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Stormwater Quality Documentation of Roadside Shoulders Borrow Ditches

by

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CHAPTER 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 design parameters such as length, width, and vegetative cover are not specified. 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.

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 implement. Quantifying and controlling the nonpoint sources, however, is a much greater challenge. These reduction measures are known as best management practices (BMPs) for nonpoint source discharges such as stormwater runoff from highways. In the state of Texas, the Texas Department of Transportation (TxDOT) is the party responsible for controlling and mitigating the 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 on the rise. As the trends of increased urbanization continue, development projects will be implemented in previously undeveloped areas. Among these projects will be the construction of new roadways to accommodate the growing population. Increases in road surface area, among other things, will decrease the permeable ground cover over which infiltration of rainwater and runoff can occur. A decrease in pervious ground cover will lead to a greater impact of runoff on receiving water bodies. These trends in development add further importance to being able to assess the contribution of pollutants in runoff from roadways and to mitigate their 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 has not yet gained wide acceptance as a pollutant control mechanism. Regulatory agencies generally have a lack of understanding of 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 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 as part of the design of 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 scope of this project included:

- Selection of three sampling sites in the Austin 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 12 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.

The effects of vegetation cover and slope on pollutant concentrations were assessed. Two geographic areas in Texas, Austin and College Station, were used in this study to further 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. Only the work completed in the Austin area is addressed in this report.

CHAPTER 2 LITERATURE REVIEW

2.1 INTRODUCTION

The origins, control, and treatment of nonpoint source pollution have become an increasingly important environmental concern. 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 metals 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 on the topic also has been reported for vegetative controls for highway runoff including grassy swales and vegetated filter strips.

2.2 SOURCES OF HIGHWAY RUNOFF

Numerous sources of highway runoff pollutants include vehicles (exhaust emissions, fuel losses, lubrication system losses, and tire wear), litter, spills, pavement wear, atmospheric deposition (dustfall and precipitation), and roadway maintenance operations (salt, herbicides, and road repairs) (Folkeson, 1994; Barrett et al., 1995). The most important groups of highway runoff pollutants reported in the published literature include suspended particles, oxygen-consuming pollutants, nutrients, heavy metals, organic pollutants, petroleum products, and microorganisms (Folkeson, 1994). Therefore, the most frequently studied constituents of highway runoff include (Folkeson, 1994):

- Total suspended solids (TSS)
- Biological Oxygen Demand (BOD)
- Chemical Oxygen Demand (COD)
- Phosphorus (P)
- Nitrogen (N)
- Cadmium (Cd)
- Chromium (Cr)
- Copper (Cu)
- Iron (Fe)
- Lead (Pb)
- Nickel (Ni)
- Zinc (Zn)
- Hydrocarbons
- Coliform bacteria
- Sodium and chlorine (if chemical de-icing agents are used)

Young et al. (1996) concluded that the primary sources of some of the constituents in roadway runoff are:

- Particulates – pavement wear, vehicles, atmosphere, maintenance, snow/ice abrasives, sediment disturbance
- N, P – atmosphere, roadside fertilizer use, sediments
- Pb – leaded gasoline (formerly), tire wear, lubricating oil and grease, bearing wear, atmospheric fallout
- Zn – tire wear, motor oil, grease
- Cu – metal plating, bearing wear, engine parts, brake lining wear, fungicides and insecticides
- Pathogenic bacteria – soil litter, bird and animal droppings, trucks hauling livestock/stockyard waste

2.3 CHARACTERISTICS OF HIGHWAY RUNOFF

Fluxes of pollutants in highway runoff can be influenced by traffic conditions, precipitation and atmospheric conditions, and road conditions (Folkeson, 1994; Barrett et al., 1995). Traffic conditions that may have an effect on runoff pollutant levels are types of traffic, traffic volume, traffic patterns, and traffic intensity, especially during storm events. Important precipitation and atmospheric characteristics that affect the quality of runoff include wind, seasonal rainfall patterns, antecedent dry period, storm intensity, storm duration, and volume of runoff.

Correlations between concentrations of pollutants in runoff and factors such as antecedent dry period, traffic volume, and storm intensity have been reported. Irish et al. (1998) indicated that antecedent dry period conditions and runoff intensity during the preceding storm are the most significant factors that influence loadings of TSS and volatile suspended solids (VSS). However, antecedent dry period and antecedent traffic count are highly correlated variables, suggesting that the traffic count may be a better predictor of TSS and VSS loads (Irish et al., 1998). Other investigators report only slight correlations between stormwater runoff quality and the average daily traffic (ADT) count on roadways. Vehicles during a storm (VDS) is cited as a more significant indicator of expected pollutant loads than ADT. Barrett et al. (1995) point out, however, that VDS counts may only be reflecting the importance of runoff volume on the runoff quality. The effects of antecedent dry periods have also been mixed. No strong correlations have been reported for short dry periods and lower pollutant loads. Rainfall intensity has a direct impact because particulate matter (suspended solids) are more easily mobilized during high intensity storms but runoff volume is currently thought to have little effect on pollutant concentrations (but is important in determining total loads to a receiving body) (Barrett et al., 1995).

The first flush phenomenon contends that the vast majority of pollutants from a road surface will wash off during the initial stages of a rainfall event. Therefore, many stormwater treatment systems are designed to remove and treat that initial runoff and thereby reduce concentrations of pollutants (Barrett et al., 1998). The first flush effect is also referred to as the half-inch rule, in which 90% of stormwater pollutants are believed to be washed off in the first half inch of runoff (Young et al., 1996). Some investigators observed that this effect only impacts dissolved constituents. Others report that most of the washoff occurs during the initial stages of runoff before the peak runoff and is strongly correlated with rainfall intensity (Barrett et al., 1995). The first flush effect also is believed to be most pronounced for areas with highly impervious covers (Young et al., 1996). The first flush effect is most prominent during short storms of relatively constant intensity and while most of the reduction in TSS concentrations occurs during the first 5 millimeters (mm) of runoff, the overall effect of the first flush is small or negligible when all storm events are considered (Barrett et al., 1998).

Nutrients also are an important constituent of highway runoff. Nutrients in runoff most likely are found in the dissolved rather than the particulate phases. Folkeson (1994) reported that the nitrogen in runoff is made up of 20% ammonia nitrogen (NH_3), 40% nitrate and nitrite ($NO_3 + NO_2$), and 40% organic nitrogen. Dissolved phosphate makes up 5 to 50% of the phosphorus. Barrett et al. (1995) concluded that the concentrations of nitrate and nitrite do not have a strong correlation with TSS levels. Irish et al. (1998), however, indicate that nitrate and total phosphorus concentrations in runoff are most dependent on ADT during the preceding dry period as well as the duration of that dry period.

Loading of the 5-day biochemical oxygen demand, COD, and oil/grease increase as ADT increases (Irish et al., 1998). Correlations between solids and polycyclic aromatic hydrocarbons (PAHs), total organic carbon (TOC), COD, and extractable organics also have been reported (Barrett et al., 1995). Metals usually adsorb onto particulate matter and are washed from the highway. Lead loadings are significantly correlated with solids while Zn, Fe, Cd, Cu, and Cr loadings are correlated only slightly with solids (Barrett et al., 1995). Irish et al. (1998) indicated that Pb and Cu are influenced by traffic volume during a storm, but that Zn loadings are influenced most by dry period traffic count and runoff characteristics of the preceding storm. A strong correlation was reported between TSS and particulate concentrations of Cu, Cr, and Zn, which indicates that removing particulate matter in highway runoff also will reduce total metals concentrations (Kayhanian, 2001).

Other factors affecting highway pollution runoff include road conditions such as drainage and surface type, surrounding land uses, construction and maintenance activities, and bird and animal droppings on and near road surfaces. Bacterial concentrations in highway runoff usually are less than 1000 colony forming units per 100 milliliters (cfu/100mL), but are often one order of magnitude greater in urban runoff. The source of the bacteria is believed to be of animal origin.

Barrett et al. (1995) concluded that surrounding land use may be a more important indicator in assessing pollutant loads in runoff than the ADT. Salting activities in colder climates increase the solids loadings and have strong correlations with loadings of metals. Highway surface type also can be an important factor in runoff quality. Higher pollutant loadings and concentrations for COD, TOC, Pb, and Zn were found in runoff from asphalt surfaces than from concrete surfaces (Barrett et al., 1995). Worn pavement surfaces usually result in higher pollutant concentrations than newer surfaces (Folkeson, 1994). TSS and oil/grease concentrations and loadings were higher from concrete surfaces in some studies but lower in others (Barrett et al., 1995).

In summary, constituents in highway runoff can be separated into three categories: pollutants that are influenced by dry period conditions and therefore may be mitigated by dry period activities; constituents that are influenced by storm conditions and may be mitigated by runoff controls; and constituents that are influenced equally by dry periods and storms and may be mitigated through a combination of structural runoff controls as well as dry period activities (Irish et al., 1998).

2.4 Effects of Highway Runoff

Sedimentation processes dominate in most receiving water bodies. Therefore pollutant concentrations in the water generally decrease as sedimentation occurs. Heavy metals tend to adsorb onto particulate materials in runoff and these runoff particles can increase turbidity which can then affect photosynthetic processes of the biota (Folkeson, 1994).

Stormwater runoff also can affect the surrounding soil and vegetation. The primary influence of highway runoff on surrounding soil and terrestrial vegetation generally is limited to the area within a few meters of the roadway. Soil and vegetation often show elevated levels of heavy metals close to the roadway and concentrations tend to decrease logarithmically with increasing distance from the road (Folkeson, 1994). Pollutant loads reach relatively low levels within 10-20 meters (m) of the road and background levels are achieved within 200m.

The distribution of particle sizes in the runoff also is important. Large particles will settle faster while fine particles will have lower settling velocities and stay suspended in runoff. Large fractions of heavy metals, TOC, oil/grease, and COD are attached to the solid particles in the runoff and concentrations of these constituents usually are higher in the smaller size fractions (Barrett et al., 1995).

2.5 Vegetative Controls for Highway Runoff

Stormwater runoff is transported along curbsides, pavement, and shoulder areas and most of the associated pollutant load is particulate matter or is adsorbed to suspended solids. Therefore, the most effective means for controlling the quality of runoff is removal of particulate matter from runoff (Barrett et al., 1995). The results of a study of soil, plant, animal, groundwater and surface water samples taken from shoulder and ditch areas along Florida highways indicated that the soil is a major sink for heavy metals in roadside areas. Heavy metals, once retained in the soil, particularly lead, didn't leach downward, and the concentrations of metals in the soil decreased with increasing distance form the edge of pavement (Bell et al., 1979). This phenomenon was confirmed by Wigington et al. (1986). Zinc and cadmium leached from galvanized culverts and had accumulated in surface soils. Concentrations of Zn and Cd did not, however, increase with soil depth (Wigington et al., 1986).

Vegetative controls are common management tools for highway runoff pollution management. Vegetative swales are adaptable to different site conditions and are relatively inexpensive to install and maintain. Swales can be used alone or in combination with other measures such as detention basins, wetlands, or infiltration systems. Sedimentation is the primary removal mechanism in vegetative controls and secondary mechanisms include infiltration and adsorption (Dorman et al., 1996). Vegetative controls are the least expensive technique for managing highway runoff Barrett et al., 1995). Such controls also eliminate the need for curb and gutter systems and removal rates for many constituents are good (on a site-specific basis).

Various types of vegetative controls exist, but the two most important types are grassy swales and buffer/filter strips. Grassy swales are vegetated ditches with gentle slopes that cover large areas of land. Swales encourage settling of suspended solids and do not require curb and gutter systems. TSS removals of 65-70% are reported for some grassy swales (Barrett et al., 1998). Vegetated filter strips conventionally have slopes less than 5%, have permeable natural subsoils, and are most effective as large vegetated areas 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 slow the velocity of runoff, stabilize the slope, and stabilize the accumulated sediment in the root zone of the 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).

Concentrations of total and dissolved metals were lower in monitored swale flows than in highway flows while average concentrations of nitrogen and phosphorus were higher in the swale flows (Yousef et al., 1987). Swales with lower slopes help increase the retention time of runoff and increase the pollutant removal efficiency. Removal efficiency in swales increased with increasing contact time, infiltration rates, and drainage capabilities (Yousef et al., 1987).

TSS removal varied among three grassy swale sites, each with the same length (Dorman et al., 1996). The swale that created the shallowest depth of flow and longest detention times removed the most TSS. Removal of metals also was found to be directly related to TSS removal. The relationship between TSS and metals removal were consistent with settling column results which indicated that 60% of Cu, 90% of Pb, and 50% of Zn was associated with TSS. Nutrient removal varied widely among the sites and did not appear to be related to TSS removal (Dorman et al., 1996).

