRO. This chemical mixture is insoluble in water, and therefore should not have any adverse effects on sampling results.

4.5 Sampling Procedures

Preparatory activities were performed at each site prior to each predicted rain event. Each collection pipe was cleaned out to remove any dirt, leaves, grass, or trash that had accumulated during the antecedent dry period. Clean sampling containers were also placed inside each sampler and the sampler ports and flaps inspected and cleaned to remove any accumulated mud or dirt. Rain gauges also were emptied and flushed of collected leaves and dirt. The plastic sampling containers were removed and capped at the conclusion of each rain event. Occasionally sites were visited during rain events to visually inspect the systems in action and to ensure that runoff was being diverted correctly into and through the collection pipes and that the samplers were accepting the runoff properly. The samples were transported to the laboratory for preservation and analysis when storms produced enough runoff volume to adequately collect in the samplers. A minimum of half an inch of rainfall was typically needed at each site to allow enough runoff to be collected in each sampler in order for analyses to be conducted. Records were made during each site visit of rainfall volume, volume collected in samplers, and general site conditions.

4.6 Analytical Procedures

All runoff samples were transported to Environmental Laboratory Services, a division of the Lower Colorado River Authority (LCRA), for analysis. The lab is EPA certified and has been contracted for stormwater analyses in the past. Samples were delivered to the laboratory as soon after rain events as possible when permitted by operating hours. Samples collected at College Station were packed in ice and sent to the Austin lab via Greyhound bus. If samples were collected outside of the lab’s normal business hours, samples were stored in a 4°C cold room until they could be transported to the laboratory. All applicable Quality Assurance/Quality Control (QA/QC) procedures were followed during the 14 month sampling period. The analytical parameters and methods, as approved by representatives from the University of Texas at Austin and the Austin District of TxDOT, are presented in Table 4.2.

Table 4.6 Parameters for Analysis by Environmental Laboratory Services

Parameter	Units	Method (USEPA, 2003)	Practical Quantification Limit
Total Suspended Solids	mg/L	E160.2	1
Total Kjeldahl Nitrogen	mg/L	E351.2	0.02
Nitrate and Nitrite as N	mg/L	E353.2	0.02
Total Phosphorus	mg/L	E365.4	0.02
Dissolved Phosphorus	mg/L	E365.4	0.02
Total Copper	µg/L	E200.8	2
Dissolved Copper	µg/L	E200.8	1
Total Lead	µg/L	E200.8	1
Dissolved Lead	µg/L	E200.8	1
Total Zinc	µg/L	E200.8	5
Dissolved Zinc	µg/L	E200.8	4
Chemical Oxygen Demand	mg/L	E410.4	7
Fecal Coliform	cfu/100mL	M9222D	0
Semi-volatile Organics (see Table 5.3)	µg/L	SW8270C	varies

4.7 Statistical Analysis

Inherent variability in stormwater sampling leads to certain difficulties in collecting and analyzing data from this type of study. The difficulty in predicting storm occurrences as well as variations in storm intensity, duration, and volume complicates monitoring with passive stormwater samplers. Other factors, such as changing antecedent dry periods and vehicles during a storm also introduce variability into the data set of monitored events. All of these factors increase the uncertainty when analyzing the collected data, especially with a relatively small dataset.

Strecker et al. (2001) discuss these inherent problems and evaluate various data analysis methods and techniques that can affect final results. Analysis techniques that they explore include evaluating effectiveness of BMPs on a storm by storm basis, as well as on average event mean concentrations (EMCs) and loading removal rates. Their conclusions indicate that comparisons of total pollutant loading should be utilized in determining BMP effectiveness if the appropriate data are available. Since the use of passive stormwater samplers and volumetric rain gauges in this study precluded the collection of site specific data for runoff volumes and correlations, this type of analysis of changes in total pollutant loads are not possible. In the event that such comparisons cannot be made, the authors recommend the use of comparisons based on some other form of storm-specific parameter, such as rainfall volume (Strecker et al., 2001). They indicate that the use of standard statistical descriptions, box and whisker plots, and probability plots of data should be employed to demonstrate differences in EMCs as well as effectiveness of the BMP. Statistics including mean, range, and standard deviation were used for describing the data in this study. Analytical methods including analysis of variance tests and comparisons based on mean EMCs and rainfall-weighted average concentrations were used. Box and whisker plots were employed for displaying the data for this study and understanding the performance of the vegetated filter strips.

A box and whiskers plot (also called a boxplot) is a graphical tool that can be used to visually compare data sets. Within the "box," the line through the middle indicates the median of the data range and the dot indicates the mean. The box itself represents the 2nd and 3rd quartiles of the data range, that is, the 25th through 75th percentiles. The "whiskers" can extend from the top and bottom of the box to a length of up to one and a half times the difference between the first and third quartiles to represent data points in the range. Points that extend beyond the length of the whiskers are indicated with an asterisk.

Statistically significant differences in concentrations were determined through analysis of variance (ANOVA) tests. Minitab, a commercially available statistical software package, was used for these tests. As the name implies, ANOVA analyzes the means and variances of sets of values and determines whether or not they are significantly different from one another. The test returns a value known as the "P-value," which ranges from 0 to 1. A P-value of 1 indicates that the two data sets are identical, and therefore that no statistically significant difference exists between them. Conversely, a P-value approaching 0 indicates that the two sets of values are as statistically different from each other as possible. P-values less than or equal to 0.05 are often accepted as indicating a statistically significant difference between data sets. Due to the limited dataset available for this study, P-values of 0.1 or less were used to indicate statistically significant differences.

5. RESULTS

5.1 Rainfall and Sample Collection Records

Over the course of the study period, a total of 23 storm events were successfully sampled. Between February 2004 and April 2005, 13 storms were successfully sampled at the Austin sites, 10 at Site 1 and 13 at Sites 2 and 3. A total of 10 storms were successfully sampled from March 2004 to May 2005 at each of the College Station sites. Dates on which runoff samples were collected and the corresponding rainfall amounts at each research site are presented in Table 5.1 and Table 5.2. It should be noted that sample collection dates are usually one day later than the actual rainfall event dates. Fewer storms were sampled at Austin Site 1 because sampling activities were suspended during the PFC construction project conducted in the late summer and fall of 2004. Additionally, the rain event of March 24/25, 2004 in Austin produced extremely localized rainfall which did not lead to enough runoff volume at Site 1 to adequately fill any of the samplers.

Table 5.1 Rainfall Volumes and Sample Collection Dates for Austin Sites

	Rainfall (in)	
Collection Date	**Site 1**	**Sites 2 & 3**
2/24/2004	0.64	1.35
3/1/2004	0.50	0.50
3/26/2004	NA	0.30
4/12/2004	1.75	1.00
5/14/2004	1.65	1.45
6/3/2004	0.80	0.40
6/9/2004	2.50	2.75
10/25/2004	NA	2.50
11/1/2004	NA	1.75
11/15/2004	0.90	1.00
11/22/2004	1.05	5.50
1/28/2005	1.30	1.50
3/3/2005	1.00	0.80

Table 5.2 Rainfall Volumes and Sample Collection Dates for College Station Sites

Collection Date	Rainfall (in) – Sites 1, 2, and 3
3/4/04	0.53
3/24/04	0.45
5/1/04	1.09
8/1/04	0.45
8/22/04	0.37
10/2/04	2.13
11/17/04	1.55
1/12/05	0.87
1/27/05	0.54
5/8/05	1.49

5.2 Analytical Results

The analytical results from each rain event sampled were inspected to ensure all appropriate QA/QC procedures were followed by the laboratory and that the delivered reports were complete. The data were compiled into a database and inspected qualitatively to observe initial trends. Several statistical diagnostic tests were performed on the data to determine the overall distribution and to inspect and evaluate any suspected outliers.

Initial plots of the data were created to generate an idea of general trends. Datasets were evaluated for extreme outliers and probability plots were constructed to confirm that the data were normally distributed. Datasets were then tested for significant differences. All of the data collected at each of the research sites in both Austin and College Station are presented in Appendix B. After comparing the data from the first storm sampled in Austin (2/24/2004 collection date) with data from subsequent storms, it became clear that that this first set of samples produced uncharacteristic results. This is believed to be due to lingering negative effects of equipment installation and installation-related disturbances to the vegetation and soil. The data for all analytical parameters for this storm were therefore eliminated from the final analyses.

Collection and sampling of stormwater in a field setting is subject to many uncontrollable factors. There were instances during this study when samples could not be collected from all samplers at every research site for a given storm event. The samplers occasionally malfunctioned, primarily due to tipping of the sampler within its holder or clogging of the sampling ports with leaves and grass transported in the runoff. Certain rain events also did not produce enough runoff to adequately fill all of the samplers. Low intensity storms often would infiltrate into the soil before reaching the eight meter sampler resulting in an empty, or near empty, sampling container. Occasions when samples were not collected at particular sites are noted in the tables.

According to standard laboratory methods, the holding time for fecal coliform bacteria is 24 hours. That is, the sample must be analyzed within 24 hours of collection to avoid degradation of the bacteria. This holding time is further reduced by the time required for sample collection, transport to the laboratory, and the sample preservation process by the laboratory technicians. As a result of this narrow window of time, fecal coliform levels were only analyzed for a fraction of the storms collected. Storms for which the bacteria were not measured are indicated in the results data tables.

Three additional data points were eliminated from the final Austin data set and are considered to be outliers. Each of these points is more than 2 standard deviations above the mean for their respective range of reported values and is often close to, if not more, than three times the magnitude of the next highest value in the range. In a Gaussian distribution, 95.4% of all observations fall within two standard deviations of the sample mean. It is therefore assumed that observations that are substantially outside the boundaries of two standard deviations have been affected by errors that are common in environmental sampling and analysis, and should be excluded from analyses. All three of these data points are results from Site 3, and are for the following distances and parameters: Total Kjeldahl Nitrogen at the 4m sampler on 10/25/2004; Total Lead from the 0m sampler on 11/22/04; and Chemical Oxygen Demand from the 4m sampler on 10/25/2004. These three values are also denoted as outliers in the table.

One or two extremely large values can make a data set look log-normally distributed, whereas the exclusion of these values will transform the data into one that looks like a normal distribution. This trend was observed with the runoff data from this study. Probability plots were constructed for the datasets excluding the three outliers to confirm that the resulting data were indeed normally distributed. The probably plots consistently showed that the data fell reasonably within the confidence intervals for a normal distribution. For this reason, statistics based on the normal distribution were used throughout the analyses for this study.

There are a total of 1472 data points in the Austin data set not counting the data from the first sampling event and excluding the results for PAHs (since that parameter was only monitored occasionally). Removing the three data points from this collection results in a database that is 99.8% intact. As previously mentioned, no data points were eliminated from the College Station dataset, resulting in a database consisting of 1496 points. PAHs were monitored during 5 storm events at Austin Site 1, three off of traditional asphalt surfaces and two immediately after the completion of the PFC overlay. A list of compounds included in the PAH analyses and their corresponding Practical Quantification Limits (PQL) are listed in Table 5.3. Results for all constituents that make up this suite of semi-volatile organics were below detection limits for all monitored events.

Table 5.3 PAHs analyzed by LCRA Lab

Analyte	Units	PQL
1&2-Chloronaphthalene	µg/L	10.0
1,2,4,5-Tetrachlorobenzene	µg/L	10.0
1,2,4-Trichlorobenzene	µg/L	5.00
1,2-Dichlorobenzene	µg/L	5.00
1,2-Diphenylhydrazine	µg/L	5.00
1,3-Dichlorobenzene	µg/L	5.00
1,4-Dichlorobenzene	µg/L	5.00
1-Naphthylamine	µg/L	10.0
2,3,4,6-Tetrachlorophenol	µg/L	10.0
2,4,5-Trichlorophenol	µg/L	6.00
2,4,6-Trichlorophenol	µg/L	5.00
2,4-Dichlorophenol	µg/L	5.00
2,4-Dimethylphenol	µg/L	5.00
2,4-Dinitrophenol	µg/L	50.0
2,4-Dinitrotoluene	µg/L	10.0
2,6-Dichlorophenol	µg/L	5.00
2,6-Dinitrotoluene	µg/L	5.00
2-Chlorophenol	µg/L	5.00
2-Methylnaphthalene	µg/L	5.00
2-Methylphenol	µg/L	5.00
2-Naphthylamine	µg/L	5.00
2-Nitroaniline	µg/L	5.00
2-Nitrophenol	µg/L	5.00
2-Picoline	µg/L	5.00
3,3´-Dichlorobenzidine	µg/L	5.00
3-Methylcholanthrene	µg/L	5.00
3-Nitroaniline	µg/L	5.00
4,6-Dinitro-2-methylphenol	µg/L	50.0
4-Aminobiphenyl	µg/L	5.00
4-Bromophenyl phenyl ether	µg/L	5.00
4-Chloro-3-methylphenol	µg/L	5.00
4-Chloroaniline	µg/L	5.00
4-Chlorophenyl phenyl ether	µg/L	5.00
4-Nitroaniline	µg/L	15.0
4-Nitrophenol	µg/L	10.0
7,12-Dimethylbenz(a)anthracene	µg/L	5.00
Acenaphthene	µg/L	5.00
Acenaphthylene	µg/L	5.00
Acetophenone	µg/L	5.00
Aniline	µg/L	5.00
Anthracene	µg/L	5.00
Atrazine	µg/L	5.00
Benzidine	µg/L	5.00
Benzo(a)anthracene	µg/L	5.00
Benzo(a)pyrene	µg/L	5.00
Benzo(b)fluoranthene	µg/L	5.00
Benzo(g,h,i)perylene	µg/L	15.0
Benzo(k)fluoranthene	µg/L	5.00
Benzoic acid	µg/L	50.0
Benzyl alcohol	µg/L	10.0
Bis(2-chloroethoxy)methane	µg/L	5.00

Analyte	Units	PQL
Bis(2-chloroethyl)ether	µg/L	5.00
Bis(2-chloroisopropyl)ether	µg/L	5.00
Bis(2-ethylhexyl)phthalate	µg/L	5.00
Butyl benzyl phthalate	µg/L	5.00
Carbaryl	µg/L	5.00
Carbazole	µg/L	5.00
Chrysene	µg/L	5.00
Dibenz(a,h)anthracene	µg/L	10.0
Dibenz(a,j)acridine	µg/L	10.0
Dibenzofuran	µg/L	5.00
Diethyl phthalate	µg/L	5.00
Dimethyl phthalate	µg/L	5.00
Di-n-butyl phthalate	µg/L	5.00
Di-n-octyl phthalate	µg/L	5.00
Ethyl methanesulfonate	µg/L	5.00
Fluoranthene	µg/L	5.00
Fluorene	µg/L	5.00
Hexachlorobenzene	µg/L	5.00
Hexachlorobutadiene	µg/L	5.00
Hexachlorocyclopentadiene	µg/L	10.0
Hexachloroethane	µg/L	5.00
Indeno(1,2,3-cd)pyrene	µg/L	10.0
Isophorone	µg/L	5.00
m,p-cresol	µg/L	10.0
Methyl methanesulfonate	µg/L	5.00
Naphthalene	µg/L	5.00
Nitrobenzene	µg/L	5.00
N-Nitrosodiethylamine	µg/L	20.0
N-Nitrosodimethylamine	µg/L	5.00
N-Nitroso-di-n-butylamine	µg/L	5.00
N-Nitrosodi-n-propylamine	µg/L	5.00
N-Nitrosodiphenylamine	µg/L	5.00
N-Nitrosopiperidine	µg/L	5.00
p-Dimethylaminoazobenzene	µg/L	10.0
Pentachlorobenzene	µg/L	5.00
Pentachloronitrobenzene	µg/L	5.00
Pentachlorophenol	µg/L	6.00
Phenacetin	µg/L	5.00
Phenanthrene	µg/L	5.00
Phenol	µg/L	8.00
Pronamide	µg/L	5.00
Pyrene	µg/L	10.0
Pyridine	µg/L	5.00
Cresols, Total	µg/L	10.0
2,4,6-Tribromophenol	µg/L	0
2-Fluorobiphenyl	µg/L	0
2-Fluorophenol	µg/L	0
4-Terphenyl-d14	µg/L	0
Nitrobenzene-d5	µg/L	0
Phenol-d5	µg/L	0

5.3 Performance at Austin Sites

5.3.1 Comparison of Edge of Pavement Concentrations, Austin

It was expected that the initial quality of the runoff at the edge of pavement at each site would be similar because of similarities in traffic count, as well as in traffic patterns and rainfall events at the sites. With the exception of runoff from the PFC overlay at Site 1, this expectation was met. ANOVA tests were performed on the edge of pavement concentrations measured for each parameter at Site 1 (from the conventional asphalt surface only), Site 2, and Site 3 to determine if any statistically significant differences existed between the runoff generated at each site. The only two constituents found to have significantly different concentrations at the edge of pavement are the total and dissolved forms of phosphorus. Further analyses of these datasets indicate that slightly higher concentrations of phosphorus were measured at Site 3 than at Site 1 or Site 2. A boxplot of the total phosphorus EMCs at the edge of pavement are presented in Figure 5.1. The reason for higher concentrations of phosphorus at the edge of pavement at Site 3 is unknown but may be related to the application of compost at the site.

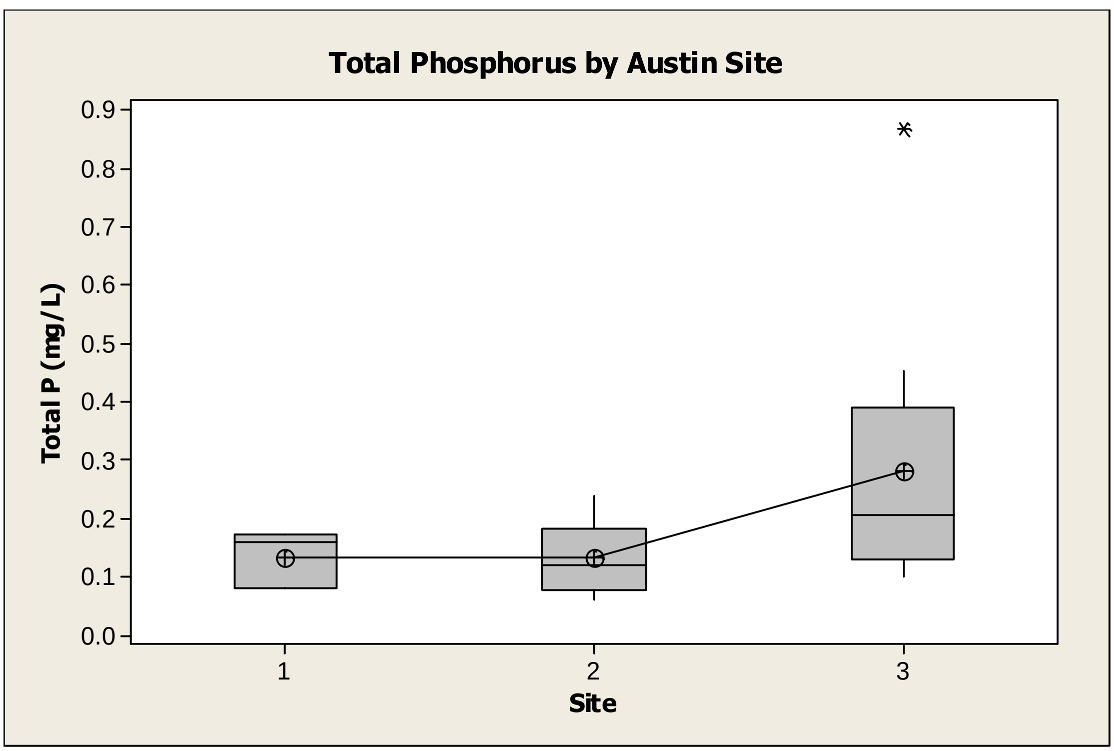

Figure 5.1 Boxplot of Edge of Pavement Total Phosphorus EMCs at Austin Sites

The results indicate that approximately equivalent pollutant concentrations exist on the road surface at each site. This similarity provides a good control for comparing trends at each site and the effectiveness of the vegetated filter strips at removing pollutants. As an illustration of these similarities, a comparison of the TSS EMCs at the edge of pavement at each research site is provided in Figure 5.2. These similarities, however, do not exist with the runoff generated from the PFC overlay surface at Site 1. The observed differences between the runoff quality from this new surface and the subsequent site performance are documented in the next section.