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 (Kaighn et al., 1996). Pollutants that are associated with larger particles are more easily removed by the vegetated buffer strip. The results of other studies confirmed this trend. Simulated highway runoff was applied to a constructed grass-lined channel and was sampled at 10, 20, 30, and 40 meters along the length of the channel (Walsh et al., 1997). The highest removal efficiencies were observed for suspended solids and metals. The removal of the majority of pollutants occurred within the first 20 meters. Correlations were found between pollutant removal and season: more solids were removed during the growing season than during the dormant season; and nutrients and organic matter removal decreased during the growing season, perhaps as a result of contributions from decaying vegetation (Walsh et al., 1997).

Reported removal efficiencies of pollutants by vegetated buffer strips were 75% for suspended solids and metals, 60-70% for organic compounds, 25-60% for nutrients (N & P), and negative removal for bacteria (Walsh et al., 1997). These results indicate that filter strips may be more effective at treating runoff from relatively small drainage areas such as highways rather than larger, urban areas. 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 (Walsh et al., 1997).

Ellis (1999b) suggested that shallow, broad V-shaped grass troughs (5-8m wide, 9-12% side slopes) may be more appropriate than conventional trapezoidal swale geometry since processes of denitrification and pollutant uptake by plants require shallow percolation and relatively long residence times (Ellis, 1999b; Walsh et al., 1997). Grass channels and filter strips provide little removal of soluble metals, nutrients, and bacteria but perform efficiently for solids, oil/grease, and heavy organics.

Average reductions in TSS of 72% were reported for three 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.

A 130 foot (ft) grassy swale with a check dam was monitored along a highway in Minnesota for TSS, total phosphorus (TP), and ortho-phosphorus (OP). Average pollutant removal rates for the swale were 22% for TP, 42% for OP, and 50% for TSS, respectively (Elfering, 2002). During the subsequent storms, after the installation of a check dam, the average pollutant removal rates were 54% for TP, 47% for OP, and 52% for TSS. These results indicate that the check dam provided little improvement for TSS and ortho-phosphorous but increased the removal rate of total phosphorus from the runoff (Elfering, 2002).

The ability of vegetated slopes adjacent to freeways to remove contaminants from stormwater 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). Regression analyses also showed a strong correlation between total Zn and TSS – confirming that the same processes are responsible for the removal of both constituents (Caltrans, 2003a; Barrett et al., 2004). 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 to have no effect on performance of the filter strips, while vegetation density and slope did have an effect. The two steepest sites outperformed the flatter sites; some sites with less vegetation density outperformed sites with higher vegetation density. 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 asses the expected performance of vegetated BMPs in different regions of the country since precipitation patterns, soil structures, and road cross-sections vary be 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.

CHAPTER 3 MATERIALS AND METHODS

3.1 SITE DESCRIPTIONS

3.1.1 General

This study was conducted at three sampling sites in Austin, Texas. Several factors and preferences were taken into account in order to ensure that the selected sites were representative of this particular region of the state. Area highways with rural type cross sections were evaluated based on their slope, soil type, and vegetation characteristics.

Site Selection Criteria:

- Location: Vegetated shoulder areas adjacent to city of Austin highways 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 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

Three sites on Loop 360 were selected for this study. A map indicating the locations of the three sites is presented in Figure 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.

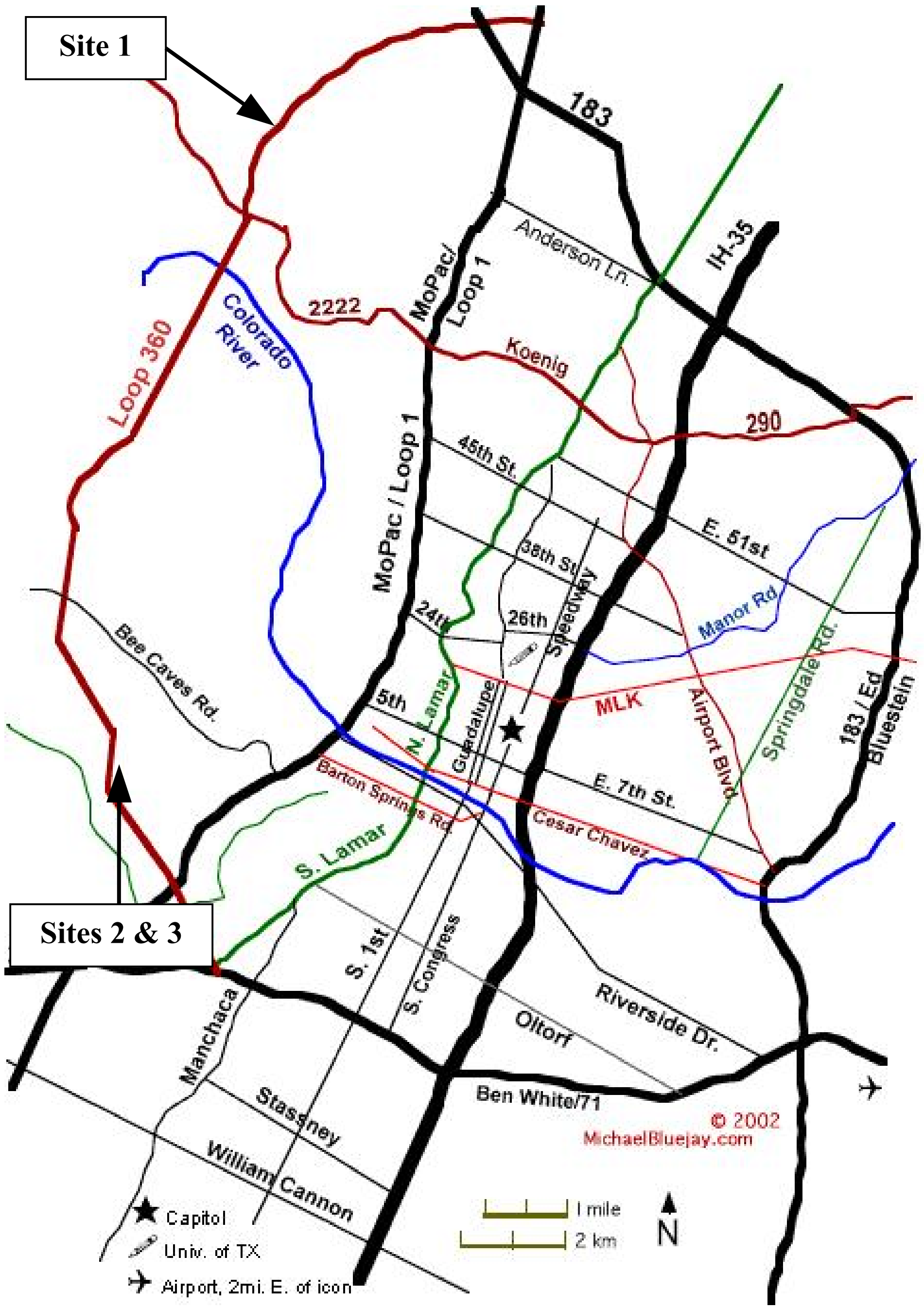

Figure 1 Map of Austin showing Loop 360 and location of 3 research sites

3.1.2 Site 1 - Loop 360 North of FM 2222

Site 1 is located at 7600 North Loop 360 near the intersection with Lakewood Avenue, north of FM 2222. The site is adjacent to the southbound lanes of the highway and is directly in front of a commercial office complex. The office complex parking lot helps ensure the safety of the researchers while working at the site. The slope of the grassy shoulder is 1:8.3 (12%) and has ample room to accommodate all sampling equipment. 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). 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 82.55%, with a range of 57.64% near the road edge to 93.77% 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. Aerial and site photographs of Site 1 are presented in Figure 2.

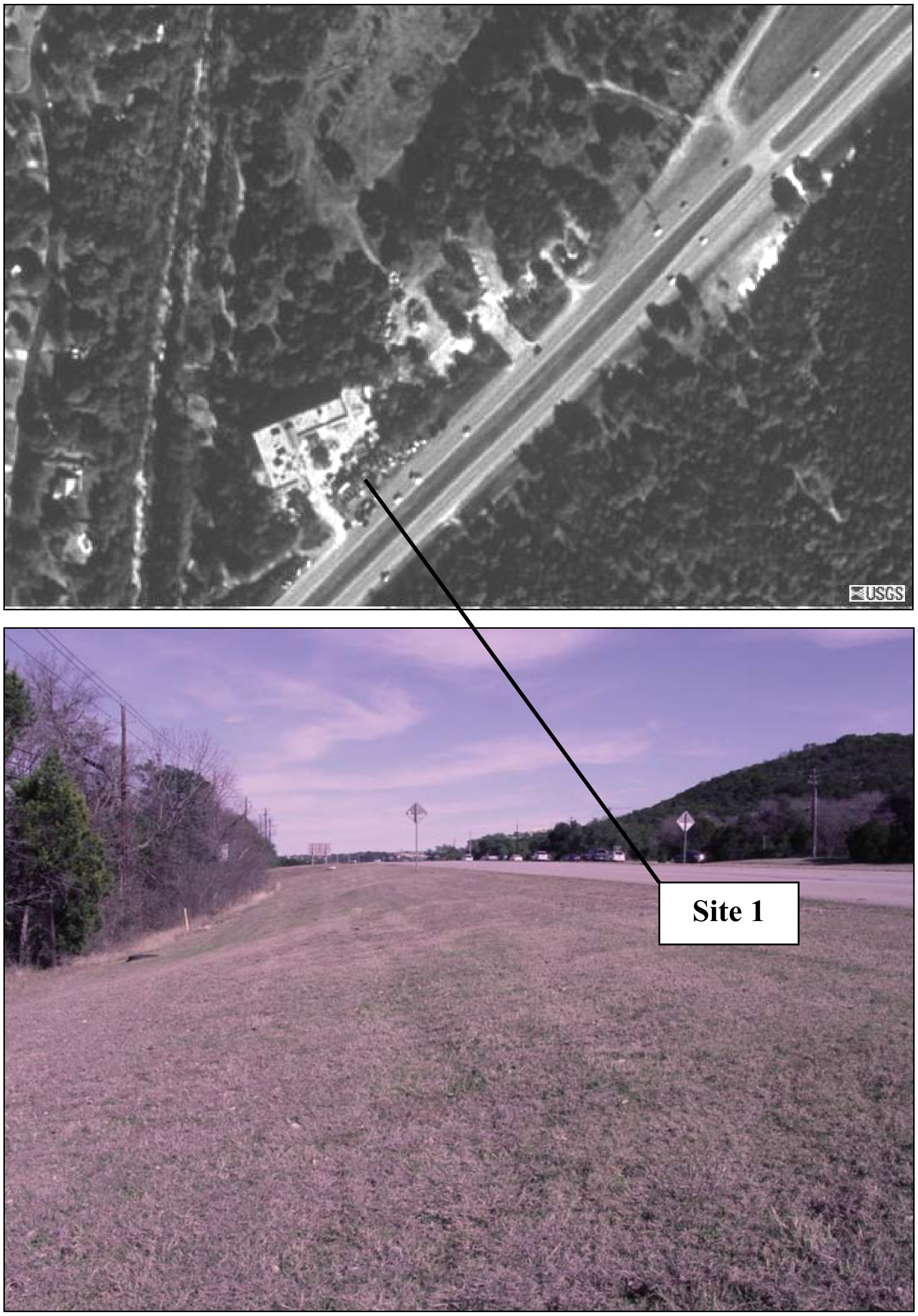

Figure 2 Aerial and site photographs of Site 1 (Aerial photograph: USGS, 2004)

3.1.3 Sites 2 and 3 - Loop 360 North of Mopac

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). Sites 2 and 3 where 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 96.97% 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 3.