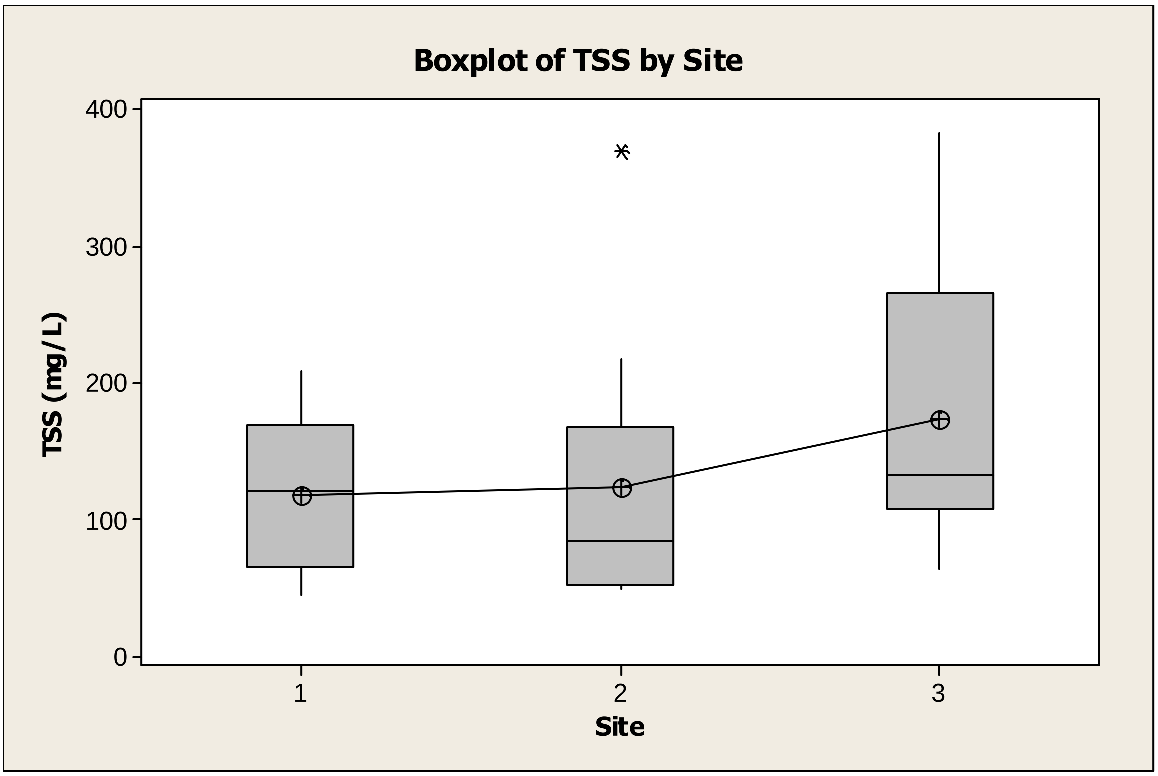

Figure 5.2 Boxplot of Edge of Pavement TSS EMCs at Austin Sites

5.3.2 Summary Statistics

Tables 5.4-5.7 contain the summary statistics (arithmetic mean, range, and standard deviation) of the monitoring data collected at each site for each constituent. The events monitored at Site 1 are separated into events monitored from the old surface and events monitored with the PFC surface in place. The rows within each table have been marked or shaded to indicate whether the observed concentrations at specified distances from the edge of pavement exhibit statistically significant increases (shown with diagonal hash marks) or decreases (shaded gray) in concentration. Constituents with no shaded or marked cells indicate that no statistically significant changes in concentration occurred for that constituent across the width of the vegetated filter strip. Rows with a marked or shaded cell only in the right-most column (representing the 8m sampling distance) indicate that the only significant increase or decrease for that constituent at that site occurred at the furthest sampling point from the edge of pavement. Rows with multiple shaded or marked cells indicate that a significant increase or decrease occurred at each of the distances indicated by the colored cell location. For example, at Site 2, the concentrations of TSS were found to significantly decrease between the zero and two-meter and the zero and eight-meter sampling points (indicated by the gray shading), but no statistically significant change in concentration occurred between the zero and four-meter sampling point.

In addition to determining the summary statistics for each constituent at each site and determining the statistically significant changes that occurred over the width of the vegetated filter, boxplots were constructed to help examine trends that occurred at each site. The entire set of plots for each monitored parameter at each site can be found in Appendix C.

The summary statistics for rainfall events monitored at Site 1 from the older, traditional asphalt surface are presented in Table 5.4. TSS was found to significantly decrease over the width of the vegetated area, as indicated by the shading at the 8m distance. Total copper and total lead also exhibited statistically significant decreases in concentrations between the zero and four meter and zero and eight meter sampling points. Figure 5.3 shows a boxplot of the changes in total copper concentrations at this site. The plot clearly shows the general trend of decreasing concentrations with increasing distance from the edge of pavement for this constituent. The only constituents to exhibit a statistically significant increase in concentration at this site were TKN and dissolved phosphorus, both of which increased over the entire area

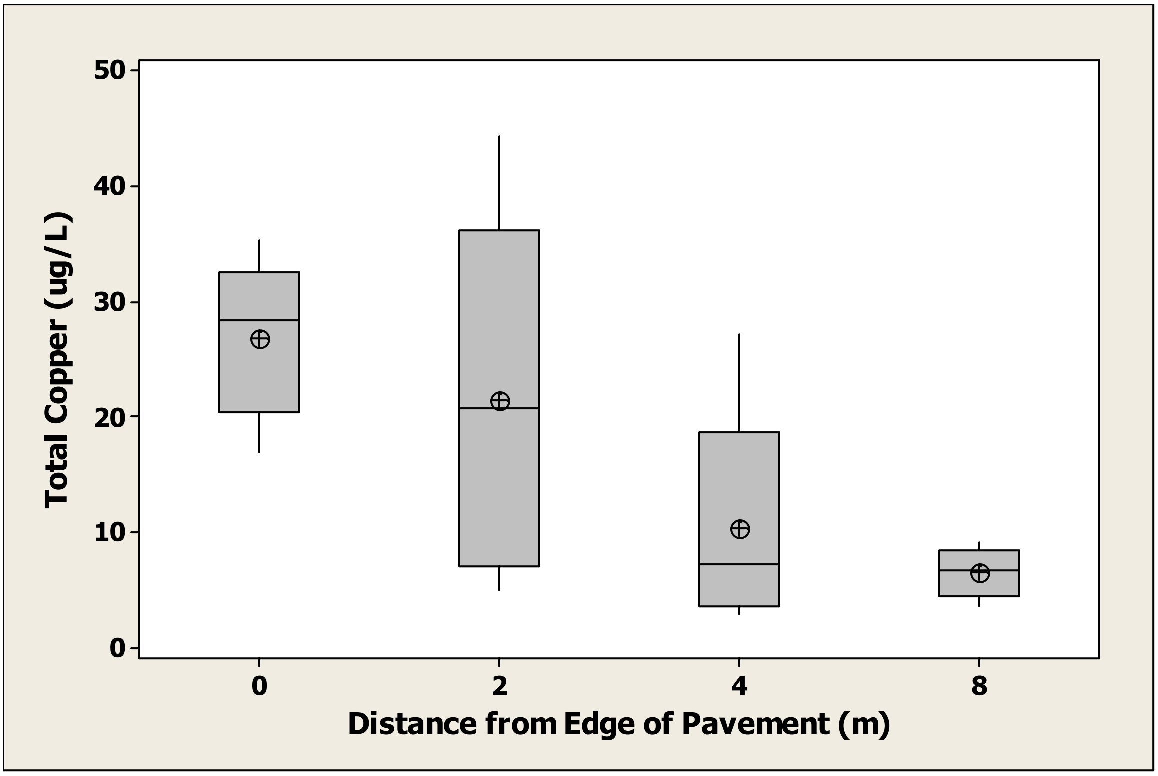

Figure 5.3 Boxplot of Total Copper EMCs at Austin Site 1, Traditional Asphalt Surface

The summary statistics for rainfall events monitored at Site 1 from the new, PFC overlay surface are presented in Table 5.5. The only significant changes observed at this site were increases in some constituent concentrations over the vegetated sampling area. No significant decreases in concentrations were observed between the edge of pavement and the various sampling distances. This is a result of the extremely clean nature of the runoff leaving the PFC. Results from events monitored at this site indicate significant increases in average EMCs for TKN within the first eight meters and for TSS within the first two meters. Figure 5.4 shows a boxplot of TKN concentrations across the vegetation width at this site. Significant increases in both the total and dissolved forms of zinc were also observed over almost the entire site. These elevated levels of zinc are believed to be due to leaching of zinc from the galvanized flashing attached to each of the collection pipes. This trend was also observed at the other research sites.

Table 5.4 Summary Statistics for Austin Site 1, Traditional Asphalt Pavement

Constituent	**EOP** mean range std. dev.	**2m** mean range std. dev. P-Value	**4m** mean range std. dev. P-Value	**8m** mean range std. dev. P-Value
TSS (mg/L)	118 44 - 330 61	121 14 - 330 137 0.959	60 4 - 102 36 0.221	42 17 - 68 21 0.031
TKN (mg/L)	1.13 0.7 - 1.5 0.31	1.86 0.4 - 2.6 0.86 0.112	2.39 0.4 - 5.4 1.81 0.162	2.15 1.1 - 3.7 1.02 0.064
NO3/NO2-N (mg/L)	0.43 0.1 - 1.4 0.55	0.25 0.0 - 0.5 0.19 0.491	0.36 0.0 - 0.9 0.38 0.810	0.27 0.1 - 0.5 0.16 0.530
Total P (mg/L)	0.13 0.1 - 0.2 0.05	0.19 0.1 - 0.3 0.10 0.262	0.32 0.1 - 0.9 0.32 0.241	0.29 0.1 - 0.6 0.22 0.142
Dissolved P (mg/L)	0.04 0.0 - 0.1 0.04	0.10 0.0 - 0.2 0.09 0.202	0.18 0.1 - 0.6 0.23 0.207	0.18 0.0 - 0.4 0.17 0.100
Total Cu (µg/L)	26.84 16.9 - 35.3 6.89	21.46 5.0 - 44.3 15.69 0.502	10.39 3.0 - 27.2 9.80 0.015	6.62 3.6 - 9.1 2.14 <0.001
Total Pb (µg/L)	12.57 6.2 - 24.2 7.32	6.54 1.4 - 18.1 6.89 0.216	2.13 0.0 - 3.7 1.48 0.014	1.17 0.0 - 2.1 1.08 0.009
Total Zn (µg/L)	167.40 101.0 - 209.0 44.26	114.82 46.5 - 204.0 71.50 0.200	158.10 42.9 - 385.0 133.74 0.886	102.42 49.3 - 243.0 83.48 0.163
Dissolved Cu (µg/L)	5.94 2.1 - 9.9 3.54	8.43 2.8 - 19.7 6.59 0.477	6.73 2.2 - 20.5 7.77 0.841	4.23 2.7 - 5.9 1.23 0.338
Dissolved Pb (µg/L)	0.00 none 0.00	0.00 none 0.00 *	0.22 0.0 - 1.1 0.50 0.347	0.00 none 0.00 *
Dissolved Zn (µg/L)	47.06 7.5 - 95.1 31.28	61.96 39.2 - 142.0 44.81 0.559	124.52 39.0 - 335.0 121.49 0.205	94.22 36.5 - 223.0 75.78 0.234
COD (mg/L)	64.0 29.0 - 84.0 20.8	77.2 12.0 - 176.0 68.5 0.691	71.0 15.0 - 213.0 80.4 0.855	53.8 36.0 - 83.0 17.5 0.426

Table 5.5 Summary Statistics for Austin Site 1, PFC

Constituent	EOP mean range std. dev.	2m mean range std. dev.	4m mean range std. dev.	8m mean range std. dev.
TSS (mg/L)	8 3 - 16 6	14 9 - 19 5 0.219	32 13 - 52 19 0.052	25 14 - 46 18 0.123
TKN (mg/L)	0.55 0.4 - 0.9 0.21	1.03 0.5 - 2.1 0.92 0.341	0.95 0.6 - 1.5 0.42 0.139	1.65 1.3 - 2.0 0.34 0.003
NO3/NO2-N (mg/L)	0.40 0.2 - 0.7 0.22	0.32 0.1 - 0.7 0.30 0.711	0.16 0.0 - 0.5 0.23 0.179	0.16 0.1 - 0.3 0.13 0.161
Total P (mg/L)	0.23 0.0 - 0.5 0.26	0.05 0.0 - 0.1 0.01 0.286	0.22 0.1 - 0.4 0.14 0.947	0.14 0.1 - 0.2 0.07 0.603
Dissolved P (mg/L)	0.08 0.0 - 0.3 0.13	0.13 0.0 - 0.0 0.01 0.406	0.18 0.0 - 0.2 0.11 0.950	0.06 0.0 - 0.1 0.03 0.801
Total Cu (µg/L)	5.74 2.8 - 11.1 3.89	9.15 3.6 - 19.6 9.05 0.521	5.84 3.2 - 11.0 3.59 0.973	4.21 3.8 - 4.8 0.50 0.538
Total Pb (µg/L)	0.67 0.0 - 1.5 0.79	1.30 1.2 - 1.6 0.23 0.247	1.29 0.0 - 2.1 0.93 0.347	0.52 0.0 - 1.6 0.91 0.828
Total Zn (µg/L)	45.08 26.7 - 58.5 14.30	63.80 45.0 - 85.4 20.35 0.208	219.25 183.0 - 243.0 27.21 <0.001	281.67 228.0 - 356.0 66.46 0.001
Dissolved Cu (µg/L)	3.94 1.9 - 8.8 3.28	5.90 2.0 - 13.1 6.25 0.609	3.78 1.5 - 9.8 4.02 0.951	2.97 2.6 - 3.4 0.41 0.640
Dissolved Pb (µg/L)	0 none 0	0 none 0 *	0 none 0 *	0 none 0 *
Dissolved Zn (µg/L)	33.75 20.3 - 47.2 13.37	56.60 41.1 - 67.0 13.68 0.077	165.75 109.0 - 207.0 41.45 0.001	225.33 175.0 - 291.0 59.50 0.001
COD (mg/L)	30.5 10.0 - 77.0 31.4	54.0 10.0 - 122.0 59.7 0.524	44.0 22.0 - 98.0 36.3 0.594	48.0 32.0 - 63.0 15.5 0.423

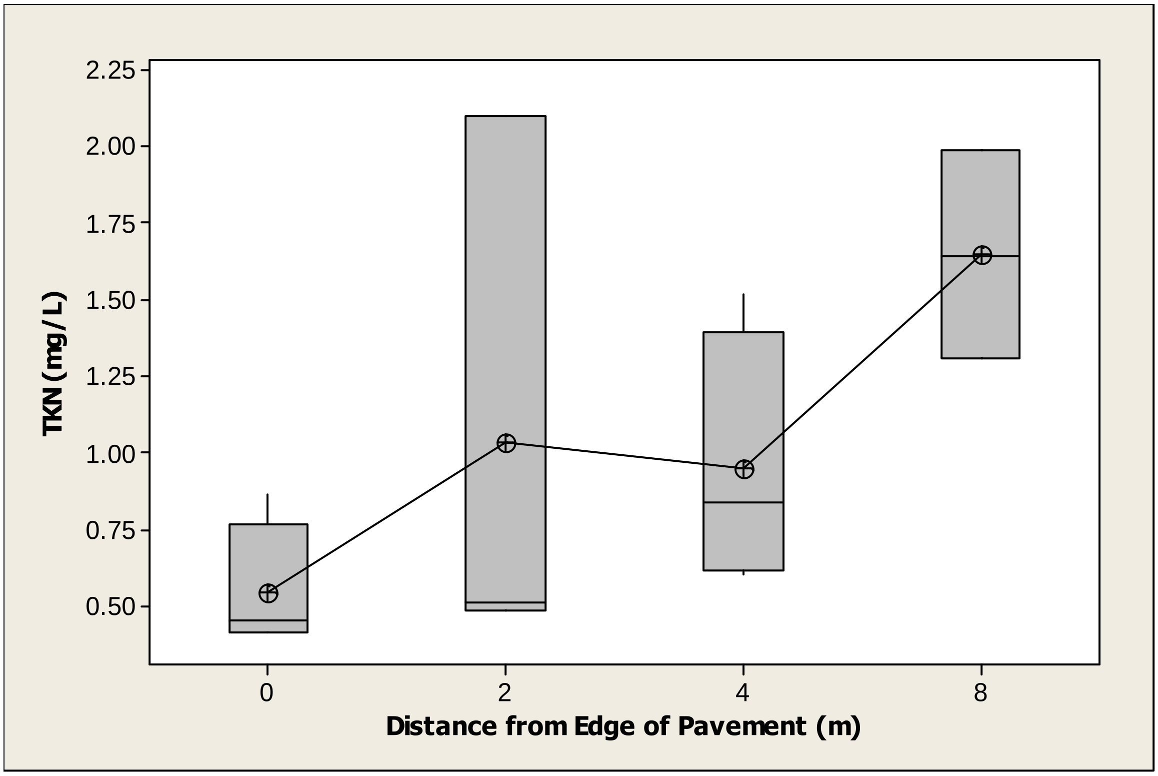

Figure 5.4 Boxplot of Total Kjeldahl Nitrogen at Austin Site 1 from the PFC Surface

The summary statistics for rainfall events monitored at Site 2 are presented in Table 5.6. These results indicate a significant decrease in TSS concentrations within the first two meters of vegetation at this site as well as over the entire eight meter sampling width. Average EMCs for total copper also exhibited significant decreases everywhere across the vegetation width. Significant decreases also were observed for COD, dissolved copper, and total lead, although these decreases only occur between the zero and eight meter sampling point. Unlike the suspended solids and metals species, nutrients were often found to increase with increasing distance from the edge of pavement at this site. Both the total and dissolved forms of phosphorus exhibited significant increases in average concentrations over the entire sampling area, and TKN showed a significant increase in concentration over the first four meters. Figure 5.5 shows a boxplot of the dissolved phosphorus concentrations at Site 2. Total and dissolved forms of zinc also were found to significantly increase over the vegetated area.

Table 5.6 Summary Statistics for Austin Site 2

Constituent	EOP mean range std. dev.	2m mean range std. dev.	4m mean range std. dev.	8m mean range std. dev.
TSS (mg/L)	124 49 - 370 96	53 12 - 103 38 0.038	71 15 - 275 88 0.190	39 7 - 185 53 0.020
TKN (mg/L)	1.5 0.6 - 2.3 0.6	1.7 0.8 - 4.6 1.1 0.543	2.5 0.8 - 6.9 1.8 0.085	1.6 0.9 - 3.7 0.8 0.659
NO3/NO2-N (mg/L)	0.34 0.0 - 1.5 0.39	0.18 0.0 - 0.4 0.15 0.236	0.33 0.0 - 0.7 0.22 0.938	0.46 0.0 - 1.8 0.55 0.552
Total P (mg/L)	0.13 0.1 - 0.2 0.06	0.24 0.1 - 0.7 0.19 0.080	0.35 0.0 - 1.0 0.29 0.022	0.29 0.1 - 0.5 0.16 0.004
Dissolved P (mg/L)	0.05 0.0 - 0.1 0.03	0.13 0.0 - 0.4 0.14 0.072	0.18 0.0 - 0.5 0.17 0.012	0.16 0.1 - 0.3 0.09 0.001
Total Cu (µg/L)	21.70 10.0 - 42.6 8.60	9.54 2.7 - 25.4 6.27 0.001	8.24 3.0 - 23.3 6.01 <0.001	3.07 0.0 - 5.9 1.61 <0.001
Total Pb (µg/L)	9.82 3.1 - 26.2 6.20	10.22 1.9 - 23.2 8.51 0.900	8.53 0.0 - 35.5 10.61 0.726	1.32 0.0 - 3.9 1.60 <0.001
Total Zn (µg/L)	140.09 82.2 - 229.0 47.57	198.27 74.0 - 439.0 131.94 0.169	286.27 52.7 - 821.0 249.97 0.060	290.09 81.6 - 825.0 226.50 0.036
Dissolved Cu (µg/L)	5.55 3.0 - 8.4 2.13	4.58 1.3 - 9.2 2.46 0.334	4.44 2.5 - 8.3 1.81 0.209	2.01 1.4 - 3.1 0.52 <0.001
Dissolved Pb (µg/L)	0.00 none 0.00	0.93 0.0 - 2.4 1.04 0.111	0.53 0.0 - 2.2 0.89 0.112	0.00 none 0.00 *
Dissolved Zn (µg/L)	49.02 16.0 - 110.0 24.22	150.70 34.8 - 386.0 112.26 0.006	218.60 54.6 - 650.0 210.33 0.011	209.34 58.6 - 395.0 127.76 <0.001
COD (mg/L)	80.9 46.0 - 130.0 26.3	68.4 19.0 - 216.0 55.7 0.496	85.5 15.0 - 286.0 78.7 0.851	39.9 19.0 - 77.0 19.2 0.001

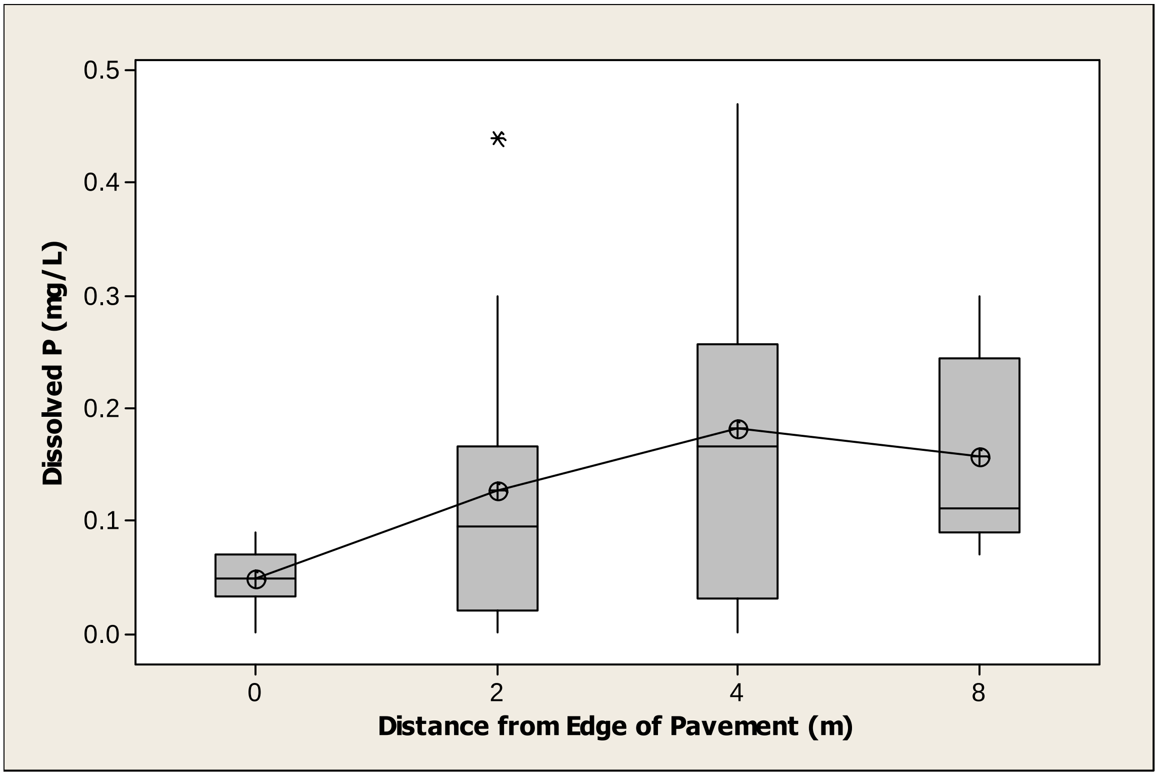

Figure 5.5 Boxplot of Dissolved Phosphorus at Austin Site 2

The summary statistics for the rainfall events monitored at Site 3 are presented in Table 5.7. These results are similar, although not identical, to the results from the adjacent research site, Site 2. Events monitored at Site 3 indicate significant decreases in TSS and COD concentrations at all distances from the edge of pavement. A boxplot demonstrating the changes in COD concentrations is provided in Figure 5.6. Increases in total and dissolved phosphorus are similar to those observed at Site 2 and exhibit significant changes at all distances from the pavement edge. Nitrate/nitrite concentrations also were found to significantly increase over the first four meters of vegetation. Total forms of copper and lead were found to significantly decrease over the width of the vegetated filter. Unlike copper and lead, the total and dissolved forms of zinc showed significant increases in concentration over the site. Again, this is believed to be due to leaching from the galvanized zinc used in the collection mechanisms and will be addressed in a later section.

Table 5.7 Summary Statistics for Austin Site 3

Constituent	**EOP** mean range std. dev.	**2m** mean range std. dev.	**4m** mean range std. dev.	**8m** mean range std. dev.
TSS (mg/L)	173 64 - 384 100	50 13 - 158 48 0.001	40 14 - 150 38 <0.001	50 13 - 230 63 0.002
TKN (mg/L)	1.76 0.8 - 3.4 0.81	1.77 0.6 - 3.5 0.99 0.989	1.72 0.5 - 3.1 0.93 0.924	2.40 0.4 - 6.0 1.87 0.308
NO3/NO2-N (mg/L)	0.22 0.0 - 0.7 0.17	0.27 0.0 - 0.7 0.25 0.561	0.56 0.0 - 1.7 0.56 0.062	0.72 0.0 - 4.9 1.41 0.251
Total P (mg/L)	0.28 0.1 - 0.9 0.22	0.79 0.2 - 1.7 0.42 0.002	1.21 0.4 - 3.4 0.78 0.001	0.88 0.3 - 2.0 0.57 0.004
Dissolved P (mg/L)	0.09 0.0 - 0.2 0.05	0.63 0.1 - 1.5 0.35 <0.001	1.06 0.3 - 2.9 0.66 <0.001	0.72 0.1 - 1.6 0.49 <0.001
Total Cu (µg/L)	29.75 12.3 - 62.2 14.64	9.46 4.3 - 19.8 5.34 <0.001	11.17 5.2 - 32.3 7.53 0.001	8.23 3.4 - 22.5 5.73 <0.001
Total Pb (µg/L)	11.54 4.8 - 18.4 4.37	8.49 2.3 - 28.6 9.59 0.369	3.54 0.0 - 8.1 2.49 <0.001	1.55 0.0 - 6.8 2.05 <0.001
Total Zn (µg/L)	175.48 67.7 - 307.0 75.04	281.92 52.3 - 659.0 168.54 0.070	324.93 68.2 - 495.0 146.57 0.007	488.27 116.0 - 985.0 271.95 0.001
Dissolved Cu (µg/L)	5.11 2.2 - 10.2 2.29	5.45 1.8 - 12.7 3.43 0.786	6.38 2.6 - 10.4 2.48 0.228	5.03 2.1 - 14.6 3.82 0.951
Dissolved Pb (µg/L)	0.00 none 0.00	0.68 0.0 - 3.8 1.32 0.130	0.00 none 0.00 *	0.11 0.0 - 1.2 0.37 0.329
Dissolved Zn (µg/L)	50.15 28.0 - 88.5 17.46	220.52 53.7 - 553.0 136.30 0.001	265.92 35.1 - 450.0 127.44 <0.001	397.89 74.8 - 927.0 265.64 <0.001
COD (mg/L)	99.5 42.0 - 160.0 38.5	45.8 11.0 - 107.0 26.9 0.001	48.1 23.0 - 74.0 18.7 0.001	62.9 25.0 - 149.0 40.9 0.043

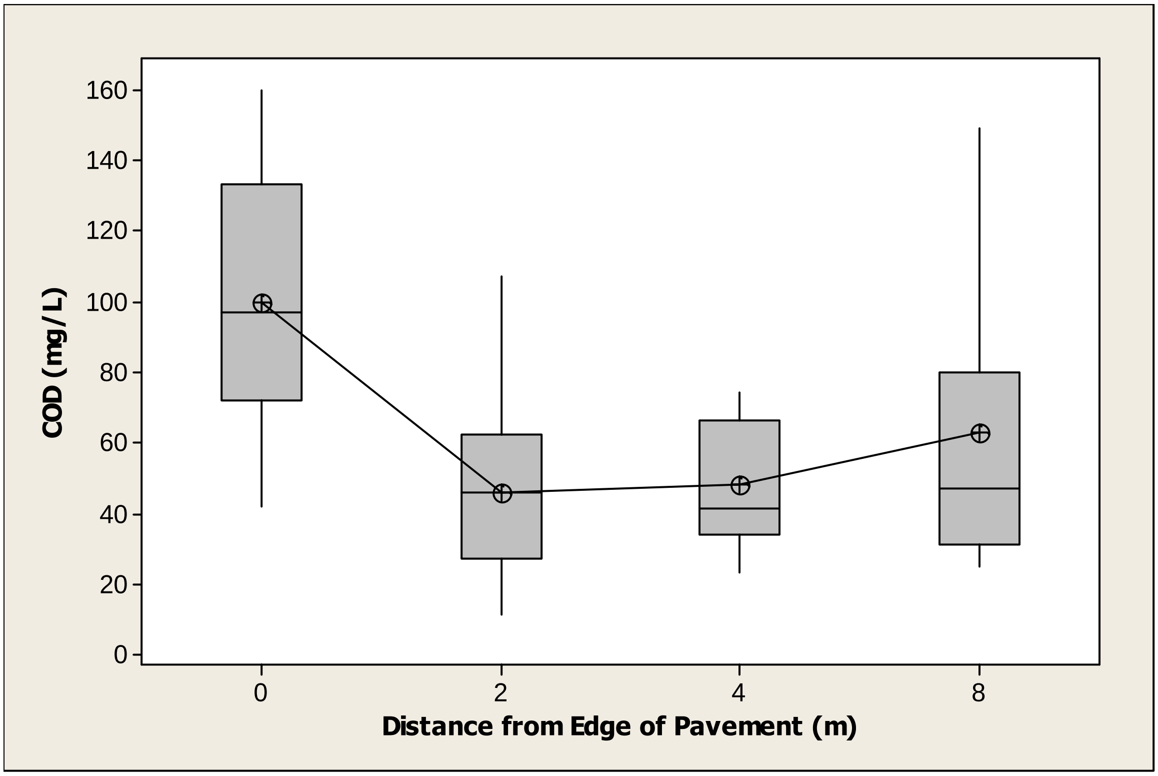

Figure 5.6 Boxplot of Chemical Oxygen Demand at Austin Site 3

5.3.3 Comparison of Traditional and Porous Asphalt Surfaces

The concentrations observed in runoff at the edge of pavement from the two surface types are presented in Table 5.8. Statistically significant differences in edge of pavement concentrations were observed from the runoff originating from the new, porous asphalt overlay and from the older, traditional asphalt surface. ANOVA tests were performed on the edge of pavement concentrations at Site 1 in Austin both before and after the installation of the PFC surface. The results of those tests are presented in Table 5.9. For the constituents with resulting P values less than 0.1, the surface condition that produced the significantly higher concentrations at the edge of pavement is also indicated in the table. The asterisk in Table 5.9 indicates that all observed concentrations were below the detection limit and no statistical comparison was possible.

Table 5.8 Edge of Pavement Concentrations at Austin Site 1

	Conventional Pavement		PFC Overlay	
	mean EMC	rainfall weighted average	mean EMC	rainfall weighted average
TSS (mg/L)	117.80	132.40	8.00	8.48
TKN (mg/L)	1.13	1.04	0.55	0.53
NO3/NO2-N (mg/L)	0.43	0.25	0.40	0.38
Total P (mg/L)	0.13	0.14	0.23	0.25
Dissolved P (mg/L)	0.04	0.03	0.08	0.07
Total Cu (µg/L)	26.84	30.76	5.74	5.61
Total Pb (µg/L)	12.57	15.21	0.67	0.67
Total Zn (µg/L)	167.40	165.58	45.08	45.17
Dissolved Cu (µg/L)	5.94	4.57	3.94	3.72
Dissolved Pb (µg/L)	ND	ND	ND	ND
Dissolved Zn (µg/L)	47.06	38.74	33.75	33.94
COD (mg/L)	64.00	60.58	30.50	28.60

ND – concentrations not detectable at reporting limits

Table 5.9 Statistical Comparison of Edge of Pavement Concentrations at Austin Site 1

Constituent	ANOVA – P Value	Higher average EMC source
TSS	0.01	old pavement
TKN	0.02	old pavement
NO3/NO2	0.91	
Total P	0.42	
Dissolved P	0.51	
Total Cu	0.001	old pavement
Dissolved Cu	0.42	
Total Pb	0.02	old pavement
Dissolved Pb	*	
Total Zn	0.001	old pavement
Dissolved Zn	0.46	
COD	0.095	old pavement

Concentrations of TSS, TKN, COD, and the total forms of Cu, Pb, and Zn were found to be significantly lower in runoff generated from the PFC surface than in runoff from the conventional surface. It was previously noted that many stormwater pollutants, especially metals, tend to adsorb to, and are therefore transported with, particulate matter in the runoff. This phenomenon appears to be confirmed by the concurrent decreased concentrations of total suspended solids and total metal concentrations. The only species to not exhibit a significant difference between road surfaces are the nitrate/nitrite forms of nitrogen and the dissolved forms of copper, zinc, and phosphorus. This indicates that the porous road surface has no effect upon the concentrations of some stormwater constituents, especially those in the dissolved form. Note that the runoff volume generated from the PFC seems to be much lower than from conventional asphalt, so even though the concentrations of some constituents are unchanged, the load discharged may in fact be lower. Boxplots demonstrating the differences between TSS and total zinc concentrations between events monitored from the old and new road surfaces are presented in Figure 5.7 and Figure 5.8, respectively. From these results it is evident that the runoff generated from the PFC surface is of better quality than that from the traditional asphalt surface. This observation was also noted upon visual inspection of the runoff samples collected at the edge of pavement.

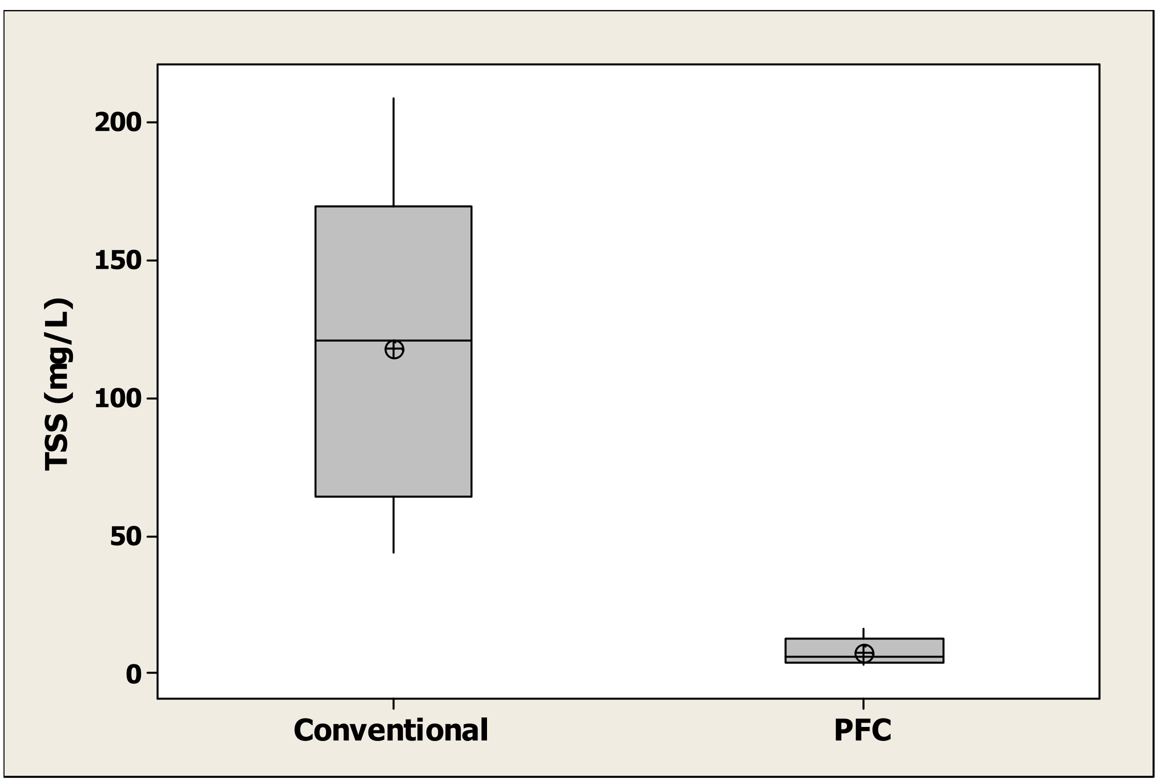

Figure 5.7 Boxplot of Edge of Pavement TSS at Austin Site 1

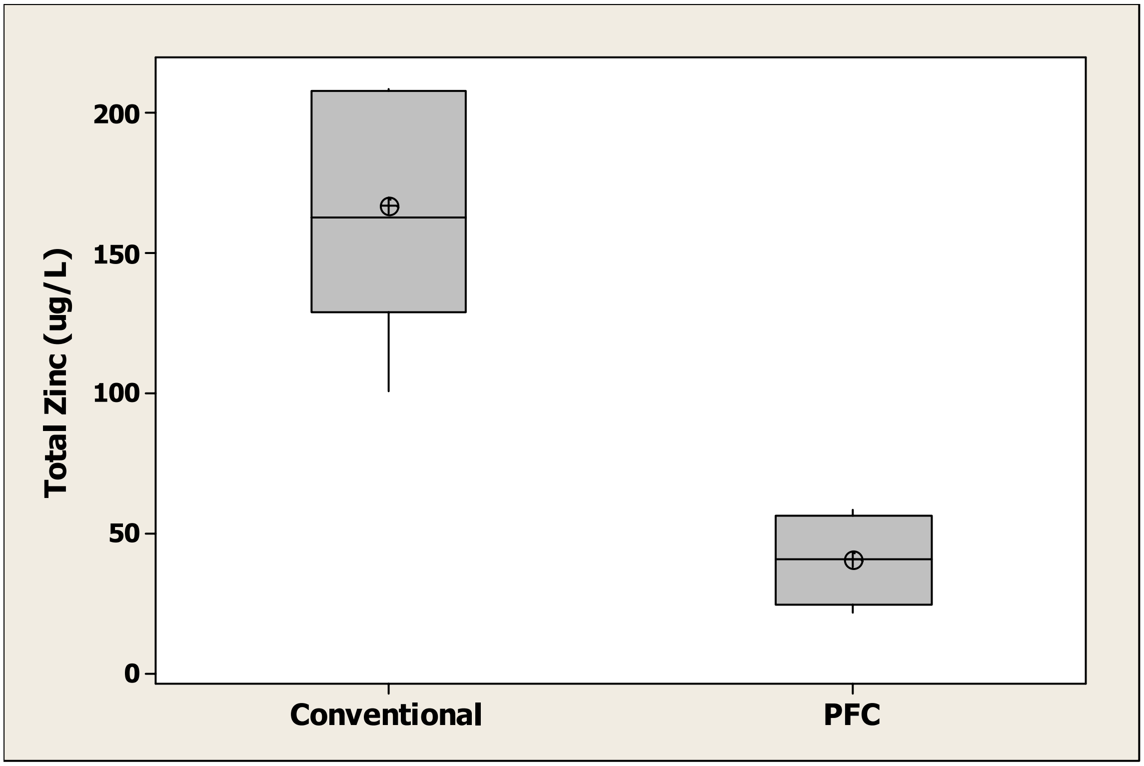

Figure 5.8 Boxplot of Edge of Pavement Total Zn at Austin Site 1

The impact of PFC on stormwater runoff quality has been evaluated in recent scientific studies. There are several reasons to think that improved water quality may result from the use of this material. The structure of PFC may cause it to act as a filter for the stormwater. Water penetrates through the pores in the overlay surface and then is diverted towards the shoulder when it hits the underlying road base. As it penetrates through the pores, pollutants in the water can be trapped in the pores and thereby filtered out of the runoff, especially large pollutants in the particulate form. In addition, in their study of highway runoff quality on an expressway in Austin, TX, Irish et al. (1998) reported that the concentrations of selected constituents was affected by the number of vehicles passing the site during a storm event. These constituents included oil/grease, copper, and lead. The assumption was that spray generated from tires was washing pollutants from the engine compartment and bottom of the vehicle. Since PFC surfaces reduce splash and spray, it is reasonable to expect that the amount of material washed off vehicles while driving in the rain will be reduced. This reduction in the amount of material washed from vehicles is expected to decrease the loading of pollutants on the road surface, and therefore decrease the concentrations of these pollutants in the runoff generated from roads paved with porous asphalt.