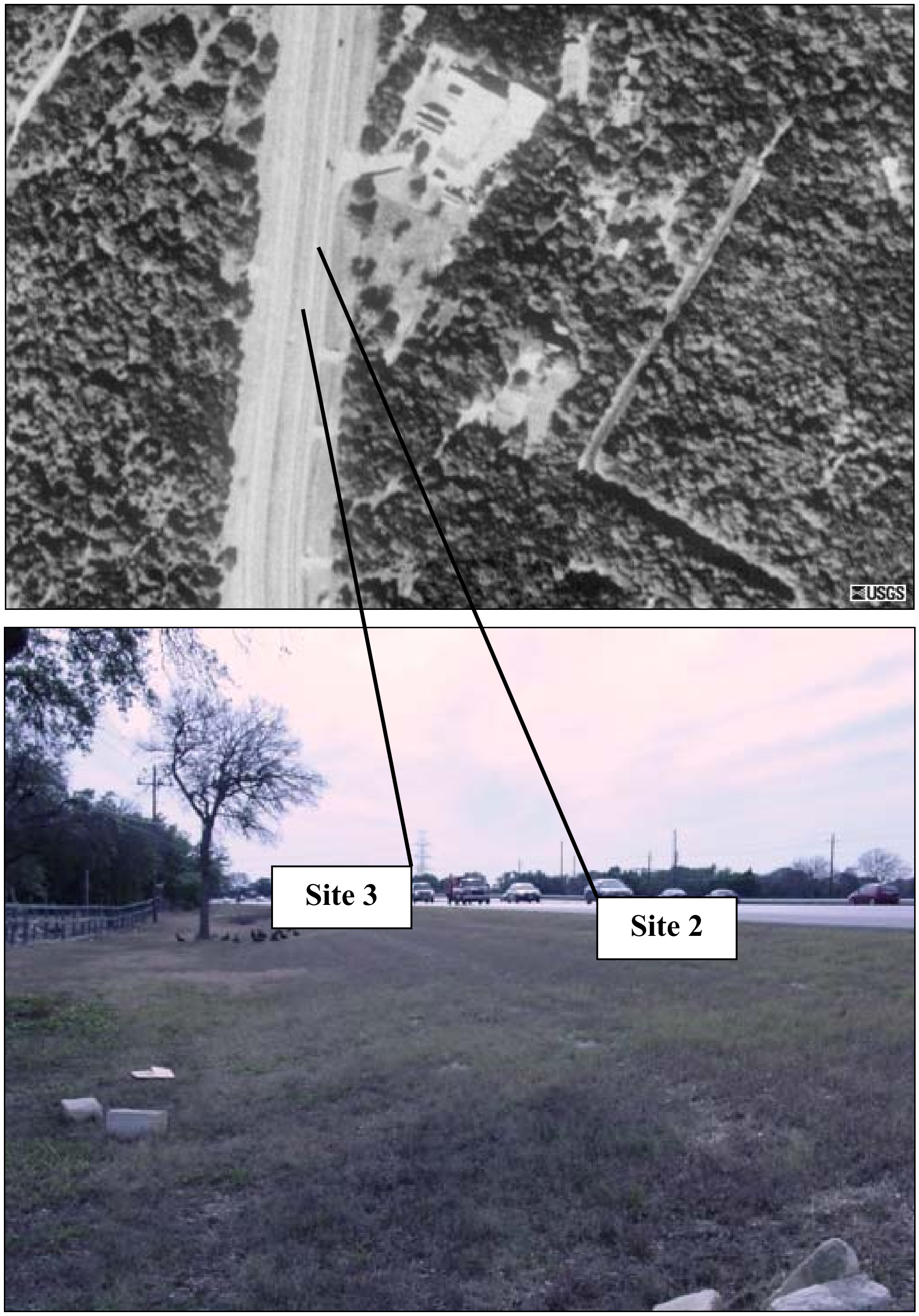

Figure 3 Aerial and site photographs of Sites 2 and 3 (Aerial photograph: USGS, 2004)

3.1.4 Site 1, Permeable Friction Course Overlay

The specific location for Site 1 was also chosen because of 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 implemented a porous asphalt overlay project, known as a permeable friction course (PFC), on a section of Highway 360 which included Site 1. The overlay project included the application of a layer of porous asphalt on top of the existing road bed.

Interest in the use of porous pavements is growing due to their potential to be effective runoff control methods. Porous asphalt is an alternative to traditional asphalt which is created by eliminating the fine aggregate from the asphalt mix. As an overlay, a layer of porous asphalt approximately 2 inches thick is placed on top of an existing road base. The asphalt in an overlay layer generally has 15-20% void space. When rainfall hits the friction course, it drains through the PFC until it hits the impervious road bed at which point it will drain away from the road just as with traditional road surfaces. The volume of surface runoff and the amount of spray created during rain events are greatly reduced as a result of the semi-permeable nature of this surface. This suppression of spray improves visibility and increases the level of safety for motorists. The PFC also provides a reduction in the noise level produced by vehicles on the road.

Porous pavements can reduce the amount of surface water runoff generated and can provide water quality benefits such as reductions in small sediments, nutrients, organic matter, and trace metals (Young et al., 1996). Early studies recommended that porous pavements only be used in low traffic volume areas as higher traffic volumes could lead to premature clogging. Asphalt overlays, however, are increasingly being used by many state transportation departments. Young et al. (1996) cite the removal rates of various pollutants from a study conducted by Schueler in 1987 at two sites with full porous pavement constructions (including a high-void aggregate sub-base):

Pollutant	Removal Rate (%)
Sediment	82-95
Total Phosphorus	65
Total Nitrogen	80-85
Chemical Oxygen Demand	82
Zinc	99
Lead	98

While not an initial objective of this project, the scheduled change in road surface at Site 1 during the sampling period provided an ideal opportunity to compare the runoff quality from the two surfaces and the associated performance of the vegetated filter strip at the site.

3.2 SITE SETUP

3.2.1 Preparation

Each site was photographed and measured prior to installation of the collection and sampling systems. Placement of pipes and samplers were determined according to the schematic presented in Figure 4 and marked with spray paint and landscaping flags. Appropriate notification of installation at each site was provided to the adjacent commercial complexes.

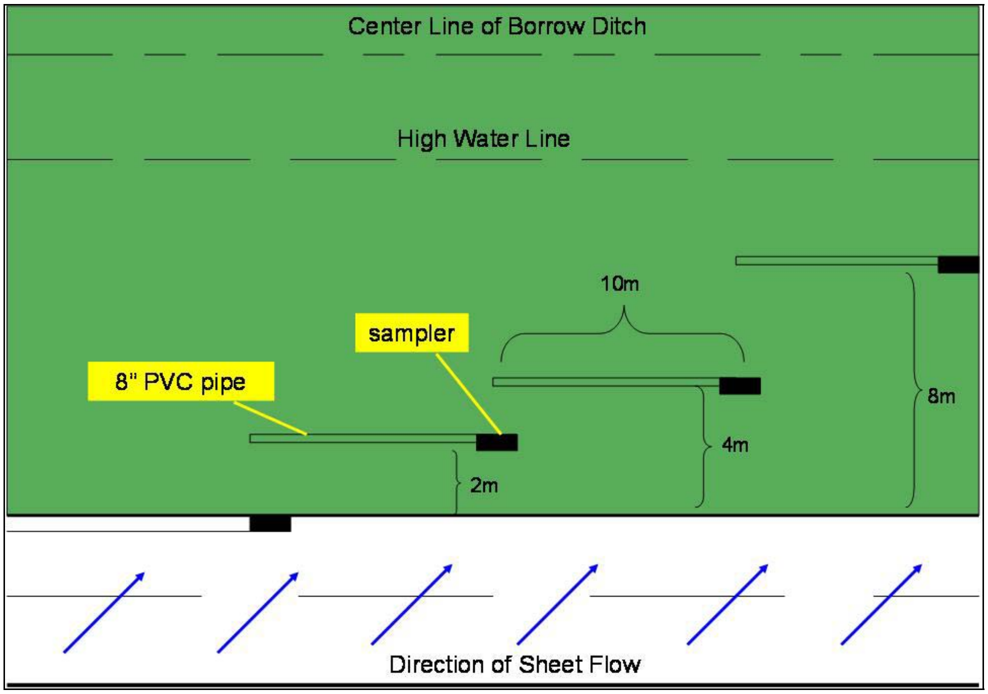

Figure 4 Schematic diagram of site layout (not to scale)

3.2.2 Installation

A series of runoff collection and sampling systems were installed at each site in early February 2004. 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 5. The 1-inch layer of bio-solids compost was applied to Site 3 by researchers shortly after the installation of the collection and sampling systems. Volumetric rain gauges also were installed at each research site.

Figure 5 Photograph of installed collection pipe at 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 6 shows a diagram of the GKY sampler and its components.

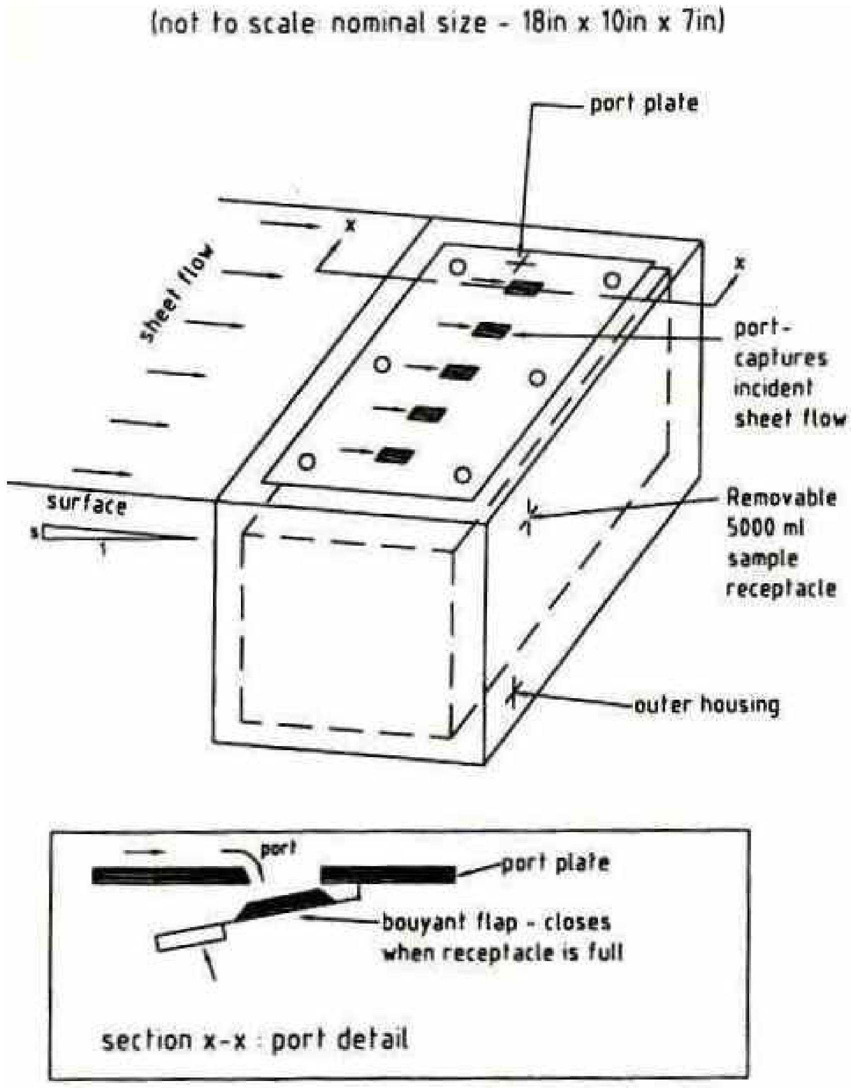

Figure 6 GKY First Flush Sampler (GKY, 2005)

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. A photograph of an installed sampler at the edge of pavement is shown in Figure 7.

Figure 7 Photograph of installed sampler at the edge of pavement at Site 1

3.2.3 Pre-sampling and Maintenance

A large quantity of dirt and grass was dug up and disturbed during the installation processes 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. Mowing occurred three to four times a year at each site, mostly during the wet summer months, but also occasionally during the drier months. Sites were mowed in early May, July, September, and late December 2004. Standard mowing practices for highway shoulders are limited to cutting only and not 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, except perhaps for adding to the TSS levels in the collected runoff.

3.3 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 collected 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.

3.4 Analytical Procedures

All runoff samples were transported to Environmental Laboratory Services, a division of the Lower Colorado River Authority (LCRA), for analysis. The LCRA's 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. 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 1.

Table 1 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 6)	µg/L	SW8270C	varies

3.5 Statistical Analysis

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. It was immediately obvious that the results from the first storm sampled were much higher than any subsequent set of samples. This is believed to be due to lingering disturbances to the soil and vegetation at the research sites that resulted from the installation processes. The data from this storm were therefore excluded from final analyses on the basis of them being uncharacteristic of true site and sampling conditions.

In an effort to preserve the integrity of an already small data set, very few additional data points were excluded from the final analyses. The three points that were excluded are:

- TKN, Site 3, 4m sampler, 10/25/2004 rain event
- Total Pb, Site 3, 0m sampler, 11/22/2004 rain event
- COD, Site 3, 4m sampler, 10/25, 2004 rain event

These points were excluded because their values were more than three to four times the closest value reported in that range, which clearly indicates they were outliers.

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.