Comparisons of the mean EMCs and rainfall weighted average concentrations for each constituent also were made in addition to the ANOVA tests of the runoff generated from both kinds of pavement. These results are presented in Table 5.8 and provide another piece of evidence showing that the runoff generated from the PFC surface is indeed of higher quality that the runoff generated from the conventional pavement. While the mean EMC and rainfall weighted average concentration methods provide different results, the results are similar to one another and exhibit the same trend. Concentrations of TSS as well the total forms of copper, lead, and zinc are often one order of magnitude lower from the porous asphalt than from the traditional asphalt. Average concentrations of total and dissolved phosphorus as well as the dissolved forms of copper and lead show little change between the two surface types.

The same storm events as those monitored at Site 1 after the completion of the PFC overlay project were also monitored at Sites 2 and 3. The results from these events at the other two sites are consistent with the earlier results. The disparity in the quality of runoff between the sites during these latter storm events is further proof that the improved runoff quality from the PFC is a function of the new asphalt surface and not other weather or environmental conditions.

One of the concerns that arise with any road construction or paving project is the levels of contamination generated by the new asphalt surface. Results from a recent United States Geological Survey study (Mahler et al., 2004) indicate that lead and zinc are the trace metals most likely to be found in elevated levels in runoff from newly paved or sealed surfaces. PAHs were also found to be of concern for some sealant types (Mahler et al., 2004). For this reason, semi-volatile organics in the runoff from the porous asphalt at Site 1 were monitored during two storm events soon after the completion of the overlay project in order to assess the validity of these concerns. For both events, all PAH concentrations were below detection limits. PAHs were also monitored during three previous rain events on the traditional asphalt surfaces and those concentrations were also below detection limits.

In addition to understanding and quantifying the differences in runoff quality generated from the two different highway surfaces, it is also important to evaluate the subsequent performance of the vegetated filter strip at Site 1 both before and after the installation of the porous asphalt overlay. ANOVA tests were performed to compare the concentrations of each constituent at each sampling distance as an initial assessment of differences or similarities in the data. The results indicate that very few significant differences exist between the measured concentrations in the vegetated filter strips despite the differences in the quality of the runoff at the edge of pavement.

These results can be somewhat misleading, however. A comparison of both the mean EMCs and rainfall weighted average concentrations in the runoff at each sampling distance from the old and new road surface indicate that the filter strip may no longer be having the same effect upon the runoff. While additional removal of pollutants may not be occurring, concentration stabilization over the width of the filter does seem to be taking place.

Figure 5.9 and Figure 5.10 show boxplots of total copper concentrations at Site 1 in runoff sampled from the old asphalt and new porous asphalt surface, respectively. In events monitored from the traditional road surface, it appears that average copper concentrations decrease with increasing distance from the edge of pavement. This indicates that the filter strip is acting as a buffer and is removing copper from the runoff. From the PFC, however, copper concentrations increase within the first two meters of the edge of pavement and then gradually drop off again. This indicates that while the initial runoff is indeed cleaner, the runoff may be picking up copper from the soil as it travels through the first two meters of the shoulder area. Despite this increase, the final effluent quality at the 8m sampling point is as good, if not better, with the porous asphalt in place than with the traditional asphalt surface. This trend was observed for almost all of the constituents whose edge of pavement concentrations were found to be significantly lower from the porous surface.

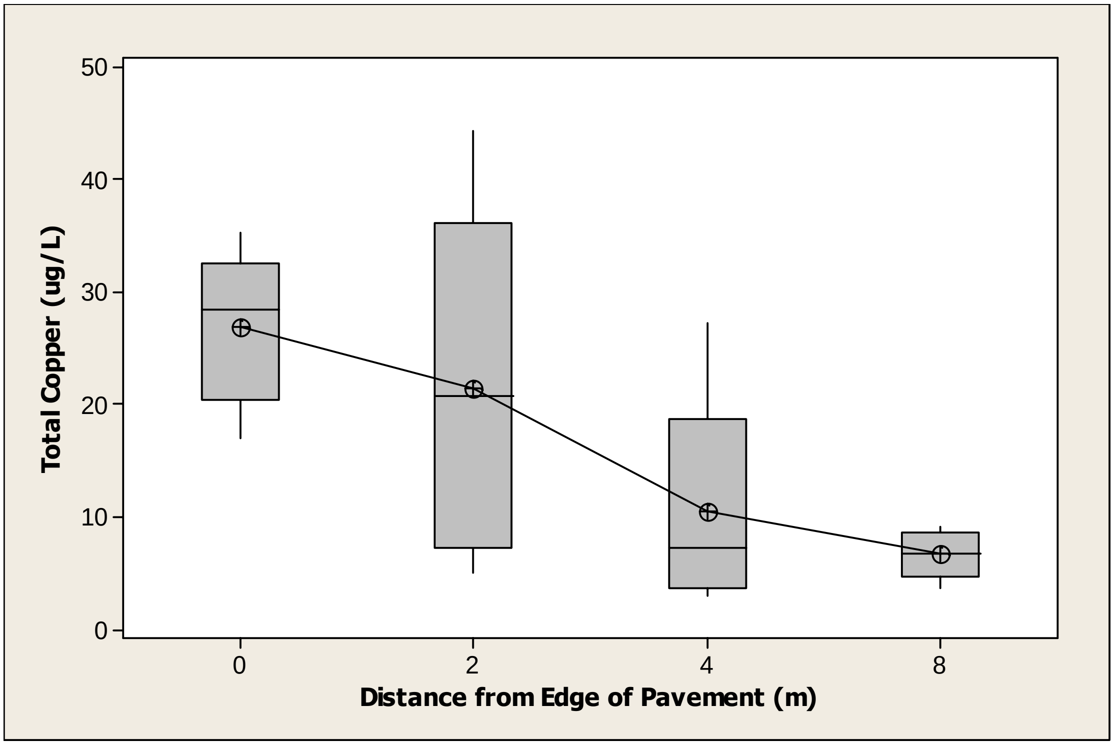

Figure 5.9 Boxplot of Total Copper at Austin Site 1, conventional pavement

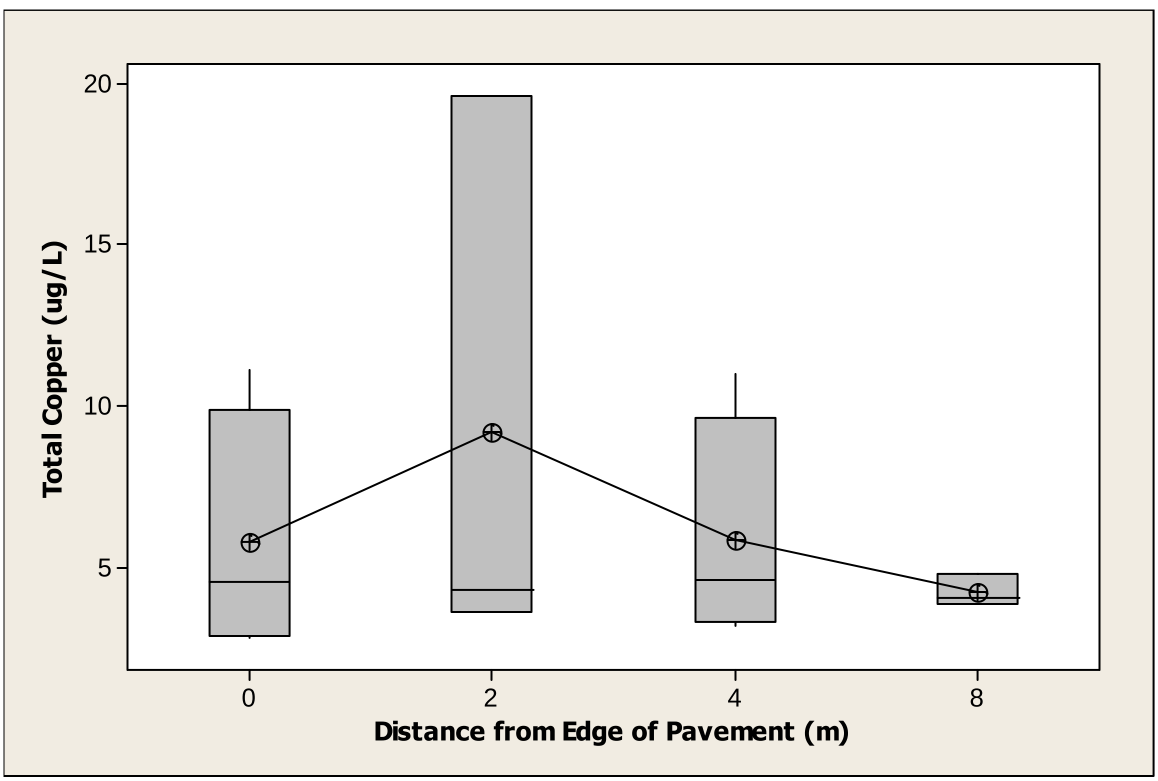

Figure 5.10 Boxplot of Total Copper at Austin Site 1, PFC

5.3.4 Effect of Compost on Site Performance

All statistical and analytical results indicate that the performance of Site 3 with compost was not significantly different from that of Site 2 without compost. The compost layer did, however, lead to a visible difference in the height and growth rate of the vegetation at the site. The only other notable difference between the two sites is that measured phosphorus concentrations were higher from the site with the compost. This trend was also noted by Yonge et al. (2000) in their study of vegetated filter strips. Despite these differences in phosphorus concentration, the performance at the two sites was very similar. These results lead to the conclusion that a 1-inch layer of biosolids compost applied to the vegetated area did not improve the effectiveness of the vegetated filter. It should be noted, however, that since Site 3 had nearly 100% vegetative cover before the application of the compost layer, little or no increase in vegetation density could be expected. Therefore, it is not unexpected that the compost layer did not improve the performance of the vegetated filter strip. As previously discussed, however, in the section on initial runoff quality, a statistically significant difference was found between the total and dissolved phosphorus concentration at Sites 2 and 3 at the edge of pavement. Higher levels of phosphorus in the initial runoff could be the reason for its higher concentrations throughout the vegetated area.

5.3.5 Site Conditions Affecting Sampling

As previously noted, fire ants and their mounds were persistent problems at all of the research sites. The presence of these mounds posed a challenge to sampling and monitoring activities. The mounds were therefore treated on an as needed basis with AMDRO, an insecticide in the amidinohydrazone chemical family. Successive treatments were often required. Ant mounds often led to increased build-up of soil in the collection pipes in between sampling events. These mound materials were cleaned out of each pipe prior to expected rain events. However, it is possible that some of these solids were inadvertently collected in the samplers and were counted in the TSS measurements.

Also as previously noted, all three of the research sites exhibited consistently elevated total and dissolved zinc concentrations at all sampling locations other than the edge of pavement. The concentrations at the edge of pavement were similar to other reported concentrations found in highway runoff. It is therefore clear that some other factor at the sites is affecting the zinc levels. Because galvanized metal flashing was attached to each collection pipe to help direct runoff into the pipe rather than under it, it is possible that this flashing is the source of the zinc. With excessive exposure to the weather and environment, it appears that the galvanized coating on the metal is wearing away and that zinc is leaching out into the runoff. Zinc concentrations were also generally lower during the first events monitored, and increased over the 14 month sampling period. This trend lends further credence to the idea that the elevated levels of zinc are leaching from the galvanized metal with increasing exposure time to the environment and the weather.

To confirm this hypothesis, an 8-in by 5-in piece of galvanized flashing was submerged in 3L of de-ionized water in a clean plastic container in the laboratory for 20 hours. The water was then analyzed for total and dissolved zinc. The resulting concentrations are as follows: total zinc – 1070μg/L, dissolved zinc - 822μg/L. These concentrations are much higher than those observed in runoff leaving the highway. Average concentrations measured in runoff leaving Loop 360 at three monitoring points were in the following ranges: total zinc – 140 – 175μg/L, dissolved zinc - 47 – 50μg/L.

5.3.6 Overall Performance of Filter Strips - Austin

Each of the vegetated filter strips in this study area exhibited similar trends in overall performance with the exception of events monitored at Site 1 with the porous asphalt overlay in place. Table 5.10 provides a summary of the net removal efficiencies for each constituent at each research site. The table provides removal percentages calculated based on rainfall weighted average concentrations measured at each of the sampling distances (an "*" in the table indicates that the majority of monitored concentrations were below the detection limits for that parameter). The events monitored at Site 1 after the installation of the PFC surface are not included in these summary tables, as the factors affecting pollutant concentrations and removal mechanisms under this condition differ from the other research sites.

Table 5.10 Net Removal Efficiencies

	Site 1, conventional asphalt			Site 2			Site 3		
	0-2m	0-4m	0-8m	0-2m	0-4m	0-8m	0-2m	0-4m	0-8m
TSS	36.1%	58.8%	72.9%	73.4%	78.4%	88.9%	82.1%	84.7%	84.8%
TKN	-96.4%	-126.8%	-154.4%	7.5%	-27.1%	19.0%	29.3%	35.5%	-21.4%
NO_3/NO_2	32.6%	9.4%	6.3%	60.2%	-11.5%	-63.9%	10.3%	-113.0%	-132.6%
Total P	-9.4%	-1.6%	-90.1%	33.9%	-72.0%	-45.9%	-109.1%	-333.5%	-250.9%
Diss. P	-138.7%	-105.4%	-400.4%	34.5%	-132.6%	-124.7%	-400.8%	-1061.2%	-801.6%
Total Cu	37.8%	64.4%	75.5%	67.8%	74.6%	90.8%	80.2%	70.7%	79.8%
Total Pb	70.0%	88.8%	94.9%	27.8%	70.9%	92.7%	22.5%	51.6%	84.2%
Total Zn	48.6%	29.3%	47.6%	7.8%	-43.2%	-20.7%	-5.0%	-22.6%	-83.6%
Diss. Cu	-41.7%	-8.1%	12.0%	28.5%	17.3%	61.1%	12.6%	-22.9%	-6.7%
Diss. Pb	*	*	*	*	*	*	*	*	*
Diss. Zn	-39.2%	-134.4%	-111.5%	-148.0%	-328.7%	-262.7%	-247.7%	-321.1%	-543.9%
COD	16.2%	55.1%	18.6%	69.4%	64.9%	66.0%	70.6%	68.8%	47.6%

Total Suspended Solids – Net decreases were observed for TSS over the vegetated filter strip at each research site. Higher removal efficiencies were measured at Sites 2 and 3 with a maximum of 89% removal within eight meters of the edge of pavement. Site 1 exhibited the lowest efficiency, achieving 73% removal between the zero and eight-meter sampling point.

Total Kjeldahl Nitrogen – Net increases in TKN concentrations were observed at each site. Large increases in concentration occurred at all sampling points at Site 1, with concentrations consistently increasing with increasing distance from the road surface. This resulted in negative removal efficiencies across the site. Sites 2 and 3 exhibited smaller increases and occasional decreases in concentrations between sampling distances.

A maximum removal rate of 36% was measured within the first four meters of vegetation at Site 3. Since nitrate was also observed in the runoff, it is apparent that the runoff was aerobic, so that virtually all the nitrogen in the TKN was in the form of organic nitrogen. The increase in organic nitrogen is likely due to the runoff incorporating bits of grass and leaves that were present in the vegetated area. The smaller removal efficiency observed in this study may be due to the fact that sampling occurred over the entire year including many times when grass clippings were present. This is in contrast to the monitoring in California, which only occurred during the winter wet weather growing season (Barrett et al., 2004). Mowing in California only occurs after the end of the rainy season.

Nitrate/Nitrite – Net decreases in concentrations of nitrate and nitrite were observed at Site 1. The majority of removal occurred at this site within first two meters of vegetation, resulting in a maximum removal efficiency of 33% over this distance. Initial decreases in concentration occurred within the first two meters at Sites 2 and 3 followed by increases in concentration with increasing distance from the edge of pavement. Maximum removal efficiencies over the first two meters at these sites were 60% and 10%, respectively.

Total and Dissolved Phosphorus – Net increases in phosphorus concentrations and negative removal efficiencies were measured at all sites over the width of the vegetated filter strips with the exception of initial decreases within the first 2 meters at Site 2. Removal efficiencies of just below 35% were observed for both constituents over this distance. The increases observed at Site 3 were likely the result of compost application. Increases in phosphorus concentration have also been observed in studies conducted on other roadside shoulders (Barrett et al., 2004). The increases observed at the other sites are likely related to the same causes that resulted in increases of TKN (i.e. grass clippings and sampling occurring outside of the growing season).

Total Copper – High removal efficiencies were measured at all sites for total copper, generally with increasing efficiency observed with increasing distance from the edge of pavement. Maximum removal rates occurred between the edge of pavement and the eight meter sampling point at Sites 1 (76%) and 2 (91%). An 80% removal efficiency was measured at Site 3 within the first 2m of vegetation. The removal rate remained relatively consistent over the remainder of the strip.

Total Lead – High removal efficiencies for total lead were observed at all sites. 70% removal occurred within the first two meters at Site 1, with a maximum removal of 95% occurring within the first eight meters. Lower removal rates were measured close to the road surface at Sites 2 and 3, but total removal of 93% and 84% occurred over the entire filter strip.

Total Zinc – While removal efficiencies indicate that zinc levels decreased at Site 1, the concentrations of total zinc tended to increase with increasing distance from the edge of pavement at both Site 2 and Site 3. This is believed to be due to the adverse effects of the galvanized metal flashing used on the collection pipes as described previously.

Dissolved Copper – Initial increases in dissolved copper concentrations were observed at Site 1 before achieving a final removal rate of 12% by the eight meter point. The opposite trend occurred at Site 3, with an initial decrease in concentrations close to the road surface but a negative overall removal over the entire width. Site 2 exhibited gradual increases in removal efficiency over vegetated area.

Dissolved Lead – Concentrations of dissolved lead were below the detection limits for the majority of events monitored. Not enough data above detection limits exists to understand any possible removal trend, but this lack of values over the detection limit also indicates an absence of dissolved lead originating from the highway surfaces and vegetated strips.

Dissolved Zinc – Similar to total zinc, dissolved zinc concentrations consistently increased at each site with increasing distance from the edge of pavement. This is again believed to be due to leaching from the galvanized metal.

Chemical Oxygen Demand – A maximum COD removal of 70% occurred at Sites 2 and 3 within the first two meters of the road surface. A maximum removal of 50% occurred within the first four meters at Site 1.

The results from this study indicate that higher vegetation densities in the vegetated filter areas at the Austin sites result in higher removal efficiencies for most pollutants commonly found in stormwater runoff, especially those found in the particulate form. These results are consistent with earlier studies. A recent California study reported that a minimum vegetation density of 65% is needed in order to achieve reductions in pollutant concentrations and that performance falls off rapidly when the vegetative cover is below 80% (Caltrans, 2003a; Barrett et al., 2004). Sites 2 and 3, with close to 100% vegetation densities over both sites, consistently outperformed Site 1, which had slightly more than 50% cover near the road surface and an average density of 85% at the bottom of the study area. These differences in site performance are particularly evident within the first two meters of the road surface for total suspended solids. Figure 5.11 and Figure 5.12 demonstrate these differences with boxplots of TSS concentrations at Site 1 and at Site 2. A comparison of these two graphs shows that the majority of TSS removal occurs between the two and four meter sampling points at Site 1, whereas the majority of the removal at Site 2 occurs within the first two meters of the edge of pavement; indicating that the higher vegetation density close to the road surface at Site 2 may be helping remove the particles from the runoff.

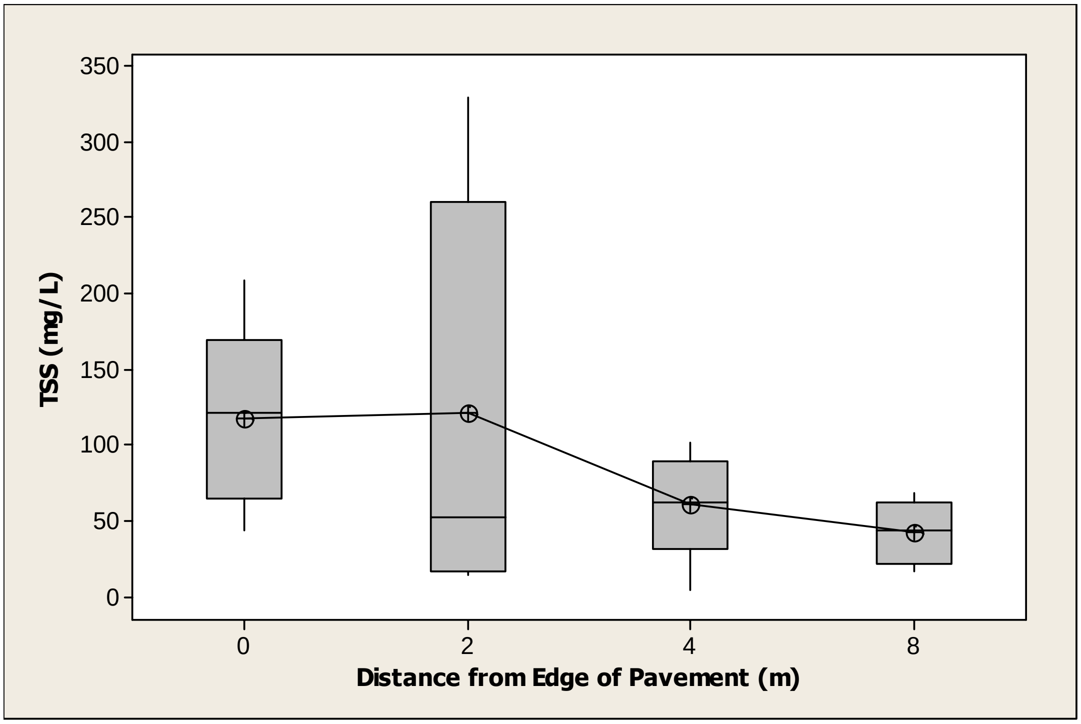

Figure 5.11 Boxplot of TSS at Site 1, Conventional Pavement

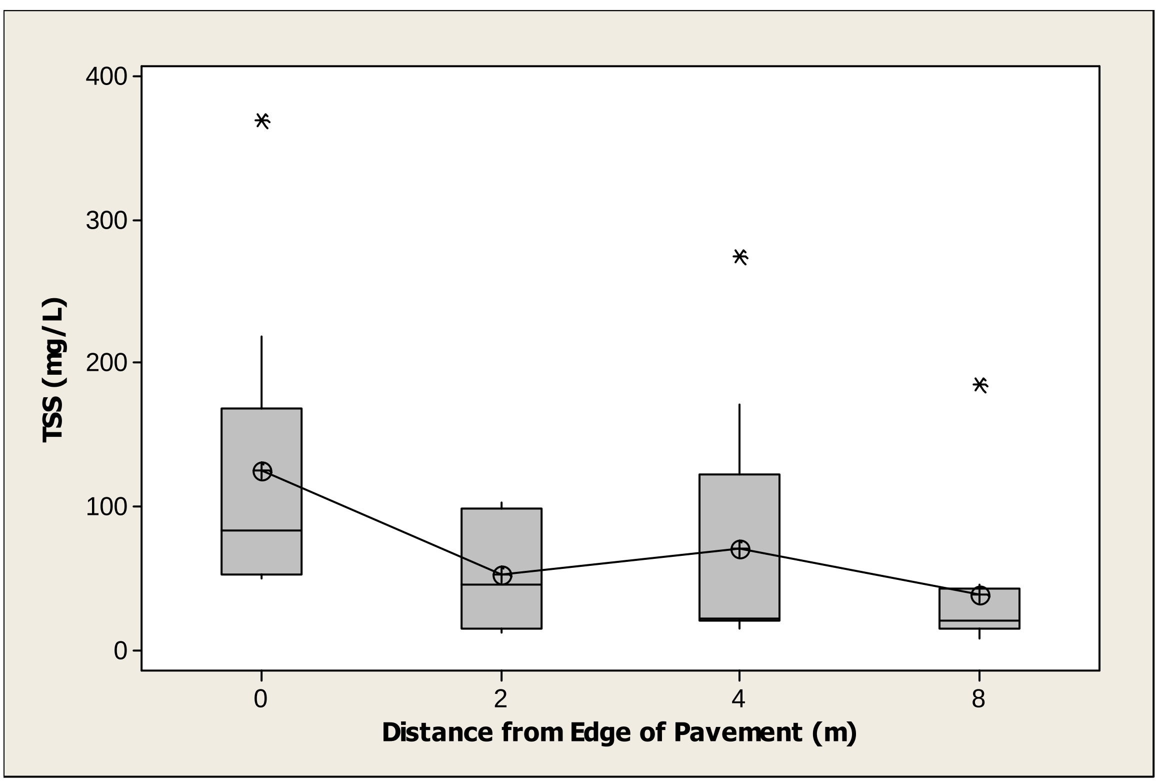

Figure 5.12 Boxplot of TSS at Site 2

Differences in slope do not appear to be a factor in the removal efficiencies of the vegetated areas at the study sites. Sites 2 and 3 had a slope of 18% and generally outperformed Site 1, which had a slope of only 12%. In a study of California roadside shoulders, Barrett et al. (2004) also reported that no differences in performance could be distinguished between sites with different slopes.

Two previous studies of the pollutant removal in vegetated areas adjacent to highways were conducted in the Austin area. The first of these was a study of a grassy swale near MoPac at Walnut Creek. Measurements were made of concentrations of pollutants in runoff at the road surface as well as at the outlet of the grassy swale in the median. The second evaluated the pollutant reduction of grassy medians at a site on US 183. The mean road and swale concentrations, as well as the percent reduction in concentrations over the vegetated area for each study area are presented in Table 5.11 (Barrett et al., 1998).

Table 5.11 Reductions in Concentrations Observed from Previous Studies in Austin

	US 183 Median			**MoPac Expressway Median**		
Constituent	**Road Mean**	**Swale Mean**	**Removal (%)**	**Road Mean**	**Swale Mean**	**Removal (%)**
TSS (mg/L)	157	21	87	190	29	85
TKN (mg/L)	2.17	1.46	33	2.61	1.45	44
Nitrate (mg/L)	0.91	0.46	50	1.27	0.97	23
Total P (mg/L)	0.55	0.31	44	0.24	0.16	34
Copper (µg/L)	--	--	--	--	--	--
Lead (µg/L)	138	82	41	93	77	17
Zinc (µg/L)	347	32	91	129	32	75
COD (mg/L)	94	37	61	109	41	63

The pollutant reductions documented in this study for TSS, copper, lead, and COD at the three Austin sites are consistent with those found in the prior studies. Removal of total metals concentrations appear to be highly associated with TSS removal, while concentrations of dissolved metals are not. The most notable difference in removal efficiencies between this study and the previous studies, however, is for the nutrient constituents. The removal rates found in the earlier studies exceed those observed for the filter strips used in this study. Other studies have also reported higher levels of nutrients in runoff flow over vegetated areas. Yousef et al. (1987) reported higher nitrogen and phosphorus concentrations in flows over grassy swales. Similarly, Dorman et al. (1996) concluded that nutrient removal over a vegetated area is not associated with TSS reduction. The results of this project at the Austin sites are consistent with those findings. One reason for the differences may be that the previous studies were conducted primarily in swales, where the water depth is high enough to transport grass clippings beyond the sampling point. This unrecognized export of nutrients in the previous studies may explain the higher apparent removal efficiencies.

5.4 Performance of College Station Sites

5.4.1 SUMMARY STATISTICS

Summary statistics were calculated for each constituent at each sampling point at the College Station sites. The method of calculation and analysis is identical to that used for the Austin sites.

The summary statistics for sampled events at Site 1 are presented in Table 5.12. Only total copper exhibited a statistically significant decrease in concentrations between the zero and eight meter sampling points. The only constituents to exhibit a statistically significant increase in concentration at this site were total zinc and dissolved zinc. This latter finding mirrors the results from the Austin sites showing higher concentration of zinc resulting from the metal flashing used in the sampler installation. The concentrations of all other constituents at the site furthest from the road were not significantly different than those at the edge of pavement.

The summary statistics for monitored events at Site 2 are presented in Table 5.13. Total copper exhibited a statistically significant decrease in concentration between the zero and four meter and zero and eight meter sampling points. However, significant increases in some constituent concentrations such as total phosphorus, total zinc, and dissolved zinc occurred over the vegetated sampling area.

The summary statistics for rainfall events monitored at Site 3 are presented in Table 5.14. Total copper and dissolved copper exhibited statistically significant decreases in concentrations between the zero and four meter and zero and eight meter sampling points. No other constituents exhibited a statistically significant decrease in concentration.

5.4.2 Edge of Pavement Comparisons, College Station Sites

ANOVA tests were performed on the edge of pavement concentrations measured for each parameter at Site 1, Site 2, and Site 3 to determine if any statistically significant differences existed between the runoff generated at each site. No significant differences in concentration at the edge of pavement were observed.

5.4.3 Site Conditions Affecting Sampling

Fire ants were a problem at the College Station sites just as they were at the Austin sites. Ant mounds were treated when necessary, and mound materials were removed from the collection pipes and samplers as part of the regular maintenance routine. These mounds are believed to contribute to the concentrations of total suspended solids collected from the runoff.

As mentioned previously, leaching of the galvanized metal flashing used on each of the collection pipes contributed total and dissolved forms of zinc to the runoff collected and sampled at each research site. This leaching resulted in concentrations of zinc in the collected runoff that are uncharacteristic of average runoff water quality. As a result of these artificially elevated concentrations throughout the vegetated study areas, overall removal efficiencies could not be adequately determined.

Table 5.12 Summary Statistics for College Station Site 1

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std.Deviation	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value
TSS (mg/L)	116.4 8 - 421 130	79.1 9 - 192 58 0.418	85.1 8- 229 87 0.534	96.7 4 - 326 95 0.703
TKN (mg/L)	2.13 0.549 – 5.34 1.61	2.43 0.65 – 7.55 1.91 0.71	2.45 0.433 – 7.53 2.25 0.722	2.88 0.861 – 8.49 2.34 0.412
NO3/NO2-N (mg/L)	0.41 0.25 – 0.75 0.15	0.42 0.14 – 0.77 0.24 0.976	6.26 0.037 – 53.66 17.78 0.338	1.26 0.029 – 7.2 2.44 0.311
Total P (mg/L)	0.22 0.064 – 0.584 0.16	1.01 0.125 – 6.31 1.9 0.202	0.47 0.05 – 2.03 0.64 0.238	0.4 0.12 – 1.36 0.39 0.185
Dissolved P (mg/L)	0.13 0.03 – 0.29 0.09	0.87 0.06 – 6.05 1.85 0.253	0.38 0.02 – 1.75 0.58 0.226	0.28 0.03 – 0.8 0.29 0.171
Total Cu (µg/L)	14.33 5.67 – 29.5 7.42	10.23 5.79 – 15.9 3.22 0.126	17.72 2.94 - 119 35.65 0.772	6.95 3.01 – 13.4 3.64 0.011
Total Pb (µg/L)	7.17 1.08 - 22.9 6.92	5.25 1.12 – 11.6 3.84 0.474	7.88 1.72 – 15.1 5.24 0.821	4.68 2.01 – 13.7 4.17 0.412
Total Zn (µg/L)	117 33.6 - 241 76.3	237.7 88.1 - 538 134.8 0.024	358.9 78.6 - 855 223.2 0.005	393.4 48.3 - 1520 424.8 0.058
Dissolved Cu (µg/L)	6.18 3.26 – 11.6 2.61	5.4 2.11 – 10.7 2.55 0.505	5.1 2.27 - 11 2.76 0.38	4.21 1.38 – 9.81 2.75 0.117
Dissolved Pb (µg/L)	0.00 0.0 – 4.12	0.00 0.0 – 1.03 NA*	0.00 0.0 – 2.84 NA	0.00 0.0 – 1.13 NA
Dissolved Zn (µg/L)	48.3 17.9 – 97.9 26.3	172.8 81.6 - 340 96 0.001	268 73.3 - 479 119 <0.001	290.4 44.5 - 953 260.3 0.009
COD (mg/L)	73.3 26 - 138 42.97	76.3 46 – 128 27.41 0.854	72.9 21 - 215 56.05 0.986	88.6 26 - 279 74.34 0.58

Table 5.13 Summary Statistics for College Station Site 2

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std.Deviation	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value
TSS (mg/L)	172.4 19 - 504 185.8	119.3 11 - 618 179.4 0.524	105.2 8 - 486 141.5 0.375	135.9 4 - 475 155.7
TKN (mg/L)	1.94 0.64 – 3.99 1.06	2.94 1.16 – 5.85 1.76 0.34	2.55 0.86 – 5.01 1.57 0.336	3.87 0.57 – 13.7 3.92 0.376
NO3/NO2-N (mg/L)	1.06 0.054 – 7.78 2.37	1.37 0.05 – 5.32 1.76 0.764	0.44 0.02 – 1.97 0.62 0.456	0.51 0.039 – 2.03 0.65 0.53
Total P (mg/L)	0.24 0.051 – 0.434 0.14	0.58 0.198 – 1.5 0.41 0.023	0.64 0.114 – 2.14 0.58 0.048	0.6 0.084 – 1.63 0.49 0.04
Dissolved P (mg/L)	0.14 0.05 – 0.18 0.04	0.36 0.03 – 1.36 0.41 0.151	0.47 0.09 – 1.96 0.56 0.115	0.37 0.06 – 1.18 0.42 0.138
Total Cu (µg/L)	17.23 7.28 – 31.1 8.78	14.26 6.05 – 28.7 7.44 0.426	9.09 3.72 – 22.4 5.811 0.025	8.99 2.84 - 26 6.82 0.037
Total Pb (µg/L)	9.05 1.34 – 23.1 7.5	7.0 1.15 – 19.7 6.38 0.53	8.66 1.51 – 21.5 9.02 0.927	6.09 1.46 - 13 4.91 0.376
Total Zn (µg/L)	118.3 26 - 259 84.3	236.7 71.4 - 443 128 0.025	225.8 31.4 - 557 199.8 0.134	281.1 54.2 - 1110 325.7 0.145
Dissolved Cu (µg/L)	5.81 2.6 – 11.4 2.64	5.49 3.25 – 15.1 3.51 0.819	4.95 3.04 – 10.4 2.04 0.427	4.08 2.3 – 5.95 1.05 0.084
Dissolved Pb (µg/L)	0.00 none	0.00 none NA*	0.00 none NA	0.00 none NA
Dissolved Zn (µg/L)	44.3 20.2 – 89.4 26.6	144.5 44.1 - 427 123.1 0.022	159.3 24.3 - 799 238.4 0.147	161.3 51.6 - 276 84.3 0.001
COD (mg/L)	71.4 19 - 132 43.25	79.7 25 - 129 39.35 0.659	75.9 26 - 143 44.48 0.821	97.67 18 - 420 123.54 0.536

Table 5.14 Summary Statistics for College Station Site 3

Constituent	Sample Location			
	Edge of Pavement	2m	4m	8m
	Mean Range Std.Deviation	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value	Mean Range Std.Deviation P-Value
TSS (mg/L)	124.4 7 - 341 115.7	161.8 4 - 482 178.7 0.606	221.8 7 - 928 295.2 0.371	115.9 4 - 315 120.1 0.88
TKN (mg/L)	1.79 0.674– 3.41 0.96	3.04 0.87 – 8.8 2.46 0.173	2.56 1.11 – 5.56 1.45 0.203	2.53 0.91 – 3.96 1.19 0.168
NO3/NO2-N (mg/L)	1.01 0.05 – 2.19 0.87	2.04 0.045 – 10.97 3.67 0.455	0.36 0.031 – 1.424 0.45 0.081	1.52 0.093 – 7.49 2.67 0.614
Total P (mg/L)	0.22 0.08 – 0.385 0.08	0.39 0.081 – 1.01 0.3 0.125	0.46 0.104 – 1.11 0.36 0.071	0.51 0.143 – 2.15 0.63 0.18
Dissolved P (mg/L)	0.13 0.03 – 0.27 0.09	0.2 0.08 – 0.62 0.17 0.276	0.22 0.03 – 0.81 0.29 0.358	0.45 0.05 – 1.83 0.62 0.137
Total Cu (µg/L)	15.57 6.81 – 32.2 7.47	11.87 8.23 – 18.2 4.55 0.222	9.51 4.55 – 16.4 4.17 0.05	6.18 3.11 – 13.5 3.35 0.003
Total Pb (µg/L)	5.66 1.22 – 11.5 3.2	10.77 3.73 – 21.4 7.37 0.086	8.77 1.21 – 28.1 8.98 0.344	4.35 1.61 – 9.92 3.41 0.442
Total Zn (µg/L)	112.4 25.3 - 223 65.4	387.4 95.8 - 708 239.8 0.004	337.4 54.6 - 932 276.1 0.03	408.4 63.6 - 1080 285 0.008
Dissolved Cu (µg/L)	6.41 3.41 - 14 3.08	6.48 4.14 – 13.7 3.02 0.964	4.53 2.3 – 9.24 2.08 0.149	3.99 1.85 – 7.92 1.89 0.062
Dissolved Pb (µg/L)	0.00 0.0 – 1.29	0.00 none NA*	0.00 0.0 – 1.25 NA	0.00 0.0 – 3.75 NA
Dissolved Zn (µg/L)	44.8 22.1 - 110 29.5 0.008	221.8 71.4 - 600 174.6 0.008	239.5 39 - 746 275.6 0.051	345.7 50.6 - 1020 272.9 0.005
COD (mg/L)	91.78 40 - 144 36.38	77.89 31 - 151 42.55 0.486	91.11 24 - 214 63.6 0.979	61.87 0.85 - 175 49.22 0.162

5.4.4 Overall Performance of Vegetative Filters in College Station

Overall, the vegetated filters at the College Station sites showed inconsistent performance. Removal efficiencies vary by site despite very similar physical characteristics (slope, vegetation density, vegetation type) and identical traffic counts. The removal efficiencies of the vegetated roadsides with respect to various constituents are listed in Table 5.15.

Table 5.15 Net Removal Efficiencies (in %) at College Station Sites

	Site 1			Site 2			Site 3		
	0-2 m	**0-4 m**	**0 -8m**	**0-2m**	**0-4m**	**0-8m**	**0-2m**	**0-4m**	**0-8m**
TSS	16.7	20.2	8.8	47	48.9	56.3	-14.6	-79.5	14.6
TKN	-18	-48.3	-63.4	-55.1	-31.4	-121.7	-74.2	-73.5	-41.6
NO3/NO2	22.6	-760	-159.1	-3.9	50.9	58.2	-174.4	45.1	-76
Total P	-678.5	-263.6	-173.6	-149	-160	-205	-50.3	-119	-72
Diss P	-1217	-425	-171	-205	-291	-322	-35.1	-81.6	-102
Total Cu	19.2	-90.4	38.7	8.8	45	38.9	29.4	37.6	62.8
Diss Cu	-5.7	-4.7	5.1	3.5	13	22.7	-0.9	19.6	33.7
Total Pb	23.1	10.7	49.3	37.8	42	39.6	0.8	-27.9	49.2
Diss Pb	87.5	-31.3	44.9	*	*	*	*	*	*
Total Zn	-103.7	-320.4	-239.6	-99.4	-135	-199.4	-179.9	-271	-223
Diss Zn	-290	-493	-513.6	-231	-284	-401	-296	-620	-616
COD	-26.7	-50.9	-81.6	-23.6	-25.8	-82	17.8	-17.5	30.1

Total Suspended Solids – Higher removal efficiencies were measured at Site 2 with a maximum of 56% removal within eight meters of the edge of pavement. Site 1 exhibited the lowest efficiency, achieving 8.8% removal between the zero and eight-meter sampling point. None of these differences is statistically significant.