CHAPTER 4: RESULTS AND ANALYSIS

4.1 RAINFALL AND SAMPLE COLLECTION RECORDS

Over the course of the 14-month study period, a total of 13 storms were successfully sampled, 10 at Site 1 and 13 at sites 2 and 3. Dates on which runoff samples were collected and the corresponding rainfall amounts at each research site are presented in Table 2. It should be noted that sample collection dates are usually one day later than the actual rainfall event dates. The primary reason for fewer storms having been sampled from Site 1 is that sampling activities were halted during the PFC construction project conducted by TxDOT crews in the late summer and fall of 2004. Additionally, the rain event of March 24/25, 2004 produced extremely localized rainfall which did not lead to enough runoff volume at Site 1 to adequately fill any of the samplers.

Table 2 Rainfall Volumes and Sample Collection Dates

	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

4.2 ANALYTICAL METHODS

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 makes monitoring with passive stormwater samplers complicated. 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 lead to difficulty in understanding and 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 difference 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; however 0.1 was used in this study because of the limited number of storms.

4.3 Analytical Results

As mentioned in Chapter 3, the data from each sampled storm event were qualitatively inspected upon receipt from the laboratory. Initial plots of the data were created to generate an idea of general trends. Data sets 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 are presented in Tables 3, 4, and 5.

Concentrations which were not detected at a parameter's reporting limit are indicated in the tables as "ND". After comparing the data from the first storm sampled (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 tables.

Table 3 EMCs for all storm events monitored at Site 1

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved P (mg/L)				Total Copper (µg/L)				Dissolved Copper (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	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	84	81.3	10.5	6.17	10.5	20.2	4.14	4.09
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	23.9	44.3	7.22	6.73	9.88	7.98	4.15	3.89
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	16.9	20.7	10.2	9.14	5.24	6.62	4.52	5.85
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	28.4	9.28	4.37	5.62	2.06	5.1	2.3	3.71
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	29.7	28	27.2	7.99	9.32	19.7	20.5	5.02
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	35.3	5.0	2.98	3.6	3.18	2.75	2.16	2.66
11/15/2004 ^	9	‡	19	‡	0.863	‡	1.52	‡	0.728	‡	0.494	‡	0.029	‡	0.328	‡	0.04	‡	0.23	‡	11.1	‡	11	‡	8.84	‡	9.78	‡
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	2.94	3.57	3.65	3.83	2.26	1.97	1.47	2.63
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	6.13	19.6	5.53	4.78	2.73	13.1	2.26	3.43
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	2.8	4.29	3.17	4.03	1.94	2.62	1.6	2.86

	Total Lead (µg/L)				Dissolved Lead (µg/L)				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	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	34.8	30.6	6.8	1.7	ND	ND	ND	ND	389	417	261	52.8	28.2	67.1	127	34.2	302	345	58	61	240	440	20	40
3/1/2004	6.17	18.1	3.03	2.13	ND	ND	ND	ND	207	204	156	52.7	95.1	39.2	110	36.5	72	119	48	47	†	†	†	†
4/12/2004	7.56	7.61	3.71	1.69	ND	ND	ND	ND	101	95.8	83.6	51.1	45.4	40.9	45.7	72.6	29	49	42	52	†	†	†	†
5/14/2004	15	1.4	1.29	ND	ND	ND	ND	ND	157	52.8	123	116	7.5	42.1	92.9	95.6	65	30	37	51	240	3000	1130	7000
6/3/2004	9.93	3.39	2.61	2.01	ND	ND	1.11	ND	163	175	385	243	46.3	142	335	223	84	176	213	83	100	0	137000	9200
6/9/2004	24.2	2.2	ND	ND	ND	ND	ND	ND	209	46.5	42.9	49.3	41	45.6	39	43.4	70	12	15	36	†	†	†	†
11/15/2004 ^	1.54	‡	1.27	‡	ND	‡	ND	‡	58.5	‡	243	‡	47.2	‡	207	‡	77	‡	98	‡	†	‡	†	‡
11/22/2004 ^	ND	1.15	2.11	1.57	ND	ND	ND	ND	26.7	45	237	228	20.3	61.7	181	175	13	10	24	63	†	†	†	†
1/28/2005 ^	1.14	1.57	1.79	ND	ND	ND	ND	ND	54	85.4	183	356	43.1	67	109	291	22	122	32	49	†	†	†	†
3/3/2005 ^	ND	1.18	ND	ND	ND	ND	ND	ND	41.1	61	214	261	24.4	41.1	166	210	10	30	22	32	†	†	†	†

(shaded) 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 4 EMCs for all storm events monitored at Site 2

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)				Total Copper (µg/L)				Dissolved Copper (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	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	52.6	39.8	17.9	8.63	9.51	1.42	1.38	1.32
3/1/2004	52	54	‡	‡	0.962	1.43	‡	‡	0.52	0.43	‡	‡	0.08	0.14	‡	‡	ND	0.02	‡	‡	19.9	12.1	‡	‡	7.41	5.5	‡	‡
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	17.2	8.48	10.6	5.02	8.33	4.61	4.31	3.14
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	19.7	11	10.5	2.35	8.35	3.86	5.45	1.57
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	18.7	7.25	7.58	3.02	3.61	3.91	5.32	2.13
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	9.99	8.49	8.81	5.92	5.15	5.61	5.91	1.68
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	18.6	2.67	3.16	2.18	2.97	1.79	2.66	1.77
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	15	25.4	23.3	3.26	5.3	9.17	8.31	2.04
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	28.2	3.85	4.2	3.3	3.24	2.6	3.23	2.48
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	‡	20.3	7.1	6.92	‡	7.81	7.45	3.34	‡
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	42.6	9.03	3	2.29	3.66	1.31	2.52	1.68
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	31.5	‡	4.29	3.36	3.61	‡	3.36	2.21
3/3/2005	53	‡	‡	7	1.75	‡	‡	1.03	1.476	‡	‡	0.2635	0.071	‡	‡	0.093	0.046	‡	‡	0.101	18.7	‡	‡	ND	7.18	‡	‡	1.4

	Total Lead (µg/L)				Dissolved Lead (µg/L)				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	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	33.7	160	121	13.9	ND	1.43	ND	ND	279	317	315	205	38.4	23.3	33.9	43.7	221	387	282	92	0	60	60	60
3/1/2004	7.85	12.6	‡	‡	ND	1.46	‡	‡	124	148	‡	‡	48.9	88.5	‡	‡	84	70	‡	‡	†	†	‡	‡
3/26/2004	6.31	22.4	35.5	3.81	ND	2.3	1.89	ND	125	133	238	190	68.7	77.8	88.4	121	111	71	123	77	†	†	†	†
4/12/2004	6.6	19.6	17.6	1.56	ND	2.36	2.2	ND	106	326	139	289	59.2	215	79	246	87	58	73	29	†	†	†	†
5/14/2004	8.61	3.63	3.91	1.42	ND	ND	ND	ND	107	137	210	160	39.7	115	171	131	68	45	71	44	1500	5000	860	1270
6/3/2004	3.11	6.27	6.86	3.94	ND	2.02	1.22	ND	82.2	141	173	825	54	132	129	388	53	86	115	34	35000	152000	0	40
6/9/2004	12.9	2.76	4.5	ND	ND	ND	ND	ND	118	74	90	91.3	44.7	75.2	64.6	90.6	98	19	27	26	†	†	†	†
10/25/2004	4.62	5.86	7.13	ND	ND	1.15	ND	ND	180	383	821	458	110	293	650	395	46	216	286	45	†	†	†	†
11/1/2004	12.5	1.9	1.69	ND	ND	ND	ND	ND	199	105	393	280	47.4	89.7	340	256	89	39	61	69	3360	31000	143000	15000
11/15/2004	12.3	4.01	4.79	‡	ND	ND	ND	‡	129	439	612	‡	44.5	386	511	‡	48	51	49	‡	†	†	†	‡
11/22/2004	26.2	23.2	ND	2.47	ND	ND	ND	ND	229	96.7	52.7	81.6	21.4	34.8	54.6	58.6	130	29	15	19	†	†	†	†
1/28/2005	12.2	‡	3.35	ND	ND	‡	ND	ND	192	‡	134	397	16	‡	98.4	318	96	‡	35	29	†	‡	†	†
3/3/2005	4.66	‡	‡	ND	ND	‡	‡	ND	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 5 EMCs for all storm events monitored at Site 3

	Total Suspended Solids (mg/L)				Total Kjeldahl Nitrogen (mg/L)				Nitrate & Nitrite (mg/L)				Total Phosphorus (mg/L)				Dissolved Phosphorus (mg/L)				Total Copper (µg/L)				Dissolved Copper (µg/L)			
	0m	2m	4m	8m	0m	2m	4m	8m	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	61.7	‡	252	181	7.59	‡	15.1	17.6
3/1/2004	‡	‡	‡	54	‡	‡	‡	1.27	‡	‡	‡	0.58	‡	‡	‡	0.41	‡	‡	‡	0.32	‡	‡	‡	9.06	‡	‡	‡	4.06
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	19.7	13.5	14.2	22.5	5.1	7.84	10.2	14.6
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	28.9	19.8	6.34	4.08	10.2	9.49	4.42	2.06
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	12.3	9.88	11.2	6.11	3.17	7.04	5.76	4.06
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	16.8	17.7	12.7	4.37	7.47	12.7	10.4	2.77
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	19	4.83	9.06	13.3	2.23	3.09	7.55	10
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	28.7	8.31	32.3	11.6	6.36	3.95	7.91	2.89
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	35.8	5.3	8.52	6.14	5.65	2.83	6.48	4.58
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	24.6	6.48	8.01	4.18	5.17	4.04	5.17	3.25
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	62.2	5.24	5.2	5.81	3.42	1.76	2.63	4.41
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	48	8.75	9.1	3.42	4.12	4.95	5.88	2.64
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	‡	31.2	4.32	6.19	‡	3.35	2.31	3.75	‡

	Total Lead (µg/L)				Dissolved Lead (µg/L)				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	0m	2m	4m	8m	0m	2m	4m	8m
2/24/2004	33.3	‡	101	37.3	ND	‡	ND	ND	360	‡	810	782	43.1	‡	24.3	61.6	124	‡	579	636	0	‡	1200	200
3/1/2004	‡	‡	‡	2.46	‡	‡	‡	1.22	‡	‡	‡	343	‡	‡	‡	206	‡	‡	‡	31	‡	‡	‡	†
3/26/2004	9.98	28.6	8.14	6.81	ND	3.82	ND	ND	133	216	250	452	39.1	175	187	317	97	62	64	128	†	†	†	†
4/12/2004	11.2	26.6	2.7	2.1	ND	2.63	ND	ND	185	333	495	312	68	211	450	239	133	68	34	25	†	†	†	†
5/14/2004	5.45	3.7	3.01	ND	ND	ND	ND	ND	67.7	154	492	985	40	147	402	927	42	47	64	45	580	4000	30000	2000
6/3/2004	4.8	3.78	0	ND	ND	1.04	ND	ND	93.6	218	354	516	50.5	187	346	451	77	107	74	45	2700	0	12000	30
6/9/2004	11.6	2.84	3.08	2.58	ND	ND	ND	ND	115	52.3	111	314	48	53.7	100	190	57	15	34	63	†	†	†	†
10/25/2004	9.44	3	7.45	1.3	ND	ND	ND	ND	216	338	446	402	88.5	242	318	333	88	50	351 *	149	†	†	†	†
11/1/2004	16	4.56	1.52	ND	ND	ND	ND	ND	232	295	271	290	52.8	227	237	249	114	46	72	52	7000	10000	197000	4000
11/15/2004	14.7	5.46	2.71	ND	ND	ND	ND	ND	147	659	253	788	60.3	553	200	652	72	35	37	80	†	†	†	†
11/22/2004	46.5 *	8.28	5.58	1.76	ND	ND	ND	ND	307	91.8	68.2	116	29.7	56	35.1	74.8	160	11	23	27	†	†	†	†
1/28/2005	18.4	4.3	1.92	ND	ND	ND	ND	ND	272	317	408	853	46.8	253	354	738	157	36	46	47	†	†	†	†
3/3/2005	13.8	2.27	2.88	‡	ND	ND	ND	‡	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
* outliers, excluded from final analyses
ND not detected at reporting limit

Three additional data points were eliminated from the final 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 Table 5.

There are a total of 1472 data points 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. PAHs were monitored during 5 storm events, three off of traditional asphalt surfaces and two at Site 1 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 6. Results for all constituents that make up this suite of semi-volatile organics were below detection limits for all monitored events.

Table 6 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

4.4 SUMMARY STATISTICS

Tables 7-10 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 color coded to indicate whether the observed concentrations at specified distances from the edge of pavement exhibit statistically significant increases (shown in red) or decreases (shown in green) in concentration. Constituents with no colored cells indicate that no statistically significant changes in concentration occurred for that constituent across the width of the vegetated filter strip. Rows with a colored 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 colored 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 green 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. Select boxplots are presented on the following pages that illustrate some of the trends seen at the research sites. The entire set of plots for each site can be found in Appendix B.