Total Kjeldahl Nitrogen – Net increases in TKN concentrations were observed at each site. Large increases in concentration occurred at all sampling points at Site 1, with concentrations consistently increasing with increasing distance from the road surface, which resulted in negative removal efficiency rates. Since nitrate was also observed in the runoff, it is apparent that the runoff was aerobic, so that virtually all the nitrogen in the TKN was in the form of organic nitrogen. The increase in organic nitrogen is likely due to the runoff incorporating bits of grass and leaves that were present in the vegetated area. The smaller removal efficiency observed in this study may be due to the fact that sampling occurred over the entire year including many times when grass clippings were present. This is in contrast to the monitoring in California, which only occurred during the winter wet weather growing season (Barrett et al., 2004). Mowing in California only occurs after the end of the rainy season.

Nitrate/Nitrite – The majority of removal occurred at site 2 within first eight meters of vegetation, resulting in a maximum removal efficiency of 58.2% over this distance. Initial decreases in concentration occurred within the first two meters at Site 1 and within the first four and eight meters at Site 2, but were higher at 8m than at the edge of pavement.

Total and Dissolved Phosphorus – Net increases in phosphorus concentrations and negative removal efficiencies were measured at all sites over the width of the vegetated filter strips. Increases in phosphorus concentration have also been observed in studies conducted on other roadside shoulders (Barrett et al., 2004). The increases observed at the other sites are likely related to the same causes that resulted in increases of TKN (i.e. grass clippings and sampling occurring outside of the growing season).

Total Copper – Reductions in concentration were measured at all sites for total copper, generally with increasing efficiency observed with increasing distance from the edge of pavement. Maximum removal rates at various sites occurred between the edge of pavement and the eight meter sampling point at Site 1 (39%), the four meter sampling point at Site 2 (45%), and the eight meter sampling point at Site 3 (63%).

Total Lead – Although some reductions in lead concentration were observed at all sites, none of the differences are statistically significant.

Total Zinc – The removal efficiencies indicate that the concentrations of zinc increased at all sites with increasing distance from the edge of pavement. This is believed to be due to the adverse effects of the galvanized metal flashing used on the collection pipes and not a performance characteristic of the vegetated area.

Dissolved Copper – A significant decrease in concentration was observed at Site 3, but the reductions at other sites were not statistically different.

Dissolved Lead – Concentrations of dissolved lead were below the detection limits for the majority of events monitored. Not enough data above detection limits exists to understand any possible removal trend, but this lack of values over the detection limit also indicates an absence of dissolved lead originating from the highway surfaces and vegetated strips.

Dissolved Zinc – Similar to total zinc, dissolved zinc concentrations consistently increased at each site with increasing distance from the edge of pavement. This is again believed to be due to leaching from the galvanized metal.

Chemical Oxygen Demand – No significant differences in COD concentration were observed at any of the three sites. A maximum COD removal of 30% occurred at Site 3 within the first eight meters of the road surface. Negative removal efficiencies were observed at Sites 1 and 2.

5.5 Comparison of Performance of Austin and College Station Sites

5.5.1 Comparison of Water Quality Leaving Highway Surface

ANOVA tests were performed on the edge of pavement concentrations observed at all six research sites for each constituent monitored. These results indicate that statistically significant differences exist between the concentrations of dissolved phosphorus and total copper leaving the road surfaces.

- All three research sites in College Station had higher concentrations of dissolved phosphorus at the edge of pavement than the three Austin sites.

- Conversely, the Austin research sites had higher concentrations of total copper at the edge of pavement than the College Station sites.

All other constituents were not found to be statistically different from one another.

5.5.2 COMPARISON OF WATER QUALITY LEAVING VEGETATED STUDY AREA

ANOVA tests were also performed on the concentration values of each constituent observed at the 8m sampling point at each research site. The results, shown in Table 5.16, indicate that all but four of the monitored constituents were found to have no statistical differences between research sites. The four constituents with statistically significant differences are the total and dissolved forms of phosphorus, total copper, and dissolved zinc.

- Site 3 in Austin was found to have much higher phosphorus concentrations than the other sites in Austin and College Station. At the beginning of the study, a thin layer of biosolids compost was applied to this site; therefore, it is not surprising that higher concentrations of this nutrient were measured at this site.
- In the comparison of 8m total copper concentrations observed at each site, it can be seen that the concentrations at Austin Site 2 are lower than all of the other research sites
- Dissolved zinc concentrations at Austin Site 3 were slightly higher than at the other research sites, and Austin Site 1 had a range of concentrations that included values lower than those observed at any other site.

5.5.3 REMOVAL EFFICIENCIES OF VEGETATED FILTERS

In addition to comparing the quality of the runoff leaving the highway surfaces and the vegetated filter areas at each research site, the efficiency of each vegetated area at removing the monitored constituents also was compared. Cumulative removal efficiencies (from the edge of pavement to the 8m sampling point) for each constituent at each research site have been calculated based on rainfall-weighted average concentrations and are presented in Table 5.17.

Table 5.16 Results of ANOVA Tests at 8m

Constituent	p-value
Total Suspended Solids	0.175
Total Kjeldahl Nitrogen	0.377
Nitrate/Nitrite	0.831
Total Phosphorus	0.062
Dissolved Phosphorus	0.021
Total Copper	0.081
Dissolved Copper	0.112
Total Lead	0.198
Dissolved Lead	0.297
Total Zinc	0.233
Dissolved Zinc	0.051
Chemical Oxygen Demand	0.440
Fecal Coliform	0.590

Table 5.17 Performance Characteristics of Grass Shoulders

Constituent	Removal Efficiencies (%)					
	Austin			College Station		
	Site 1	Site 2	Site 3	Site 1	Site 2	Site 3
TSS	72.9	88.9	84.8	16.7	20.2	8.8
TKN	-154.4	19.0	-21.4	-63.4	-121.7	-41.6
NO3/NO2	6.3	-63.9	-132.6	-159.1	58.2	-76.3
Total P	-90.1	-45.9	-250.9	-173.6	-205	-72
Dissolved P	-400.4	-124.7	-801.6	-171	-322	-102
Total Cu	75.5	90.8	79.8	38.7	38.9	62.8
Dissolved Cu	12.0	61.1	-6.7	5.1	22.7	33.7
Total Pb	94.9	92.7	84.2	49.3	39.6	49.2
COD	18.6	66.0	47.6	-81.6	-82	30.1

- TSS – All Austin sites achieved much higher cumulative removal rates for TSS. College Station Site 1, with the lowest slope, had the smallest removal rate. College Station Site 2, with the highest slope, had the higher removal rate among the College Station sites. Site 1 in Austin, with the smallest of the Austin slopes, and the lowest overall vegetation density, had the smallest removal rate among the Austin sites.

- TKN – Both locations generally showed net gains in TKN concentrations over the vegetated areas
- NO_3/NO_2 – Comparable increases in concentration were observed in both locations. Among the Austin sites, the site with the lowest vegetation density (Site 1) was the only site to achieve any removal of the nutrient.
- Total P – Negative removals were observed at all sites. The largest increase in this species was at Site 3 in Austin, which was the site that received the compost application.
- Dissolved P – Increases of dissolved phosphorus were observed at all six research sites. Similar to total phosphorus, the largest increase in dissolved phosphorus occurred at Austin Site 3.
- Total Cu – Higher removal rates of total copper were achieved at the Austin sites than at College Station sites. Similar to TSS, the sites with the smallest slopes exhibited the lowest removal efficiencies of the sites in that area.
- Dissolved Cu – Similar removal efficiencies for dissolved copper were observed at all research sites, with the exception of a net increase at Site 3 in Austin
- Total Pb – Higher removal rates of total lead were achieved at the Austin sites than at College Station sites.
- Dissolved Pb – Concentrations of dissolved lead were almost always below detectable limits at all of the research sites; therefore, removal efficiency could not be calculated.
- COD – The Austin sites generally exhibited higher removal rates for COD than the College Station sites (two of which had net increases over their vegetated areas).

There are a number of possible explanations of the differences in performance between Austin and College station. These include traffic mix, sampling conditions, and herbicide application. Vegetation assemblages at both sites were reasonably similar, consisting primarily of King Ranch Bluestem and Bermuda grass. Consequently, differences in vegetation likely did not contribute to the differences in performance.

The analysis of stormwater data collected from monitoring sites in Austin and College Station, Texas has been challenging since the first data was obtained. Partly, this was because the data showed some uncertainties in the treatment effect from the College Station data, and could not confidently confirmed that vegetated roadsides in College Station significantly improve stormwater quality.

Despite the lack of statistical confidence in confirming the treatment effectiveness, the researchers would like to first point out the overall means of TSS concentration observed from all sites in College Station. The TSS means for edge of pavement, 2m, 4m and 8m from Site 1 are 116 mg/L, 79 mg/L, 85 mg/L and 97 mg/L, respectively. From Site 2, they are 172 mg/L, 119 mg/L, 105 mg/L and 136 mg/L. From Site 3, they are 124 mg/L, 162 mg/L, 222 mg/L and 116 mg/L, respectively. Except for Site 3, both Site 1 and 2 show some level of TSS concentration reduction; not significant but somehow promising. Note that no outliers were removed in calculating the above mean TSS concentrations.

In addition, the sampler installed at 8m on Site 2 in College Station was observed underwater after some rainfall events during the early stage of the monitoring period. Because the sampler is not designed to function in a submerged condition, some data collected from that sampler are suspected to be "contaminated." For example, the high 475 mg/L TSS concentration on May 2, 2004 is suspected to be the outcome resulting from the submergence of the sampler during that rainfall event. If this data point is removed, the means of TSS concentration on Site 2 become 172 mg/L, 119 mg/L, 105 mg/L and 94 mg/L, a more promising downward trend.

The College Station sites are located between a very busy on ramp (SH60-University Drive) and the off ramp (SH30-Harvey Rd.) This section also has a high percent of truck traffic in the stream (a little less than 10%). More importantly the truck traffic has a very high percentage of construction materials haulers, sand, gravel, concrete. The supply sources are located in Bryan around and off SH21 and the destinations are to the south of College Station where several new subdivisions are being developed. In addition, to the construction materials vehicles all of the solid waste and trash trucks from Bryan and College Station us this route to access the municipal landfill located off Rock Prairie Rd. about two miles to the south.

This combined traffic contributes to a very dirty site. During dry periods we observed buildup of silt and sand size particles that would completely cover the rubber gaskets at the pavement edge. During rain events the trucks interacting with merging, accelerating and decelerating vehicles seemed to stir up clouds of mist that would drift some distance from the paved surface. This was particularly true at Site 1 which was just south of the University Drive on ramp. Trucks and cars entering here seemed to really stir the air currents near the pavement and subsided as the distance increased.

We only observed one rain event after we got the results but around Site 1 in College Station there seemed to be a lot of mist and air disturbance caused by the interaction of merging vehicles, particularly gravel haulers and garbage trucks. We can only hypothesize at a lot of very dirty mist was stirred up in the near pavement area which remained suspended up to about 7-10 meters from the pavement. In retrospect we had a very dirty site in College Station and it was also not typical in that it was between two very busy intersections with heavy weaving of accelerating and decelerating traffic. .

Finally, the researchers at times observed herbicide application on sites in College Station. Some areas of the site turned brown and later become spotty bare ground. The survey conducted on August 24, 2004 show the vegetation coverage varied between 36% and 68% on Site 1. Vegetation still has not recovered as of August 2005. This could also significantly affect the treatment performance of vegetated roadside.

6. SUMMARY AND CONCLUSIONS

The purpose of this project was to provide documentation of the stormwater quality benefits of the vegetated sideslopes typical of common rural highway cross sections. A growing body of research indicates that these sideslopes can improve significantly the quality of runoff that enters receiving bodies by reducing pollutant concentrations and loads. It is important that these benefits be documented so the roadside can be used to meet stormwater treatment requirements. Such requirements are becoming an increasingly important subject for many regulatory agencies as well as those directly involved with stormwater discharges. In the case of this study, TxDOT is responsible for the mitigation and control of stormwater discharges from state roadways to receiving water bodies.

The objectives of this project were achieved by installing 24 passive stormwater runoff collection and sampling systems at six sites in the Austin and College Station areas. Each site consisted of four samplers, one at the edge of the highway to collect runoff directly from the road surface and three to collect runoff at distances of two, four, and eight meters from the edge of pavement. Storm events were monitored over a 14-month sampling period and were analyzed for a suite of pollutants commonly found in stormwater. The results were compiled into an extensive database and analytical and statistical tests were then conducted in order to assess the performance characteristics associated with each site.

The key findings of this study are as follows:

1. The pollutant concentrations in runoff at the edge of pavement were similar for most sites and within the expected range of concentrations for highway runoff. This allows for direct comparisons of the vegetated buffer strips and their associated site characteristics (vegetation density, slope, etc.).

2. Although concentrations observed at the edge of pavement and at 8m in Austin and College Station were similar, the high degree of variability observed at the College Station sites meant that no statistically significant differences could be documented for those sites for almost all constituents.
3. Vegetation density was observed to have a direct effect on the performance of vegetated filter strips. Areas with dense vegetative covers had better pollutant removal than other sites, even when the other sites had lower slopes. Vegetative covers of at least 90% provided the best performance, but substantial reductions in concentration were observed for sites with as little as 80% coverage.
4. A thin layer of biosolids compost material had no discernable effect (positive or negative) on the performance of densely covered vegetated filter strips. However, the test site had good vegetation coverage before application of the compost. Further testing is required to determine if compost could provide an improvement where the initial vegetation establishment is poor.
5. Statistically significant reductions in TSS concentrations were observed at all three research sites in Austin, but not in College Station. The majority of removal occurred within the first two meters of the vegetated filter at two sites, and within the first four meters at another site.
6. Concentrations of total copper exhibited statistically significant decreases at all six research sites (College Station and Austin) within the first eight meters.
7. Concentrations of total lead also exhibited statistically significant decreases at all three of the Austin sites with those decreases occurring within the first eight meters. No significant difference was documented at College Station.
8. Statistically significant reductions in COD occurred over the width of the vegetated filter at the Austin sites, but not in College Station.
9. No consistent increases or decreases were observed for nutrients.
10. Total and dissolved concentrations of zinc were elevated at the two, four, and eight meter sampling points at all of six sites, believed to be caused by leaching of zinc from the galvanized metal flashing used in the collection apparatuses.

11. Pollutant removal performance at the College Station sites was less consistent than the Austin sites due to fire ants, herbicide use, and heavy truck traffic.
12. Vegetated filter strips with a minimum width of 4m and a minimum vegetation density of 80% are recommended for treating stormwater runoff from highways with rural type cross sections in Texas.
13. The permeable friction course has a significant impact on the quality of runoff leaving the road surface. Runoff generated from the PFC has lower concentrations of TSS, total metals, and COD. These improvements in water quality are as great, if not greater, than the improvements gained from the vegetated area adjacent to the roadway.

The results from this study indicate that vegetated filter strips should be utilized by TxDOT as a best management practice for controlling and treating stormwater runoff from Texas highways. These filter strips demonstrate consistently high removal efficiencies for many of the pollutants of concern in stormwater runoff and can therefore mitigate the effects of discharging untreated highway runoff directly into receiving bodies of water. In addition to providing water quality benefits, these vegetated areas are inexpensive and easy to implement, easy to manage, and provide aesthetic benefits to the surrounding environment.

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Appendix A Vegetation Survey Results

Table A-1 Vegetation Survey Results, Austin Site 1

V-CAP LOG FORM
(revision 2003)

SITE	Austin Water Sampler Site 1
DATE OF V-CAP TEST	9/14/2004
DATE V-CAP LOGGED ONTO FORM	9/27/2004
TECHNICIAN	Hao (test) Derrold (data entry)

SITE 1

2 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
2 METER-1	2200321	1231513	55.9697	%
2 METER-2	2259065	1404694	62.18033	%
2 METER-3	2244217	1229245	54.77389	%
	Average Vegetative cover for 2 METER		57.64131	%

4 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
4 METER-1	2379480	2379480	100	%
4 METER-2	2294004	2116397	92.25777	%
4 METER-3	2085468	2011060	96.43207	%
	Average Vegetative cover for 4 METER		96.22995	%

8 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
8 METER-1	2323859	2316189	99.66995	%
8 METER-2	2287065	1889460	82.61505	%
8 METER-3	2222973	2201339	99.0268	%
	Average Vegetative cover for 8 METER		93.7706	%

Average Vegetative cover for SITE 1	82.54728	%

Table A-2 Vegetation Survey Results, Austin Site 2

V-CAP LOG FORM
(revision 2003)

SITE	Austin Water Sampler Site 2
DATE OF V-CAP TEST	9/14/2004
DATE V-CAP LOGGED ONTO FORM	9/27/2004
TECHNICIAN	Hao (test) Derrold (data entry)

SITE 2

2 METER

	Total Pixels	**Total Vegetation Pixels**	**% Vegetative cover**	
2 METER-1	2269895	1837624	80.95634	%
2 METER-2	2177948	2177948	100	%
2 METER-3	2279141	2162087	94.86412	%
	Average Vegetative cover for 2 METER		91.94015	%

4 METER

	Total Pixels	**Total Vegetation Pixels**	**% Vegetative cover**	
4 METER-1	2202542	2202542	100	%
4 METER-2	2243827	2243827	100	%
4 METER-3	2334455	2283537	97.81885	%
	Average Vegetative cover for 4 METER		99.27295	%

8 METER

	Total Pixels	**Total Vegetation Pixels**	**% Vegetative cover**	
8 METER-1	2240814	2219955	99.06913	%
8 METER-2	2265230	2265230	100	%
8 METER-3	2296484	2296484	100	%
	Average Vegetative cover for 8 METER		99.68971	%

Average Vegetative cover for SITE 2	96.9676	%

Table A-3 Vegetation Survey Results, Austin Site 3

V-CAP LOG FORM
(revision 2003)

SITE: Austin Water Sampler Site 3

DATE OF V-CAP TEST: 9/14/2004

DATE V-CAP LOGGED ONTO FORM: 9/27/2004

TECHNICIAN: Hao (test)
Derrold (data entry)

SITE 3

2 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
2 METER-1	2134225	2134225	100	%
2 METER-2	2242474	2242474	100	%
2 METER-3	2266434	2266434	100	%
	Average Vegetative cover for 2 METER		100	%

4 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
4 METER-1	2267338	2267338	100	%
4 METER-2	2333303	2333303	100	%
4 METER-3	2205519	2205519	100	%
	Average Vegetative cover for 4 METER		100	%

8 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
8 METER-1	2295099	2295099	100	%
8 METER-2	2274345	2274345	100	%
8 METER-3	2274186	2274186	100	%
	Average Vegetative cover for 8 METER		100	%

Average Vegetative cover for SITE 3 100 %

Table A-4 Vegetation Survey Results, College Station Site 1

Highway 6 Water Sampling Test Sites V-Cap Results

DATE OF V-CAP TEST	8/24/2004
DATE V-CAP LOGGED ONTO FORM	8/25/2004
TECHNICIAN	Hao (V-Cap) Derrold (data entry)

Total Vegetation V-Cap

Site 1

2 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
2 METER-1	586774	583235	99.39687	%
2 METER-2	516861	508687	98.41853	%
2 METER-3	466502	454773	97.48576	%
	Average Vegetative Cover for Site 1-2 meter		98.43372	%

4 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
4 METER-1	463713	460802	99.37224	%
4 METER-2	429796	423761	98.59585	%
4 METER-3	464246	458847	98.83704	%
	Average VegitativeCover for Site 1-4 meter		98.93504	%

8 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
8 METER-1	494531	482976	97.66344	%
8 METER-2	462868	458617	99.0816	%
8 METER-3	421759	418635	99.25929	%
	Average Vegetative cover for Site 1-8 meter		98.66811	%

Average Vegetative Cover for Site 1 **98.67896** %

Table A-5 Vegetation Survey Results, College Station Site 2

Site 2

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
2 METER				
2 METER-1	468432	464163	99.08866	%
2 METER-2	517777	512044	98.89277	%
2 METER-3	563448	553320	98.2025	%
	Average Vegetative cover for Site 2-2 meter		98.72797	%
4 METER				
	Total Pixels	**Total Vegetation Pixels**	**% Vegetative cover**	
4 METER-1	515934	504975	97.87589	%
4 METER-2	416695	378636	90.86646	%
4 METER-3	531437	497035	93.52661	%
	Average Vegetative cover for Site 2-4 meter		94.08965	%
8 METER				
	Total Pixels	**Total Vegetation Pixels**	**% Vegetative cover**	
8 METER-1	492094	488578	99.2855	%
8 METER-2	443596	440420	99.28403	%
8 METER-3	467341	463433	99.16378	%
	Average Vegetative cover for Site 2-8 meter		99.24444	%
	Average Vegetative cover for Site 2		**97.35402**	%

Table A-6 Vegetation Survey Results, College Station Site 3

Site 3

2 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
2 METER-1	341574	336537	98.52536	%
2 METER-2	385075	380563	98.82828	%
2 METER-3	435289	428711	98.48882	%
	Average Vegetative cover for Site 3-2 meter		98.61415	%

4 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
4 METER-1	439793	436191	99.18098	%
4 METER-2	431108	424313	98.42383	%
4 METER-3	433160	428292	98.87617	%
	Average Vegetative cover for Site 3-4 meter		98.82699	%

8 METER

	Total Pixels	Total Vegetation Pixels	% Vegetative cover	
8 METER-1	466851	438778	93.98673	%
8 METER-2	449185	439711	97.89085	%
8 METER-3	415372	409671	98.6275	%
	Average Vegetative cover for Site 3-8 meter		96.83502	%

Average Vegetative cover for Site 3	**98.09206**	%

Appendix B: Raw Data

Table B-1 EMCs for all storm events monitored at Austin Site 1

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved P (mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	726	550	126	54	1.85	2.93	1.81	1.75	0.57	0.93	0.35	0.16	0.32	0.35	0.21	0.2	0.2	0.19	0.1	0.09
3/1/2004	85	330	58	44	1.3	1.89	1.78	1.67	1.4	0.38	0.51	0.19	0.08	0.24	0.18	0.14	ND	0.06	0.06	0.04
4/12/2004	44	191	102	56	0.703	2.09	2.34	3.65	0.26	0.2	0.24	0.37	0.08	0.13	0.22	0.45	0.03	0.04	0.09	0.29
5/14/2004	130	20	76	25	1.05	2.27	2.07	1.67	0.13	0.16	0.11	0.22	0.17	0.24	0.23	0.13	0.08	0.2	0.11	0.06
6/3/2004	121	52	62	68	1.53	2.64	5.35	2.68	0.32	0.49	0.94	0.48	0.16	0.3	0.88	0.6	0.07	0.18	0.6	0.44
6/9/2004	209	14	4	17	1.06	0.401	0.426	1.08	0.06	ND	ND	0.07	0.17	0.05	0.07	0.15	ND	ND	0.05	0.09
11/15/2004 ^	9	‡	19	‡	0.863	‡	1.52	‡	0.728	‡	0.494	‡	0.029	‡	0.328	‡	0.04	‡	0.23	‡
11/22/2004 ^	3	19	52	46	0.41	0.488	1.03	1.99	0.2699	0.0654	0.0541	0.0625	ND	0.04	0.127	0.224	ND	ND	0.02	0.08
1/28/2005 ^	16	9	43	14	0.48	2.1	0.606	1.64	0.2453	0.6559	ND	0.1086	0.524	0.062	0.07	0.108	ND	ND	ND	0.03
3/3/2005 ^	4	14	13	16	0.43	0.513	0.647	1.31	0.3518	0.2428	0.0739	0.3035	0.368	0.043	0.355	0.099	0.271	0.023	0.039	0.061

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	84	81.3	10.5	6.17	10.5	20.2	4.14	4.09	34.8	30.6	6.8	1.7	ND	ND	ND	ND
3/1/2004	23.9	44.3	7.22	6.73	9.88	7.98	4.15	3.89	6.17	18.1	3.03	2.13	ND	ND	ND	ND
4/12/2004	16.9	20.7	10.2	9.14	5.24	6.62	4.52	5.85	7.56	7.61	3.71	1.69	ND	ND	ND	ND
5/14/2004	28.4	9.28	4.37	5.62	2.06	5.1	2.3	3.71	15	1.4	1.29	ND	ND	ND	ND	ND
6/3/2004	29.7	28	27.2	7.99	9.32	19.7	20.5	5.02	9.93	3.39	2.61	2.01	ND	ND	1.11	ND
6/9/2004	35.3	5.0	2.98	3.6	3.18	2.75	2.16	2.66	24.2	2.2	ND	ND	ND	ND	ND	ND
11/15/2004 ^	11.1	‡	11	‡	8.84	‡	9.78	‡	1.54	‡	1.27	‡	ND	‡	ND	‡
11/22/2004 ^	2.94	3.57	3.65	3.83	2.26	1.97	1.47	2.63	ND	1.15	2.11	1.57	ND	ND	ND	ND
1/28/2005 ^	6.13	19.6	5.53	4.78	2.73	13.1	2.26	3.43	1.14	1.57	1.79	ND	ND	ND	ND	ND
3/3/2005 ^	2.8	4.29	3.17	4.03	1.94	2.62	1.6	2.86	ND	1.18	ND	ND	ND	ND	ND	ND

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				Chemical Oxygen Demand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	389	417	261	52.8	28.2	67.1	127	34.2	302	345	58	61	240	440	20	40
3/1/2004	207	204	156	52.7	95.1	39.2	110	36.5	72	119	48	47	†	†	†	†
4/12/2004	101	95.8	83.6	51.1	45.4	40.9	45.7	72.6	29	49	42	52	†	†	†	†
5/14/2004	157	52.8	123	116	7.5	42.1	92.9	95.6	65	30	37	51	240	3000	1130	7000
6/3/2004	163	175	385	243	46.3	142	335	223	84	176	213	83	100	0	137000	9200
6/9/2004	209	46.5	42.9	49.3	41	45.6	39	43.4	70	12	15	36	†	†	†	†
11/15/2004 ^	58.5	‡	243	‡	47.2	‡	207	‡	77	‡	98	‡	†	‡	†	‡
11/22/2004 ^	26.7	45	237	228	20.3	61.7	181	175	13	10	24	63	†	†	†	†
1/28/2005 ^	54	85.4	183	356	43.1	67	109	291	22	122	32	49	†	†	†	†
3/3/2005 ^	41.1	61	214	261	24.4	41.1	166	210	10	30	22	32	†	†	†	†

data from first storm eliminated from final analyses
^ samples from these storm events taken from porous asphalt overlay
† samples collected after expiration of parameter's holding time
‡ sample not collected due to sampler malfunction or inadequate collection
ND not detected at reporting limit

Table B-2 EMCs for all storm events monitored at Austin Site 2

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	430	862	800	460	2.19	1.94	0.403	0.549	0.94	0.11	0.15	0.26	0.23	0.35	0.62	0.53	0.13	0.24	0.48	0.47
3/1/2004	52	54	‡	‡	0.962	1.43	‡	‡	0.52	0.43	‡	‡	0.08	0.14	‡	‡	ND	0.02	‡	‡
3/26/2004	90	100	275	185	1.97	2.32	3.05	3.68	0.45	0.25	0.4	0.7	0.2	0.23	0.35	0.53	0.09	0.1	0.15	0.23
4/12/2004	77	103	171	41	2.09	1.98	2.91	1.11	0.42	0.26	0.36	0.26	0.18	0.23	0.36	0.16	0.06	0.09	0.17	0.1
5/14/2004	140	15	15	25	1.19	1.14	2.11	1.66	0.19	0.11	0.23	0.21	0.15	0.17	0.26	0.2	0.07	0.12	0.18	0.12
6/3/2004	49	37	38	46	0.974	1.72	3.02	1.48	0.22	0.26	0.42	0.21	0.09	0.4	0.7	0.44	0.05	0.3	0.46	0.29
6/9/2004	218	14	19	15	2.29	0.783	0.888	0.878	0.06	ND	0.11	0.08	0.18	0.05	0.09	0.13	0.04	0.02	0.04	0.09
10/25/2004	50	75	105	16	0.646	4.56	6.87	1.75	0.33	ND	ND	0.03	0.075	0.722	0.966	0.415	0.04	0.44	0.47	0.3
11/1/2004	148	12	21	18	2.06	0.917	2.4	2.32	0.06	0.1	0.25	0.87	0.17	0.117	0.373	0.354	0.07	0.05	0.19	0.17
11/15/2004	70	18	20	‡	0.757	1.24	1.48	‡	0.219	0.371	0.637	‡	0.089	0.224	0.261	‡	0.03	0.12	0.16	‡
11/22/2004	370	97	21	23	1.82	1.25	0.827	1.18	0.0414	0.0501	0.2103	0.2026	0.239	0.124	0.104	0.17	0.08	ND	ND	0.07
1/28/2005	175	‡	22	14	1.59	‡	1.27	1.34	0.1386	‡	0.7112	1.821	0.06	‡	ND	0.44	ND	‡	ND	0.09
3/3/2005	53	‡	‡	7	1.75	‡	‡	1.03	1.476	‡	‡	0.2635	0.071	‡	‡	0.093	0.046	‡	‡	0.101

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	52.6	39.8	17.9	8.63	9.51	1.42	1.38	1.32	33.7	160	121	13.9	ND	1.43	ND	ND
3/1/2004	19.9	12.1	‡	‡	7.41	5.5	‡	‡	7.85	12.6	‡	‡	ND	1.46	‡	‡
3/26/2004	17.2	8.48	10.6	5.02	8.33	4.61	4.31	3.14	6.31	22.4	35.5	3.81	ND	2.3	1.89	ND
4/12/2004	19.7	11	10.5	2.35	8.35	3.86	5.45	1.57	6.6	19.6	17.6	1.56	ND	2.36	2.2	ND
5/14/2004	18.7	7.25	7.58	3.02	3.61	3.91	5.32	2.13	8.61	3.63	3.91	1.42	ND	ND	ND	ND
6/3/2004	9.99	8.49	8.81	5.92	5.15	5.61	5.91	1.68	3.11	6.27	6.86	3.94	ND	2.02	1.22	ND
6/9/2004	18.6	2.67	3.16	2.18	2.97	1.79	2.66	1.77	12.9	2.76	4.5	ND	ND	ND	ND	ND
10/25/2004	15	25.4	23.3	3.26	5.3	9.17	8.31	2.04	4.62	5.86	7.13	ND	ND	1.15	ND	ND
11/1/2004	28.2	3.85	4.2	3.3	3.24	2.6	3.23	2.48	12.5	1.9	1.69	ND	ND	ND	ND	ND
11/15/2004	20.3	7.1	6.92	‡	7.81	7.45	3.34	‡	12.3	4.01	4.79	‡	ND	ND	ND	‡
11/22/2004	42.6	9.03	3	2.29	3.66	1.31	2.52	1.68	26.2	23.2	ND	2.47	ND	ND	ND	ND
1/28/2005	31.5	‡	4.29	3.36	3.61	‡	3.36	2.21	12.2	‡	3.35	ND	ND	‡	ND	ND
3/3/2005	18.7	‡	‡	ND	7.18	‡	‡	1.4	4.66	‡	‡	ND	ND	‡	‡	ND

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				Chemical Oxygen Demand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	279	317	315	205	38.4	23.3	33.9	43.7	221	387	282	92	0	60	60	60
3/1/2004	124	148	‡	‡	48.9	88.5	‡	‡	84	70	‡	‡	†	†	‡	‡
3/26/2004	125	133	238	190	68.7	77.8	88.4	121	111	71	123	77	†	†	†	†
4/12/2004	106	326	139	289	59.2	215	79	246	87	58	73	29	†	†	†	†
5/14/2004	107	137	210	160	39.7	115	171	131	68	45	71	44	1500	5000	860	1270
6/3/2004	82.2	141	173	825	54	132	129	388	53	86	115	34	35000	152000	0	40
6/9/2004	118	74	90	91.3	44.7	75.2	64.6	90.6	98	19	27	26	†	†	†	†
10/25/2004	180	383	821	458	110	293	650	395	46	216	286	45	†	†	†	†
11/1/2004	199	105	393	280	47.4	89.7	340	256	89	39	61	69	3360	31000	143000	15000
11/15/2004	129	439	612	‡	44.5	386	511	‡	48	51	49	‡	†	†	†	‡
11/22/2004	229	96.7	52.7	81.6	21.4	34.8	54.6	58.6	130	29	15	19	†	†	†	†
1/28/2005	192	‡	134	397	16	‡	98.4	318	96	‡	35	29	†	‡	†	†
3/3/2005	89.9	‡	‡	129	33.7	‡	‡	89.2	61	‡	‡	27	†	‡	‡	†

(shaded) data from first storm eliminated from final analyses
† samples collected after expiration of parameter's holding time
‡ sample not collected due to sampler malfunction or inadequate collection
ND not detected at reporting limit

Table B-3 EMCs for all storm events monitored at Austin Site 3

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	232	‡	1770	1530	0.721	‡	3.98	13.8	0.67	‡	6.28	73.8	0.11	‡	9.37	9.59	0.08	‡	8.75	8.55
3/1/2004	‡	‡	‡	54	‡	‡	‡	1.27	‡	‡	‡	0.58	‡	‡	‡	0.41	‡	‡	‡	0.32
3/26/2004	148	130	150	230	2.16	2.85	3.14	5.87	0.3	0.73	1.74	4.94	0.24	0.98	1	1.63	0.11	0.8	0.87	1.32
4/12/2004	121	158	38	55	3.4	3.54	1.72	1.45	0.65	0.37	0.4	0.4	0.26	0.84	0.43	0.25	0.09	0.62	0.31	0.12
5/14/2004	74	25	32	14	0.815	1.84	2.97	2.44	0.16	0.13	0.07	0	0.1	0.75	1.19	0.35	0.05	0.66	0.89	0.24
6/3/2004	64	35	14	18	1.43	2.92	2.72	2.02	0.29	0.58	1.46	0.34	0.13	1.72	1.33	0.62	0.08	1.52	1.17	0.51
6/9/2004	132	13	19	66	0.946	0.563	1.29	2.63	0.04	0.02	0.12	0.4	0.13	0.47	1.03	1.47	0.02	0.43	1.02	1.31
10/25/2004	130	42	45	30	1.87	2.01	9.66 *	6.00	0.28	ND	ND	ND	0.204	0.753	3.41	1.97	0.09	0.64	2.87	1.57
11/1/2004	266	37	22	15	1.45	1.64	0.671	0.801	0.08	0.02	0.6	0.19	0.196	0.636	1.35	0.862	0.08	0.51	1.26	0.79
11/15/2004	108	26	18	25	0.914	1.04	1.75	1.9	0.189	0.377	0.555	0.22	0.126	0.74	1.12	0.543	0.03	0.65	1.08	0.39
11/22/2004	384	41	43	26	2.69	0.677	1.24	1.68	0.0274	0.0597	0.2533	0.3244	0.39	0.213	0.592	0.957	0.14	0.14	0.48	0.8
1/28/2005	285	30	20	13	2.21	1.47	0.505	0.355	0.2337	0.2612	0.4369	0.5743	0.45	1.24	1.03	0.595	0.1	0.65	0.97	0.54
3/3/2005	196	16	34	‡	1.48	0.875	1.23	‡	0.1402	0.4374	0.5735	‡	0.867	0.349	0.86	‡	0.185	0.307	0.723	‡

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	61.7	‡	252	181	7.59	‡	15.1	17.6	33.3	‡	101	37.3	ND	‡	ND	ND
3/1/2004	‡	‡	‡	9.06	‡	‡	‡	4.06	‡	‡	‡	2.46	‡	‡	‡	1.22
3/26/2004	19.7	13.5	14.2	22.5	5.1	7.84	10.2	14.6	9.98	28.6	8.14	6.81	ND	3.82	ND	ND
4/12/2004	28.9	19.8	6.34	4.08	10.2	9.49	4.42	2.06	11.2	26.6	2.7	2.1	ND	2.63	ND	ND
5/14/2004	12.3	9.88	11.2	6.11	3.17	7.04	5.76	4.06	5.45	3.7	3.01	ND	ND	ND	ND	ND
6/3/2004	16.8	17.7	12.7	4.37	7.47	12.7	10.4	2.77	4.8	3.78	0	ND	ND	1.04	ND	ND
6/9/2004	19	4.83	9.06	13.3	2.23	3.09	7.55	10	11.6	2.84	3.08	2.58	ND	ND	ND	ND
10/25/2004	28.7	8.31	32.3	11.6	6.36	3.95	7.91	2.89	9.44	3	7.45	1.3	ND	ND	ND	ND
11/1/2004	35.8	5.3	8.52	6.14	5.65	2.83	6.48	4.58	16	4.56	1.52	ND	ND	ND	ND	ND
11/15/2004	24.6	6.48	8.01	4.18	5.17	4.04	5.17	3.25	14.7	5.46	2.71	ND	ND	ND	ND	ND
11/22/2004	62.2	5.24	5.2	5.81	3.42	1.76	2.63	4.41	46.5 *	8.28	5.58	1.76	ND	ND	ND	ND
1/28/2005	48	8.75	9.1	3.42	4.12	4.95	5.88	2.64	18.4	4.3	1.92	ND	ND	ND	ND	ND
3/3/2005	31.2	4.32	6.19	‡	3.35	2.31	3.75	‡	13.8	2.27	2.88	‡	ND	ND	ND	‡

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				Chemical Oxygen Demand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	360	‡	810	782	43.1	‡	24.3	61.6	124	‡	579	636	0	‡	1200	200
3/1/2004	‡	‡	‡	343	‡	‡	‡	206	‡	‡	‡	31	‡	‡	‡	†
3/26/2004	133	216	250	452	39.1	175	187	317	97	62	64	128	†	†	†	†
4/12/2004	185	333	495	312	68	211	450	239	133	68	34	25	†	†	†	†
5/14/2004	67.7	154	492	985	40	147	402	927	42	47	64	45	580	4000	30000	2000
6/3/2004	93.6	218	354	516	50.5	187	346	451	77	107	74	45	2700	0	12000	30
6/9/2004	115	52.3	111	314	48	53.7	100	190	57	15	34	63	†	†	†	†
10/25/2004	216	338	446	402	88.5	242	318	333	88	50	351 *	149	†	†	†	†
11/1/2004	232	295	271	290	52.8	227	237	249	114	46	72	52	7000	10000	197000	4000
11/15/2004	147	659	253	788	60.3	553	200	652	72	35	37	80	†	†	†	†
11/22/2004	307	91.8	68.2	116	29.7	56	35.1	74.8	160	11	23	27	†	†	†	†
1/28/2005	272	317	408	853	46.8	253	354	738	157	36	46	47	†	†	†	†
3/3/2005	162	427	426	‡	28	321	296	‡	98	27	33	‡	†	†	†	‡

(shaded) data from first storm eliminated from final analyses
† samples collected after expiration of parameter's holding time
‡ sample not collected due to sampler malfunction or inadequate collection
ND not detected at reporting limit

Table B-4 EMCs for all storm events monitored at College Station Site 1

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved P (mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	143	154	225	326	2.95	2.77	2.61	2.88	0.41	0.27	0.32	0.35	0.37	0.25	0.22	0.29	0.29	0.09	0.07	0.08
03/25/2004	53	81	153	134	2.87	2.19	2.15	1.96	ND	ND	0.48	0.5	0.18	0.22	0.21	0.22	0.09	0.06	0.05	0.06
05/02/2004	158	192	56	104	3.37	2.11	0.902	1.65	0.4	0.17	0.17	0.11	0.27	0.23	0.05	0.12	0.14	0.09	0.02	0.03
08/02/2004	218	46	10	56	0.908	1.9	1.66	2.23	0.4	0.45	1	ND	0.186	0.478	0.302	0.7	0.16	0.35	0.28	0.54
08/23/2004	22	9	9	4	0.549	1.73	1.29	1.54	0.33	0.64	0.36	0.34	0.064	0.26	0.137	0.191	0.03	0.2	0.1	0.13
10/03/2004	8	22	34	76	0.638	2.18	7.53	8.49	0.26	ND	ND	ND	0.1	1.24	1.2	1.36	0.07	1.06	0.87	0.8
11/18/2004	15	43	8	11	5.34	0.65	0.897	1.1	0.2504	0.2399	0.0366	0.0294	0.085	0.682	0.254	0.142	ND	0.44	0.15	ND
01/13/2005 ^	421	100	229	162	2.93	0.865	1.66	5.31	0.7456	0.1419	0.1225	7.2	0.584	0.125	0.08	0.196	0.27	0.06	ND	ND
01/28/2005 ^	115	50	44	48	0.642	2.35	0.433	0.861	0.3491	0.6253	53.66	0.1038	0.218	0.319	0.23	0.232	0.08	0.24	0.11	ND
05/09/2005 ^	11	94	83	46	1.11	7.55	5.34	2.81	0.551	0.7719	0.1906	1.471	0.115	6.31	2.03	0.536	0.064	6.05	1.75	0.325