4.4.1 Summary Statistics - Site 1, Conventional Pavement

The summary statistics for rainfall events monitored at Site 1 from the older, traditional asphalt surface are presented in Table 7. TSS was found to significantly decrease over the width of the vegetated area, as indicated by the green 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 8 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.

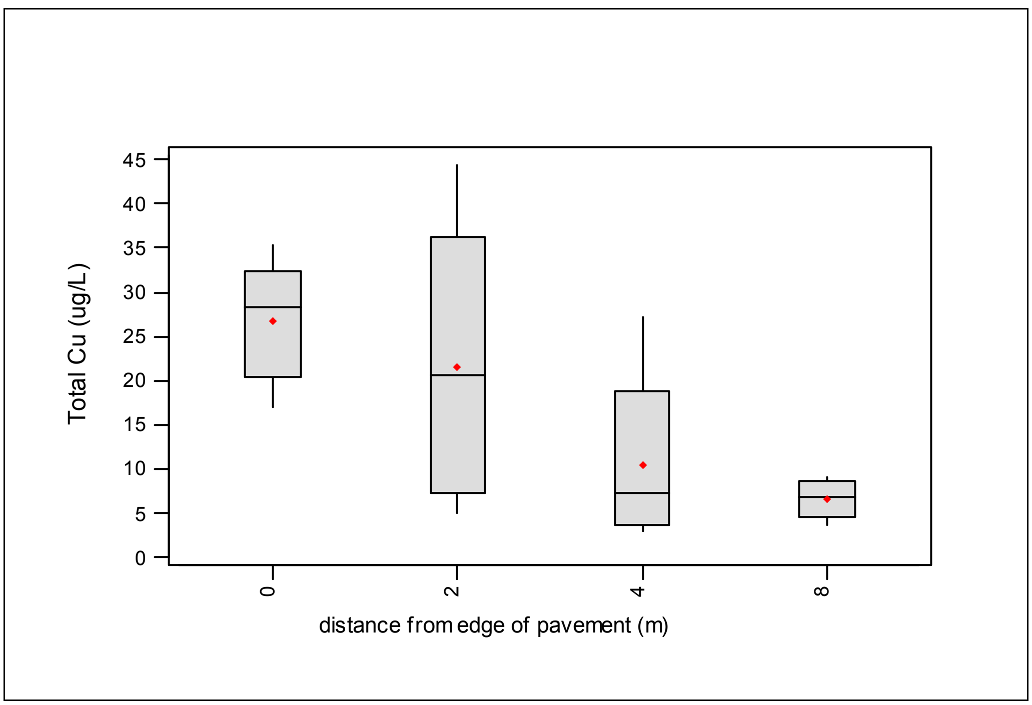

Figure 8 Boxplot of Total Copper EMCs at Site 1, old asphalt surface

Table 7 Summary Statistics for Site 1, traditional asphalt pavement

Constituent	EOP mean range std. dev.	2m mean range std. dev.	4m mean range std. dev.	8m mean range std. dev.
TSS (mg/L)	118 44 - 330 61	121 14 - 330 137	60 4 - 102 36	42 17 - 68 21
TKN (mg/L)	1.13 0.7 - 1.5 0.31	1.86 0.4 - 2.6 0.86	2.39 0.4 - 5.4 1.81	2.15 1.1 - 3.7 1.02
NO3/NO2-N (mg/L)	0.43 0.1 - 1.4 0.55	0.25 0.0 - 0.5 0.19	0.36 0.0 - 0.9 0.38	0.27 0.1 - 0.5 0.16
Total P (mg/L)	0.13 0.1 - 0.2 0.05	0.19 0.1 - 0.3 0.10	0.32 0.1 - 0.9 0.32	0.29 0.1 - 0.6 0.22
Dissolved P (mg/L)	0.04 0.0 - 0.1 0.04	0.10 0.0 - 0.2 0.09	0.18 0.1 - 0.6 0.23	0.18 0.0 - 0.4 0.17
Total Cu (µg/L)	26.84 16.9 - 35.3 6.89	21.46 5.0 - 44.3 15.69	10.39 3.0 - 27.2 9.80	6.62 3.6 - 9.1 2.14
Total Pb (µg/L)	12.57 6.2 - 24.2 7.32	6.54 1.4 - 18.1 6.89	2.13 0.0 - 3.7 1.48	1.17 0.0 - 2.1 1.08
Total Zn (µg/L)	167.40 101.0 - 209.0 44.26	114.82 46.5 - 204.0 71.50	158.10 42.9 - 385.0 133.74	102.42 49.3 - 243.0 83.48
Dissolved Cu (µg/L)	5.94 2.1 - 9.9 3.54	8.43 2.8 - 19.7 6.59	6.73 2.2 - 20.5 7.77	4.23 2.7 - 5.9 1.23
Dissolved Pb (µg/L)	0.00 none 0.00	0.00 none 0.00	0.22 0.0 - 1.1 0.50	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	124.52 39.0 - 335.0 121.49	94.22 36.5 - 223.0 75.78
COD (mg/L)	64.0 29.0 - 84.0 20.8	77.2 12.0 - 176.0 68.5	71.0 15.0 - 213.0 80.4	53.8 36.0 - 83.0 17.5

4.4.2 Summary Statistics for Site 1 - Porous Asphalt Surface

The summary statistics for rainfall events monitored at Site 1 from the new, PFC overlay surface are presented in Table 8. 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. The effects of the PFC and its resulting runoff quality will be discussed in Section 4.6. 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 9 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 and will be addressed more completely in Section 4.8.

Table 8 Summary Statistics for Site 1, porous asphalt pavement

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	32 13 - 52 19	25 14 - 46 18
TKN (mg/L)	0.55 0.4 - 0.9 0.21	1.03 0.5 - 2.1 0.92	0.95 0.6 - 1.5 0.42	1.65 1.3 - 2.0 0.34
NO3/NO2-N (mg/L)	0.40 0.2 - 0.7 0.22	0.32 0.1 - 0.7 0.30	0.16 0.0 - 0.5 0.23	0.16 0.1 - 0.3 0.13
Total P (mg/L)	0.23 0.0 - 0.5 0.26	0.05 0.0 - 0.1 0.01	0.22 0.1 - 0.4 0.14	0.14 0.1 - 0.2 0.07
Dissolved P (mg/L)	0.08 0.0 - 0.3 0.13	0.13 0.0 - 0.0 0.01	0.18 0.0 - 0.2 0.11	0.06 0.0 - 0.1 0.03
Total Cu (µg/L)	5.74 2.8 - 11.1 3.89	9.15 3.6 - 19.6 9.05	5.84 3.2 - 11.0 3.59	4.21 3.8 - 4.8 0.50
Total Pb (µg/L)	0.67 0.0 - 1.5 0.79	1.30 1.2 - 1.6 0.23	1.29 0.0 - 2.1 0.93	0.52 0.0 - 1.6 0.91
Total Zn (µg/L)	45.08 26.7 - 58.5 14.30	63.80 45.0 - 85.4 20.35	219.25 183.0 - 243.0 27.21	281.67 228.0 - 356.0 66.46
Dissolved Cu (µg/L)	3.94 1.9 - 8.8 3.28	5.90 2.0 - 13.1 6.25	3.78 1.5 - 9.8 4.02	2.97 2.6 - 3.4 0.41
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	165.75 109.0 - 207.0 41.45	225.33 175.0 - 291.0 59.50
COD (mg/L)	30.5 10.0 - 77.0 31.4	54.0 10.0 - 122.0 59.7	44.0 22.0 - 98.0 36.3	48.0 32.0 - 63.0 15.5

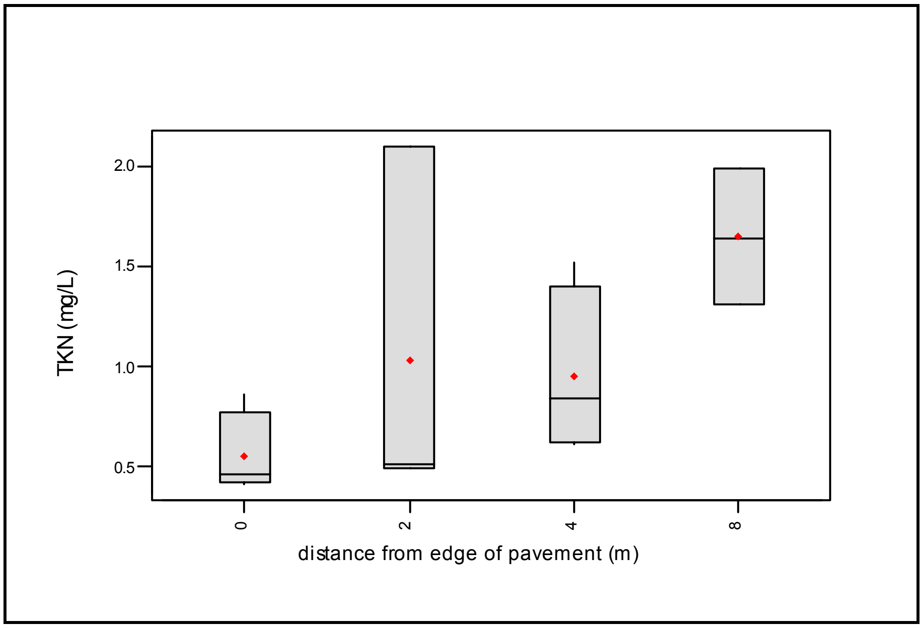

Figure 9 Boxplot of Total Kjeldahl Nitrogen at Site 1 from the PFC surface

4.4.3 Summary Statistics - Site 2

The summary statistics for rainfall events monitored at Site 2 are presented in Table 9. 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 10 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 9 Summary Statistics for 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	71 15 - 275 88	39 7 - 185 53
TKN (mg/L)	1.5 0.6 - 2.3 0.6	1.7 0.8 - 4.6 1.1	2.5 0.8 - 6.9 1.8	1.6 0.9 - 3.7 0.8
NO3/NO2-N (mg/L)	0.34 0.0 - 1.5 0.39	0.18 0.0 - 0.4 0.15	0.33 0.0 - 0.7 0.22	0.46 0.0 - 1.8 0.55
Total P (mg/L)	0.13 0.1 - 0.2 0.06	0.24 0.1 - 0.7 0.19	0.35 0.0 - 1.0 0.29	0.29 0.1 - 0.5 0.16
Dissolved P (mg/L)	0.05 0.0 - 0.1 0.03	0.13 0.0 - 0.4 0.14	0.18 0.0 - 0.5 0.17	0.16 0.1 - 0.3 0.09
Total Cu (µg/L)	21.70 10.0 - 42.6 8.60	9.54 2.7 - 25.4 6.27	8.24 3.0 - 23.3 6.01	3.07 0.0 - 5.9 1.61
Total Pb (µg/L)	9.82 3.1 - 26.2 6.20	10.22 1.9 - 23.2 8.51	8.53 0.0 - 35.5 10.61	1.32 0.0 - 3.9 1.60
Total Zn (µg/L)	140.09 82.2 - 229.0 47.57	198.27 74.0 - 439.0 131.94	286.27 52.7 - 821.0 249.97	290.09 81.6 - 825.0 226.50
Dissolved Cu (µg/L)	5.55 3.0 - 8.4 2.13	4.58 1.3 - 9.2 2.46	4.44 2.5 - 8.3 1.81	2.01 1.4 - 3.1 0.52
Dissolved Pb (µg/L)	0.00 none 0.00	0.93 0.0 - 2.4 1.04	0.53 0.0 - 2.2 0.89	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	218.60 54.6 - 650.0 210.33	209.34 58.6 - 395.0 127.76
COD (mg/L)	80.9 46.0 - 130.0 26.3	68.4 19.0 - 216.0 55.7	85.5 15.0 - 286.0 78.7	39.9 19.0 - 77.0 19.2