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	15.2	12.5	9.49	9.89	4.47	4.07	4.13	3.51	8.83	11.6	15.1	13.7	4.12	1.03	ND	ND
03/25/2004	16.5	9.85	7.86	8.39	11.6	5.21	5.46	4.69	4.13	5.04	7.32	5.27	ND	ND	ND	ND
05/02/2004	15.9	6.45	5.23	4.46	6.28	4.81	2.99	3.05	7.76	2.56	2.47	2.2	ND	ND	ND	ND
08/02/2004	22.4	8.8	4.77	8.29	6.22	5.29	5.8	1.38	13.6	2.82	ND	2.48	ND	ND	ND	ND
08/23/2004	5.67	7.3	4.31	4.08	5.25	2.4	3.21	4.1	1.22	ND	ND	ND	ND	ND	ND	ND
10/03/2004	6.62	5.79	7.61	13.4	4.5	4.95	8.57	9.81	1.08	1.51	1.72	4.52	ND	ND	1.08	1.13
11/18/2004	7.99	15.9	2.94	3.01	4.88	6.36	2.27	2.45	2.16	8.63	ND	ND	ND	ND	ND	ND
01/13/2005 ^	29.5	10.6	9.25	3.9	3.26	2.11	3.32	2.46	22.9	9.84	12.3	2.6	ND	ND	2.84	ND
01/28/2005 ^	13.2	12.3	6.73	3.43	9.95	8.07	4.26	2.29	8.4	4.16	4.55	2.01	4.04	ND	1.78	ND
05/09/2005 ^	10.3	12.8	119	10.6	5.39	10.7	11	8.32	1.58	1.12	11.7	ND	ND	ND	ND	ND

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				Chemical Oxygen Demand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	160	245	358	456	53.3	122	238	258	82	97	82	82	2360	1700	300	160
03/25/2004	111	156	412	287	66.6	87.6	317	229	117	74	72	78	7400	1100	100	1500
05/02/2004	137	118	78.6	218	54.6	114	159	194	93	50	40	42	1100	900	650	700
08/02/2004	224	255	365	1520	76.6	204	479	953	122	110	80	135	3000	76000	21000	200000
08/23/2004	42.6	374	309	452	25.5	324	290	394	28	46	39	51	17000	60000	3000	31000
10/03/2004	46.4	88.1	215	353	38.8	225	305	276	33	65	215	279	280	968000	1320000	144000
11/18/2004	33.6	232	80.2	48.3	17.9	122	73.3	44.5	26	73	21	26	9000	11300	42000	51100
01/13/2005 ^	241	238	471	99.1	24.5	108	409	120	138	49	48	86	2800	580	910	2140
01/28/2005 ^	133	538	445	81	97.9	340	212	66.7	61	71	32	29	<100	1000	<100	5500
05/09/2005 ^	42.1	133	855	420	27.2	81.6	198	369	33	128	100	78	600	17000	5700	44000

#	Sample not collected due to Fire ants
ND	not detected at reporting limit
^	Samples collected without Zero meter flow strip at the edge of the pavement

Table B-5 EMCs for all storm events monitored at College Station Site 2

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus(mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	219	618	486	184	2.38	2.96	3.07	2.15	0.37	0.37	0.33	0.14	0.19	0.45	0.66	0.2	0.11	0.17	0.27	0.06
03/25/2004	69	120	130	55	2.9	2.59	1.52	2.3	0.76	0.63	0.19	0.44	0.39	0.47	0.2	0.35	0.13	0.16	0.12	0.1
05/02/2004	500	46	82	475	2.82	1.47	1.86	4.73	0.16	0.24	0.07	0.21	0.42	0.41	0.21	0.52	0.18	0.17	0.11	0.16
08/02/2004	180	116	38	#	1.51	5.28	4.14	#	0.26	1.84	0.04	#	0.198	1.5	2.14	#	0.14	1.36	1.96	#
08/23/2004	19	11	8	4	0.636	1.25	1.41	2.86	0.26	0.44	0.32	0.34	0.088	0.367	0.465	0.534	0.05	0.31	0.4	0.45
10/03/2004	20	42	52	40	1.64	2.06	0.962	1.89	0.1	ND	0.21	0.17	0.183	1.09	0.895	1.14	0.15	0.78	0.69	0.95
11/18/2004	103	48	16	46	1.52	1.94	1.97	1.92	0.0543	0.0503	0.0202	0.0389	0.169	0.198	0.556	0.441	ND	0.03	0.47	0.29
01/13/2005 ^	504	61	148	293	3.99	4.88	4.71	4.75	7.78	5.32	0.8075	2.027	0.434	0.428	0.538	0.455	0.18	0.08	0.14	0.1
01/28/2005 ^	81	107	59	67	0.743	1.16	0.855	0.569	0.1509	ND	ND	ND	0.051	0.248	0.114	0.084	ND	0.21	0.09	0.06
05/09/2005 ^	29	24	33	59	1.26	5.85	5.01	13.7	0.7417	2.081	1.974	0.6877	0.261	0.595	0.59	1.63	0.175	0.326	0.473	1.18

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	26.7	20.2	22.4	11	6.36	4.45	4.4	4.7	14.7	19.7	21.5	10	ND	ND	ND	ND
03/25/2004	27.4	19.2	6.4	8.59	11.4	5.09	4.51	3.66	18.3	12.4	2.86	10.5	ND	ND	ND	ND
05/02/2004	31.1	9.7	3.72	7.97	4.32	3.38	3.85	3.65	23.1	5.41	2.28	13	ND	ND	ND	ND
08/02/2004	20.4	19.6	9.24	#	7.7	15.1	10.4	#	10.2	3.59	ND	#	ND	ND	ND	#
08/23/2004	8.32	6.1	7.07	7.89	4.82	3.52	5.17	4.15	2.22	ND	ND	ND	ND	ND	ND	ND
10/03/2004	10.1	12.1	10.8	5.21	3.75	5.84	5.61	5.95	3.71	1.88	5.01	ND	ND	ND	ND	ND
11/18/2004	14.7	7.88	5.17	6.74	6.58	5.14	4.13	4.39	5.45	2.55	ND	2.21	ND	ND	ND	ND
01/13/2005 ^	16.9	13.1	15.2	4.68	2.6	3.25	3.04	2.3	8.9	12.5	18.8	3.97	ND	ND	ND	ND
01/28/2005 ^	7.28	6.05	3.97	2.84	3.19	3.59	3.96	3.13	2.58	3.71	1.51	1.46	ND	ND	ND	ND
05/09/2005 ^	9.36	28.7	6.91	26	7.36	5.5	4.43	4.75	1.34	1.15	ND	1.49	ND	ND	ND	ND

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				Chemical Oxygen Demand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	192	372	360	205	30.7	77.8	58.6	209	87	105	139	60	1280	3100	1300	260
03/25/2004	218	443	81.6	324	75.3	427	95.4	195	132	129	48	75	5300	44000	700	1200
05/02/2004	259	220	164	159	32.9	88	64.6	79.3	119	72	51	85	1000	2000	650	3500
08/02/2004	155	367	557	#	81.1	288	799	#	92	126	122	#	2480	312000	200000	#
08/23/2004	43	154	98.1	317	33	124	90.1	276	33	33	53	29	800	28000	8000	3000
10/03/2004	43.2	165	486	189	23.8	174	306	242	38	93	143	73	2300	550000	642000	118000
11/18/2004	66.1	71.4	31.4	58.6	33.1	50.2	24.3	51.6	36	26	26	32	28000	15800	5900	13000
01/13/2005 ^	131	316	379	113	89.4	44.1	54.9	134	121	91	91	87	1330	400	2500	1900
01/28/2005 ^	49.5	109	46.5	54.2	20.2	60.9	43.7	53.2	19	25	29	18	400	400	700	300
05/09/2005 ^	26	150	54.3	1110	23.1	111	56.8	212	37	97	57	420	2500	<100	<100	1600

\# Sample not collected due to Fire ants
ND not detected at reporting limit
^ Samples collected without Zero meter flow strip at the edge of the pavement

Table B-6 EMCs for all storm events monitored at College Station Site 3

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	148	482	406	216	2.6	4.68	3.48	3.52	0.84	0.45	0.41	0.4	0.35	0.37	0.41	0.3	0.27	0.14	0.11	0.1
03/25/2004	276	214	48	270	3.41	2.37	1.82	1.7	2.01	0.73	0.32	0.26	0.2	0.26	0.22	0.18	0.1	0.08	0.06	0.05
05/02/2004	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
08/02/2004	144	72	138	38	1.11	3.72	2.75	3.96	0.47	1.18	0.18	ND	0.146	0.731	0.914	2.15	0.13	0.62	0.81	1.83
08/23/2004	7	4	7	4	0.909	1.35	1.26	1.26	0.05	0.26	0.22	0.18	0.08	0.186	0.227	0.484	0.03	0.16	0.19	0.43
10/03/2004	76	28	52	46	0.674	1.73	3.59	1.77	ND	ND	ND	ND	0.385	0.316	1.11	0.506	0.22	0.21	0.62	0.42
11/18/2004	46	56	66	24	1.2	1.87	1.44	0.909	0.4047	0.1652	0.0607	0.0927	0.181	0.313	0.227	0.143	0.04	0.14	0.03	ND
01/13/2005 ^	341	418	928	315	2.88	8.8	5.56	3.48	1.848	10.97	0.2321	7.485	0.317	1.01	0.68	0.262	0.16	0.26	0.04	ND
01/28/2005 ^	47	170	284	114	1.46	0.866	1.11	3.9	2.187	0.0448	0.0314	0.9654	0.112	0.081	0.104	0.255	0.06	0.04	0.03	0.17
05/09/2005 ^	35	12	67	16	1.83	1.99	2	2.22	0.2607	2.522	1.424	1.276	0.171	0.207	0.225	0.333	0.125	0.126	0.096	0.181

	Total Copper (µg/L)				Dissolved Copper (µg/L)				Total Lead (µg/L)				Dissolved Lead (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	17.9	16.9	13.5	13.5	7.08	5.39	4.65	5.13	6.26	18.2	14.3	9.92	ND	ND	ND	ND
03/25/2004	17	9.62	8.39	4.76	6.19	6.93	4.37	4.56	4.59	9.3	4.59	2.36	ND	ND	ND	ND
05/02/2004	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
08/02/2004	32.2	17.6	8.48	9.48	14	13.7	9.24	7.92	11.5	3.73	3.12	1.89	ND	ND	ND	1.21
08/23/2004	6.81	9.6	4.55	3.11	4.42	8.38	3.68	2.25	1.22	ND	ND	ND	ND	ND	ND	ND
10/03/2004	18.3	8.23	10.9	4.57	3.41	5.56	6.17	4.29	6.93	ND	4.47	1.74	ND	ND	1.25	ND
11/18/2004	12.4	8.68	5.98	3.2	6.43	5.2	3.73	2.09	4.68	4.31	3.3	1.61	ND	ND	ND	ND
01/13/2005 ^	13.6	18.2	16.4	4.58	4.28	4.74	2.3	1.85	7.67	21.4	28.1	8.09	ND	ND	ND	3.75
01/28/2005 ^	14.2	11.9	12.8	6.28	6.06	4.14	2.81	3.61	6.77	7.67	11.1	4.81	1.29	ND	ND	ND
05/09/2005 ^	7.71	6.09	4.63	6.1	5.82	4.24	3.82	4.22	1.31	ND	1.21	ND	ND	ND	ND	ND

	Total Zinc (µg/L)				Dissolved Zinc (µg/L)				ChemicalOxygenDemand (mg/L)				Fecal Coliform (cfu/100mL)			
	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m	0m	2m	4m	8m
03/05/2004	176	646	325	486	110	216	157	313	106	96	122	0.85	20	1300	1500	2800
03/25/2004	120	633	179	245	40	226	52.1	210	122	83	84	53	7000	500	2200	1700
05/02/2004	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#	#
08/02/2004	223	708	572	1080	77.3	600	647	1020	144	151	149	175	3000	223000	49000	252000
08/23/2004	36.3	432	396	496	30	402	329	438	56	39	32	32	18000	11000	8000	>400
10/03/2004	151	235	932	320	39.7	95.4	746	261	123	75	214	78	32000	183000	305000	124000
11/18/2004	60.8	125	54.6	63.6	27.7	71.4	39	50.6	40	41	24	24	22200	25800	15000	6200
01/13/2005 ^	95.8	443	309	239	31.4	165	47.1	302	105	133	108	57	1100	7200	3900	5600
01/28/2005 ^	123	169	204	362	22.1	138	75.4	228	75	31	37	62	200	300	700	35000
05/09/2005 ^	25.3	95.8	65.1	384	24.6	82.5	63.2	289	55	52	50	75	3800	16700	200	2100

Sample not collected due to Fire ants
ND not detected at reporting limit
^ Samples collected without Zero meter flow strip at the edge of the pavement

APPENDIX C:

Design Guidelines for Achieving Water Quality Benefits with Grassed Shoulders

Prepared for: Texas Department of Transportation

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Description

Grass shoulders along highways are a type of vegetated filter strip. Filter strips are also known as biofiltration strips, buffer strips, and vegetated buffers. Grass shoulders improve water quality for selected constituents by slowing runoff velocities and allowing sediment and other pollutants to settle, and by providing some infiltration into underlying soils. Filter strips were originally used as an agricultural treatment practice, and have more recently evolved into an urban stormwater treatment practice. With proper design and maintenance, filter strips can provide relatively high pollutant removal. In addition, TxDOT includes them as part of the standard roadway cross-section in rural areas, so no additional land is required where stormwater treatment is desired.

Texas Experience

Six grassed shoulders, three in Austin and three in College Station, were monitored over a 14-month period. These vegetated areas were generally effective in reducing the concentrations of pollutants in runoff generated from the highways. This was particularly true for suspended solids and total forms of metals commonly found in runoff. Table 1 documents the average edge of pavement (EOP) concentration, effluent concentration, and pollutant removal observed at the study sites based on rainfall weighted averages.

Table C-1 Performance of Vegetated Filter Strips

	Austin Sites			**College Station Sites**		
Constituent	**Mean Influent**	**Mean Effluent**	**% Removal**	**Mean Influent**	**Mean Effluent**	**% Removal**
TSS (mg/L)	181.3	30.2	83.3%	115.9	96.7	16.6%
TKN (mg/L)	1.50	2.06	-37.7%	1.88	3.34	-77.8%
NO3/NO2 (mg/L)	0.20	0.31	-51.8%	0.65	0.82	-26.3%
Total Phosphorus (mg/L)	0.19	0.49	-155.3%	0.22	0.56	-150.3%
Dissolved Phosphorus (mg/L)	0.06	0.37	-519.9%	0.12	0.35	-199.5%
Total Copper (µg/L)	31.3	5.8	81.5%	14.2	7.4	47.8%
Total Lead (µg/L)	12.5	1.0	91.7%	6.2	3.0	52.2%
Dissolved Copper (µg/L)	4.47	3.47	22.5%	5.53	4.39	20.7%
Dissolved Lead (µg/L)	ND	ND	-	0.18	0.23	-30.0%
COD (mg/L)	86.6	45.6	47.3%	69.7	95.8	-37.4%

These results indicate that concentrations of total suspended solids, total copper, and total lead were effectively reduced by the filter strips. However, increases were observed in concentrations of nitrogen and phosphorus based nutrients. On average, the sites in Austin appeared to outperform the College Station sites in terms of removal rates. At this time, these differences are believed to result from site-specific variables such as soil type, fire ant, vehicle class composition, herbicide and etc. A more thorough discussion on this can be found in the final report.

Some sites, particularly those in the Austin area, exhibited the majority of their pollutant removal within the first few meters of the road surface. Figure 1 presents a box and whisker plot of the concentrations of TSS in highway runoff after traveling various distances (shown in meters) through a vegetated filter strip with a slope of about 18%. One can see that the TSS median concentration is reduced from about 170mg/L to a minimum concentration of about 50 mg/L within 6 feet (2 meters) of the pavement edge. This particular site also had close to 100% vegetation density close to the road. Another site with substantially lower vegetation density did not achieve the same reduction this close to the road, but did achieve significant reduction within 26 feet (8m) of the road surface.

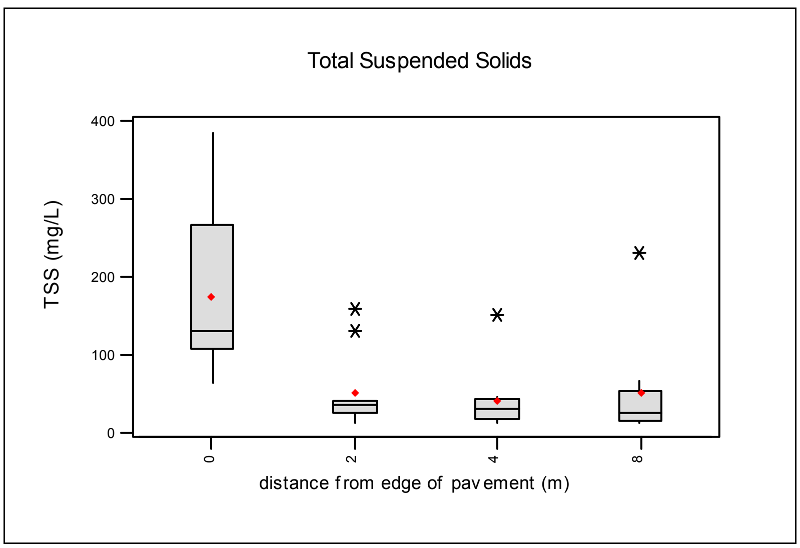

Figure C-1 Total Suspended Solids Concentrations in a Vegetated Filter Strip in Austin

Design and Sizing Guidelines

The following design guidelines are based on the water quality performance observed at the test sites in Austin and College Station.

- Slopes should not exceed 6:1 (H:V) to encourage sheet flow, increase contact time of the runoff with the vegetation, and prevent erosion.
- Where space is constrained along highways a fully vegetated grassy shoulder 6 feet wide will provide almost all the solids removal.
- To provide maximum pollutant removal for all constituents a width (in direction of flow) of 26 feet is required.
- Vegetative cover should be at least 80% to reduce the concentrations of pollutants in runoff. Best performance is obtained where coverage approaches 100%.
- Pollutant removal in grassy shoulder areas have been observed in several studies with a variety of vegetation, so no special mixture is required as long as the soil on the roadside is adequately stabilized.

Maintenance Requirements

Some maintenance of grass shoulders is required to maintain the water quality benefits. Routine mowing, which occurred approximately four times per year, and litter removal activities at the test sites were sufficient to provide the documented water quality benefits. Recommendations include:

- Grass height and mowing frequency may have little impact on pollutant removal, however, the standard mowing schedules (one each season) in Austin and College Station were employed during the study and the resulting performance of the filters was positive. Consequently, mowing may only be necessary once or twice a year for safety or aesthetics.
- Trash tends to accumulate in vegetated areas, particularly along highways and when grass is high. The need for litter and debris removal is determined through periodic inspection, but litter should always be removed prior to mowing.
- Any substantial erosion observed during routine maintenance activities should be repaired and the area re-vegetated to maintain water quality benefits, protect the roadway embankment, and for safety purposes.
- Performance of grass shoulder approaches maximum when the vegetation cover is near 100%. Herbicide application could kill all vegetation cover, leaving bare ground. Special care in applying herbicide is needed.