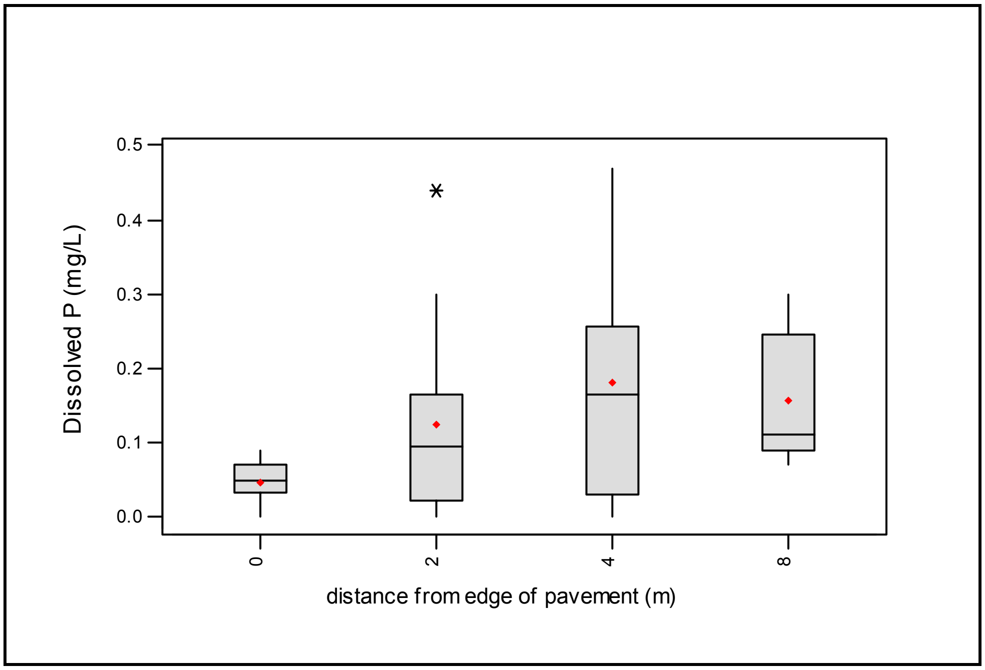

Figure 10 Boxplot of Dissolved Phosphorus at Site 2

4.4.4 Summary Statistics - Site 3

The summary statistics for the rainfall events monitored at Site 3 are presented in Table 10. 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 everywhere over the site. A boxplot demonstrating the changes in COD concentrations is provided in Figure 11. Increases in total and dissolved phosphorus are similar to those observed at Site 2 and exhibit significant changes everywhere over the research area. 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 10 Summary Statistics for 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	40 14 - 150 38	50 13 - 230 63
TKN (mg/L)	1.76 0.8 - 3.4 0.81	1.77 0.6 - 3.5 0.99	1.72 0.5 - 3.1 0.93	2.40 0.4 - 6.0 1.87
NO3/NO2-N (mg/L)	0.22 0.0 - 0.7 0.17	0.27 0.0 - 0.7 0.25	0.56 0.0 - 1.7 0.56	0.72 0.0 - 4.9 1.41
Total P (mg/L)	0.28 0.1 - 0.9 0.22	0.79 0.2 - 1.7 0.42	1.21 0.4 - 3.4 0.78	0.88 0.3 - 2.0 0.57
Dissolved P (mg/L)	0.09 0.0 - 0.2 0.05	0.63 0.1 - 1.5 0.35	1.06 0.3 - 2.9 0.66	0.72 0.1 - 1.6 0.49
Total Cu (µg/L)	29.75 12.3 - 62.2 14.64	9.46 4.3 - 19.8 5.34	11.17 5.2 - 32.3 7.53	8.23 3.4 - 22.5 5.73
Total Pb (µg/L)	11.54 4.8 - 18.4 4.37	8.49 2.3 - 28.6 9.59	3.54 0.0 - 8.1 2.49	1.55 0.0 - 6.8 2.05
Total Zn (µg/L)	175.48 67.7 - 307.0 75.04	281.92 52.3 - 659.0 168.54	324.93 68.2 - 495.0 146.57	488.27 116.0 - 985.0 271.95
Dissolved Cu (µg/L)	5.11 2.2 - 10.2 2.29	5.45 1.8 - 12.7 3.43	6.38 2.6 - 10.4 2.48	5.03 2.1 - 14.6 3.82
Dissolved Pb (µg/L)	0.00 none 0.00	0.68 0.0 - 3.8 1.32	0.00 none 0.00	0.11 0.0 - 1.2 0.37
Dissolved Zn (µg/L)	50.15 28.0 - 88.5 17.46	220.52 53.7 - 553.0 136.30	265.92 35.1 - 450.0 127.44	397.89 74.8 - 927.0 265.64
COD (mg/L)	99.5 42.0 - 160.0 38.5	45.8 11.0 - 107.0 26.9	48.1 23.0 - 74.0 18.7	62.9 25.0 - 149.0 40.9

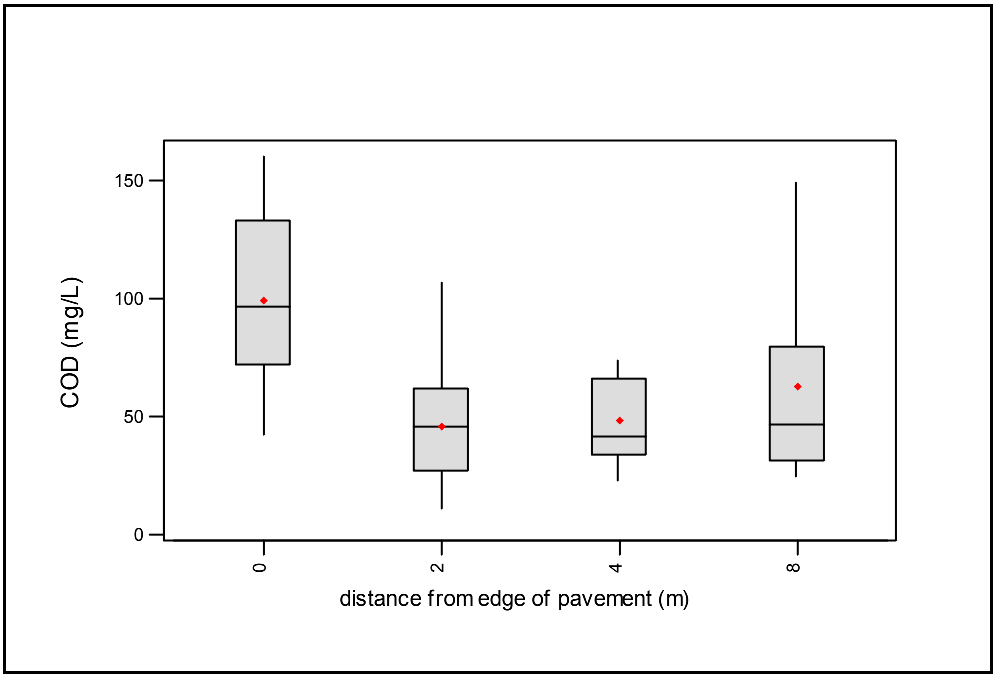

Figure 11 Boxplot of Chemical Oxygen Demand at Site 3

4.5 COMPARISON OF EDGE OF PAVEMENT CONCENTRATIONS

One of the site selection parameters for this project was an ADT of at least 35,000. This high traffic volume was desired so that the runoff associated with the highway would be sufficiently dirty. That is, it would have pollutant concentrations high enough that they could be adequately monitored during storm events. All three of the sites met this criterion, although there were slight differences in the ADT between Site 1 and Sites 2 and 3. With this similarity in traffic count, as well as a similarity in traffic patterns and rainfall events at the sites, it was expected that the initial quality of the runoff at the edge of pavement at each site would be similar and that the runoff would have high enough pollutant levels for good analyses. 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 traditional asphalt surface only), Site 2, and Site 3 to determine if any statistically significant differences existed between the runoff generated at each site. The resulting P values for each ANOVA test are listed in Table 11. (A "*" in the table indicates that all of the monitored concentrations were below the detection limits for that parameter so the P value cannot be determined.) The results of these tests indicate that no significant differences existed in the concentrations of most constituents at each research site.

Table 11 Edge of Pavement P Values

Constituent	ANOVA - P Value
Total Suspended Solids	**0.37**
Total Kjeldahl Nitrogen	**0.21**
Nitrate/Nitrite – Nitrogen	**0.49**
Total Phosphorus	**0.05**
Dissolved Phosphate as P	**0.02**
Total Copper	**0.24**
Total Lead	**0.63**
Total Zinc	**0.36**
Dissolved Copper	**0.81**
Dissolved Lead	*
Dissolved Zinc	**0.97**
Chemical Oxygen Demand	**0.11**

The only two constituents found to have P values less than 0.1 are the total and dissolved forms of phosphorus, indicating that statistically significant difference in those concentrations exists between the research sites. 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 12. The reason for higher concentrations of phosphorus at the edge of pavement at Site 3 is unknown, but may be a factor of the size of the dataset. These differences may disappear as additional samples are collected.

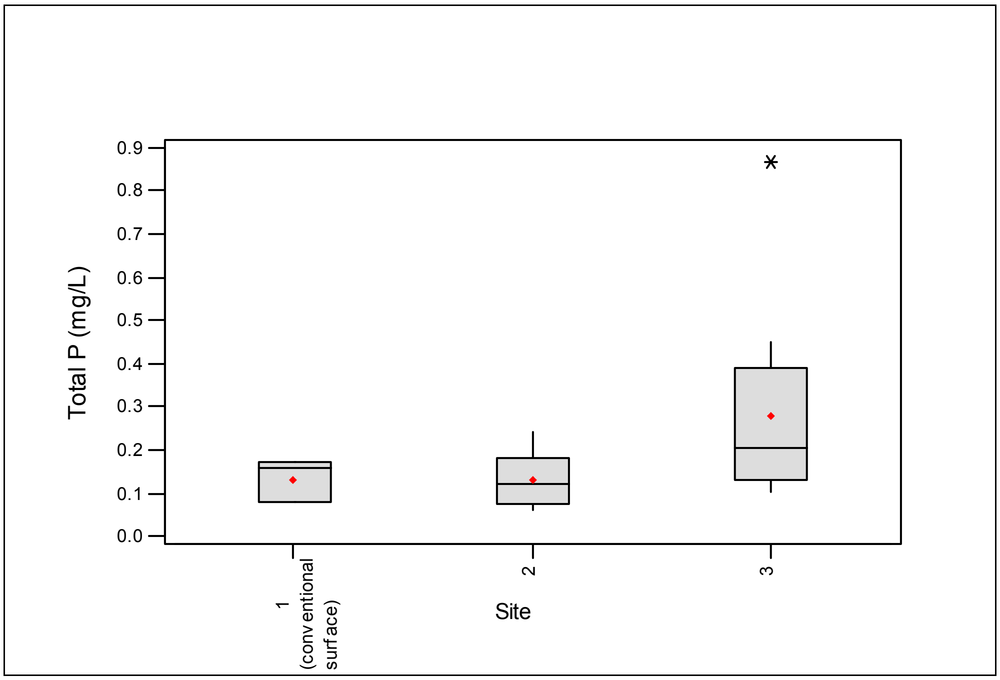

Figure 12 Boxplot of Edge of Pavement Total Phosphorus EMCs

The P value for COD at all edge of pavement sampling points is 0.11. This value is only slightly greater than the P value of 0.1, below which it is usually said that a statistically significant difference exists between the datasets. Again, further analyses of these COD data indicate that the concentrations measured at the edge of pavement at Site 3 are significantly higher than those measured at Site 1 and Site 2. Additional data collection may eliminate these differences.

These results indicate that approximately equivalent pollutant levels 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 13. 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.

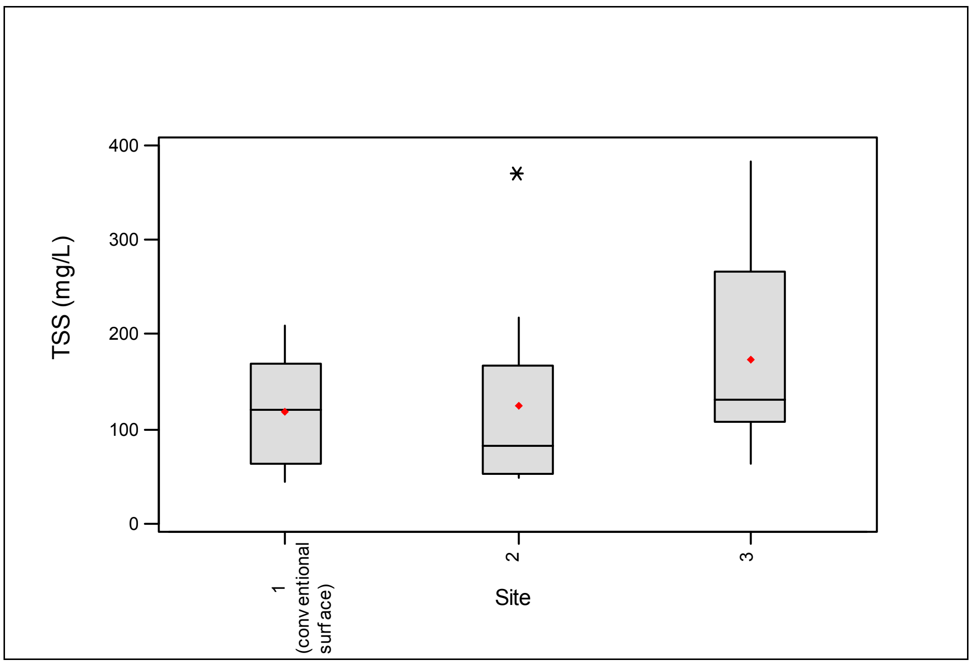

Figure 13 Boxplot of Edge of Pavement TSS EMCs

4.6 Comparison of Results from Traditional and Porous Asphalt Surfaces

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 both before and after the installation of the PFC surface. The results of those tests are presented in Table 12. 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. (A “*” in the table indicates that all of the monitored concentrations were below the detection limits for that parameter so the P value cannot be determined.)

Table 12 P Values for Edge of Pavement EMCs at 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 metals 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 Figures 14 and 15, 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.

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.

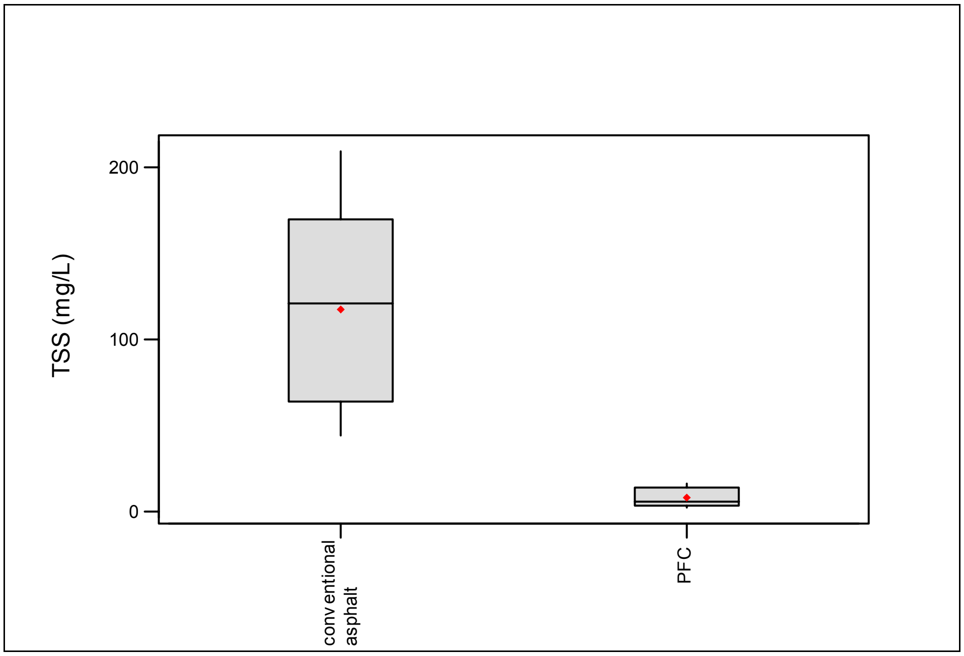

Figure 14 Boxplot of Edge of Pavement TSS at Site 1

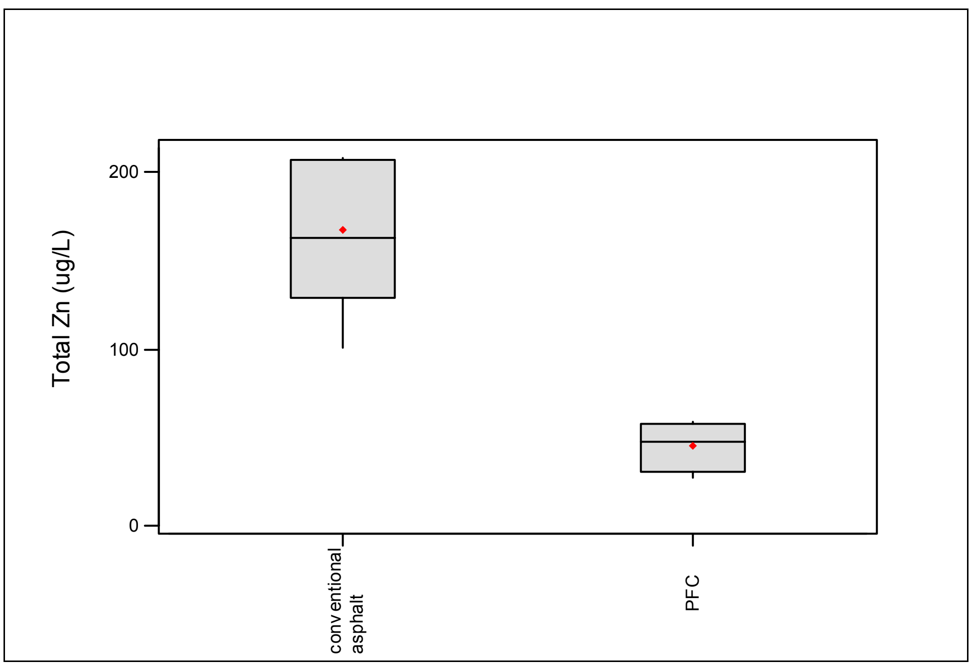

Figure 15 Boxplot of Edge of Pavement Total Zn at Site 1

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 13 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.

Table 13 Comparison of Edge of Pavement Concentrations at 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)	0.00	0.00	0.00	0.00
Dissolved Zn (µg/L)	47.06	38.74	33.75	33.94
COD (mg/L)	64.00	60.58	30.50	28.60

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. It appears, therefore, that a newly paved asphalt highway surface, unlike newly sealed parking lots, does not generate semi-volatile organics in concentrations that would be of concern to the environment.

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. These results are presented in Table 14. (A "*" in the table indicates that all of the monitored concentrations were below the detection limits for that parameter so the P value cannot be determined.) These P values indicate that very few significant differences exist between the measured concentrations in the vegetated filter strips despite the original quality of the runoff.

Table 14 P Values for each sampling distance at Site 1, before and after overlay

	ANOVA - P Value		
Constituent	**2m**	**4m**	**8m**
TSS	0.237	0.195	0.3
TKN	0.248	0.167	0.45
NO3/NO2	0.676	0.374	0.364
Total P	0.054	0.6	0.302
Dissolved P	0.148	0.419	0.27
Total Cu	0.269	0.411	0.113
Dissolved Cu	0.612	0.517	0.149
Total Pb	0.25	0.361	0.423
Dissolved Pb	*	0.407	*
Total Zn	0.285	0.404	0.02
Dissolved Zn	0.851	0.541	0.044
COD	0.646	0.557	0.655

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. Figures 16 and 17 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.

A comparison of the effect of road surface on rainfall weighted average concentrations for all constituents at each sampling point at Site 1 is presented in Table 15. Based on these average concentrations, it can be seen that concentrations of TSS, TKN, and total forms of Cu and Pb are lower over the width of the vegetated filter strip in runoff events monitored from the PFC surface than from the conventional surface. Average concentrations of phosphorus, COD, and the dissolved forms of copper and lead were observed to be higher from the porous surface than from the conventional surface. Further analytical comparisons of the performance of the vegetated filter strip at Site 1 as it receives runoff generated from the traditional and porous asphalt surfaces are limited by the number of storms monitored.

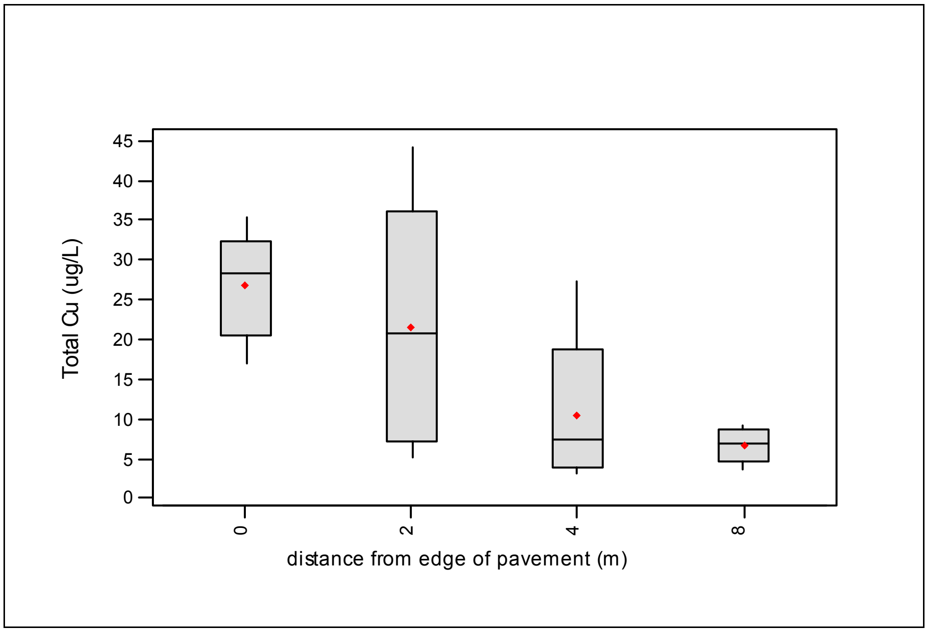

Figure 16 Boxplot of Total Copper at Site 1, conventional pavement

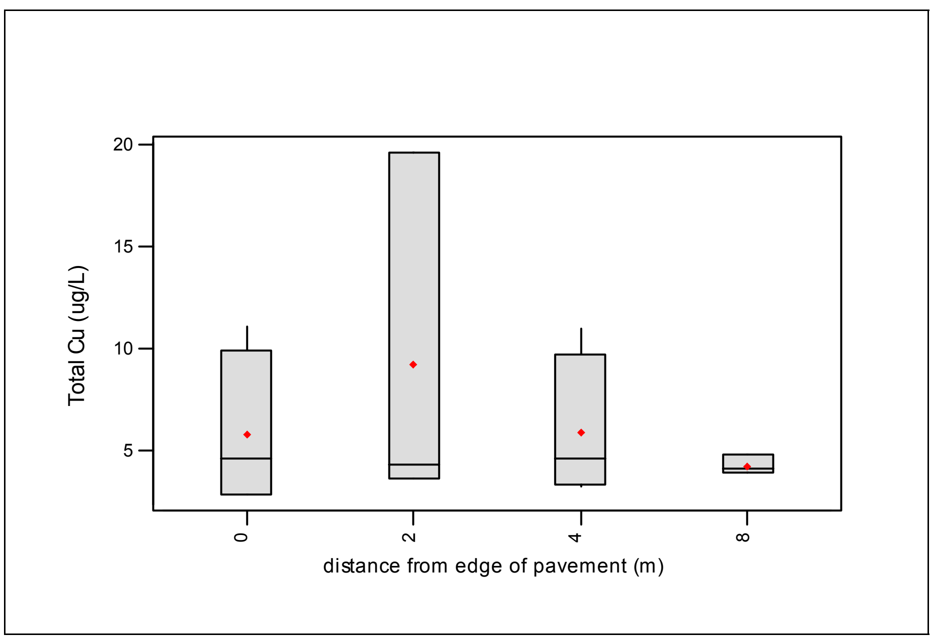

Figure 17 Boxplot of Total Copper at Site 1, PFC

Table 15 Comparison of conventional and PFC surfaces at Site 1

2m	Conventional Asphalt Surface	PFC Overlay Surface
TSS (mg/L)	84.56	10.74
TKN (mg/L)	2.04	0.88
NO3/NO2-N (mg/L)	0.17	0.27
Total P (mg/L)	0.15	0.04
Dissolved P (mg/L)	0.08	0.01
Total Cu (µg/L)	19.14	7.89
Total Pb (µg/L)	4.57	1.04
Total Zn (µg/L)	85.14	51.59
Dissolved Cu (µg/L)	6.48	5.11
Dissolved Pb (µg/L)	0.00	0.00
Dissolved Zn (µg/L)	53.92	45.41
COD (mg/L)	50.77	46.85
4m	**Conventional Asphalt Surface**	**PFC Overlay Surface**
TSS (mg/L)	54.51	33.08
TKN (mg/L)	2.36	0.91
NO3/NO2-N (mg/L)	0.22	0.14
Total P (mg/L)	0.14	0.21
Dissolved P (mg/L)	0.07	0.06
Total Cu (µg/L)	10.94	5.67
Total Pb (µg/L)	1.70	1.34
Total Zn (µg/L)	117.01	216.34
Dissolved Cu (µg/L)	4.94	3.50
Dissolved Pb (µg/L)	0.12	0.00
Dissolved Zn (µg/L)	90.80	160.95
COD (mg/L)	27.23	41.65
8m	**Conventional Asphalt Surface**	**PFC Overlay Surface**
TSS (mg/L)	35.85	19.41
TKN (mg/L)	2.64	1.30
NO3/NO2-N (mg/L)	0.23	0.12
Total P (mg/L)	0.27	0.11
Dissolved P (mg/L)	0.17	0.04
Total Cu (µg/L)	7.54	3.36
Total Pb (µg/L)	0.78	0.39
Total Zn (µg/L)	86.78	226.64
Dissolved Cu (µg/L)	4.02	2.37
Dissolved Pb (µg/L)	0.00	0.00
Dissolved Zn (µg/L)	86.78	226.64
COD (mg/L)	49.31	38.08

4.7 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 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 reasonable 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 road edge. Higher levels of phosphorus in the initial runoff could be the reason for its higher concentrations throughout the vegetated area.

4.8 Site Conditions Affecting Sampling

4.8.1 Fire Ants

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.

4.8.2 Galvanized Metal Flashing

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.

4.9 Overall Performance of Filter Strips

Each of the vegetated filter strips in this study exhibited similar trends in overall performance with the exception of events monitored at Site 1 with the porous asphalt overlay in place. Table 16 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. (A "*" in the table indicates that the majority of monitored concentrations were below the detection limits for that parameter.) Tables showing the comparison between results from the rainfall weighted average concentration method and the mean EMC method are presented in Appendix C. 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 16 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.

Nitrate/Nitrite – Net decreases in concentrations of nitrate and nitrate 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 60.2% and 10.3%, 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.

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 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. See Section 4.8.2 for further discussion.

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 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 18 and Figure 19 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.

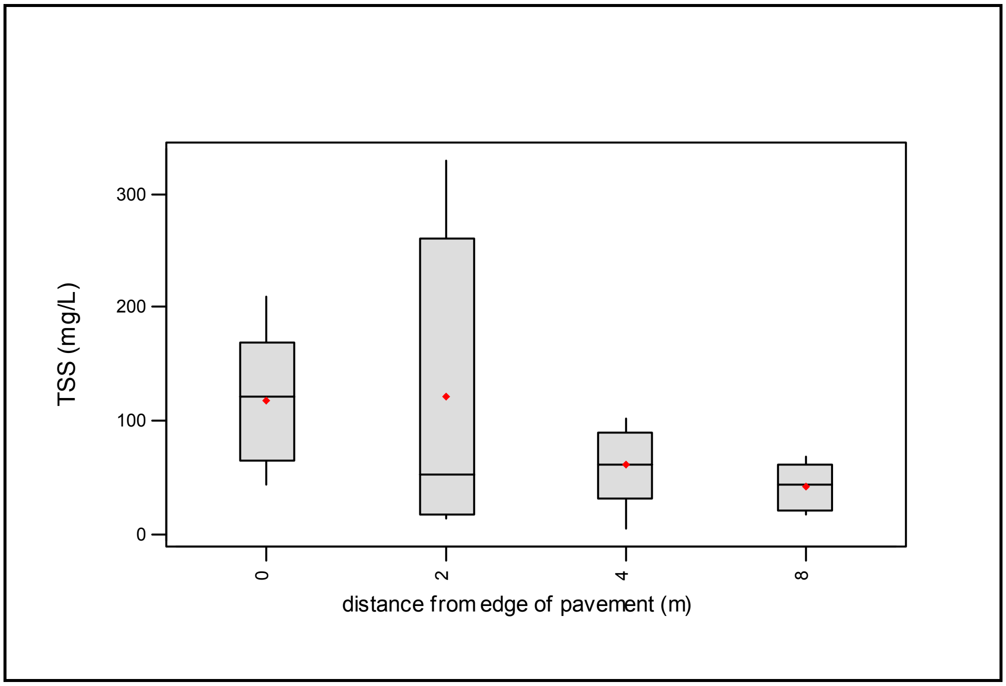

Figure 18 Boxplot of TSS at Site 1, conventional pavement

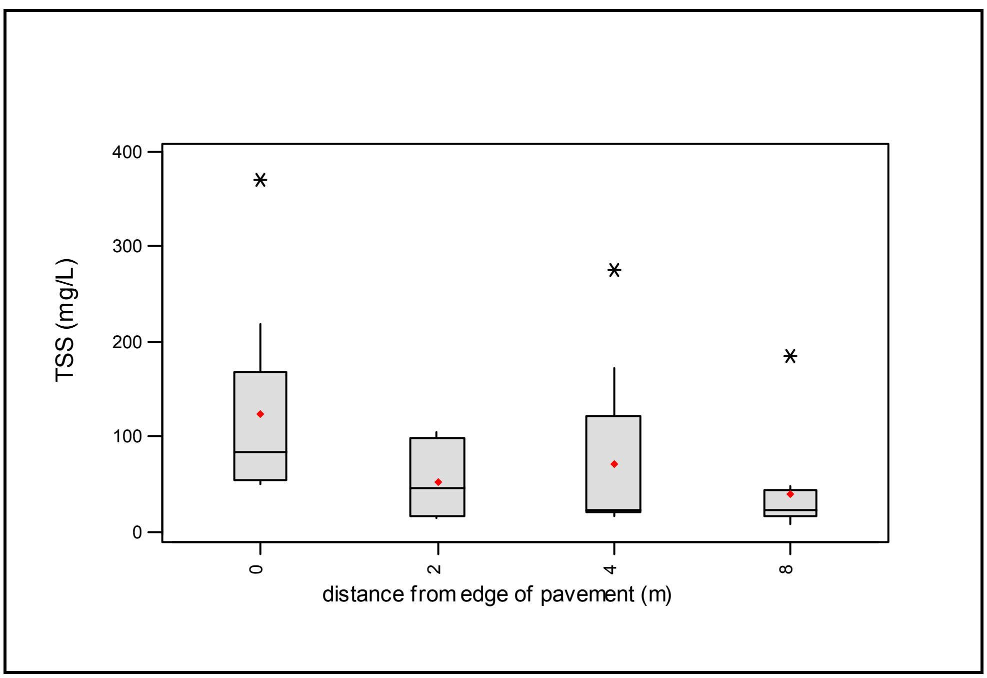

Figure 19 Boxplot of TSS at Site 2

Differences in slope may also 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 12%. These findings are contradictory to those reported in two previous studies in which grassy swales with shallower slopes exhibited increased pollutant removal efficiencies than swales with steep slopes (Yousef et al. 1987, Dorman et al. 1996). The relationship between slope and site performance is not as clear from these results as the relationship between performance and vegetation density.

Overall removal efficiencies of some constituents determined in this study are similar to those found from two previous studies of vegetative controls 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 borrow ditch. The second also studied the efficiency of grassy medians for mitigating highway runoff. 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 17 (Barrett et al., 1998).

Table 17 Reductions in Concentrations Observed from Previous Studies in Austin

	US 183 Median			MoPac Expressway Median			MoPac at Walnut Creek		
Constituent	**Road Mean**	**Swale Mean**	**Red. (%)**	**Road Mean**	**Swale Mean**	**Red. (%)**	**Road Mean**	**Swale Mean**	**Red. (%)**
TSS (mg/L)	**157**	**21**	**87**	**190**	**29**	**85**	**77**	**35**	**54**
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**	**0.83**	**0.22**	**74**
Total P (mg/L)	**0.55**	**0.31**	**44**	**0.24**	**0.16**	**34**	**0.15**	**0.07**	**53**
Copper (µg/L)	**--**	**--**	**--**	**--**	**--**	**--**	**20**	**5**	**75**
Lead (µg/L)	**138**	**82**	**41**	**93**	**77**	**17**	**18**	**3**	**83**
Zinc (µg/L)	**347**	**32**	**91**	**129**	**32**	**75**	**71**	**19**	**73**
COD (mg/L)	**94**	**37**	**61**	**109**	**41**	**63**	**46**	**32**	**30**

The results found in this study for TSS, copper, lead, and COD 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 do 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 far 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, however. 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 are consistent with those findings.

CHAPTER 5 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 as part of the design for meeting stormwater quality requirements. Such water quality 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 12 passive stormwater runoff collection and sampling systems as three sites in the Austin area. 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. Three research sites were also selected and monitored in the College Station area, the results from which will be presented in a separate report.

The key findings of this study are as follows:

1. There is no significant difference between the edge of pavement pollutant concentrations at each of the research sites with conventional asphalt surfaces with the exception of phosphorus. This allows for direct comparisons of the vegetated buffer strips and their associated site characteristics (vegetation

density, slope, etc.). Furthermore, these pollutant concentrations generally are within the expected range of concentrations for highway runoff.

2. Vegetation density has a direct effect on the performance of vegetated filter strips. Vegetated areas with highly dense vegetative covers will result in higher pollutant removal efficiencies than less dense covers. Dense vegetative cover within close proximity to the road surface and vegetative covers of at least 90% are recommended to allow for maximum pollutant removal.

3. Shallow layers of biosolids compost material have no discernable effect (positive or negative) on the performance of densely covered vegetated filter strips.

4. The permeable friction course appears to have a significant impact on the quality of runoff leaving the road surface. Pollutant concentrations in runoff sampled from a traditional asphalt-surfaced highway compared with concentrations in runoff sampled from the same road surface after the installation of a PFC overlay indicate that the runoff generated from the PFC is cleaner for TSS, total metals, and COD. These improvements in water quality are as great, if not greater, than the improvements gained from a vegetated filter.

5. Statistically significant reductions in TSS concentrations were observed at all three research sites. 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 and total lead also exhibited statistically significant removal at all three of the sites with those decreases occurring within the first eight meters.

7. Statistically significant reductions in COD occurred over the width of the vegetated filter.

8. No consistent increases or decreases were observed for nutrients.

9. Total and dissolved concentrations of zinc were elevated at the two, four, and eight meter sampling points at all of the sites, probably caused by leaching of zinc from the galvanized metal flashing used in the collection apparatuses.

10. Vegetated filter strips with a minimum width of 4m and a minimum vegetation density of 90% are recommended for treating stormwater runoff from highways in the Austin area. The results from this study indicate that filter strips with these parameters will result in significant improvements in the water quality of highway stormwater runoff.

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's 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, are easy to manage, and provide aesthetic benefits to the surrounding environment.

APPENDIX A VEGETATION SURVEY RESULTS

Table A- 1 Vegetation Survey Results, 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, 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, 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 %

APPENDIX B BOXPLOTS OF EACH CONSITUENT AT EACH SITE

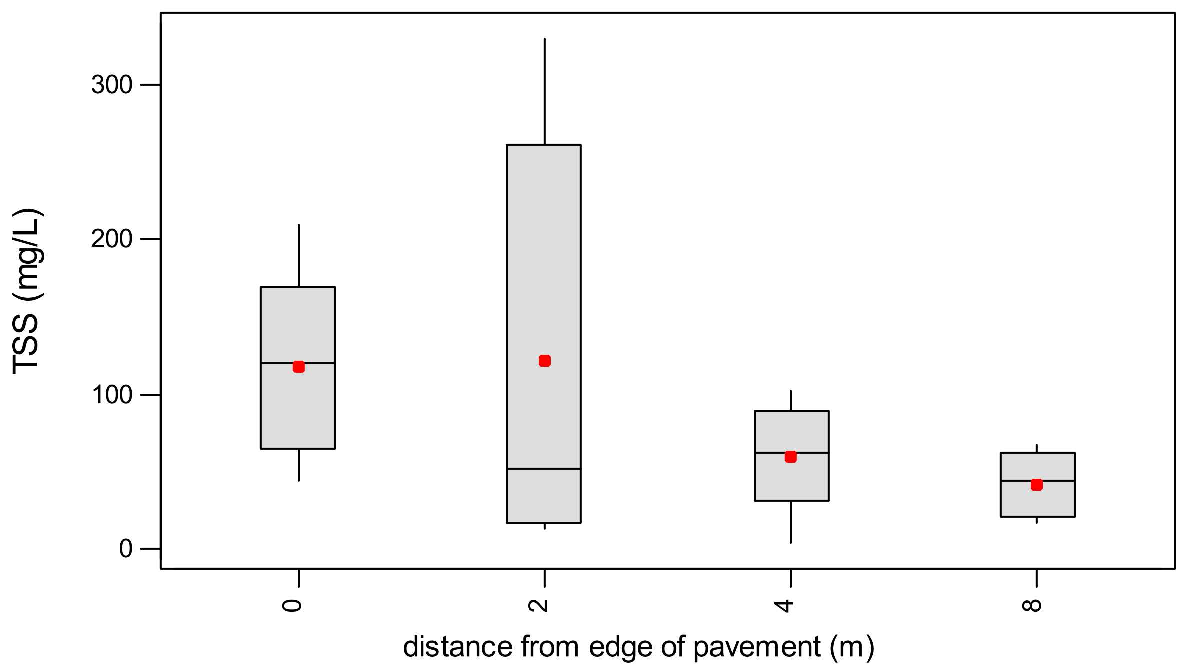

Figure B- 1 Boxplot of TSS at Site 1, conventional asphalt surface

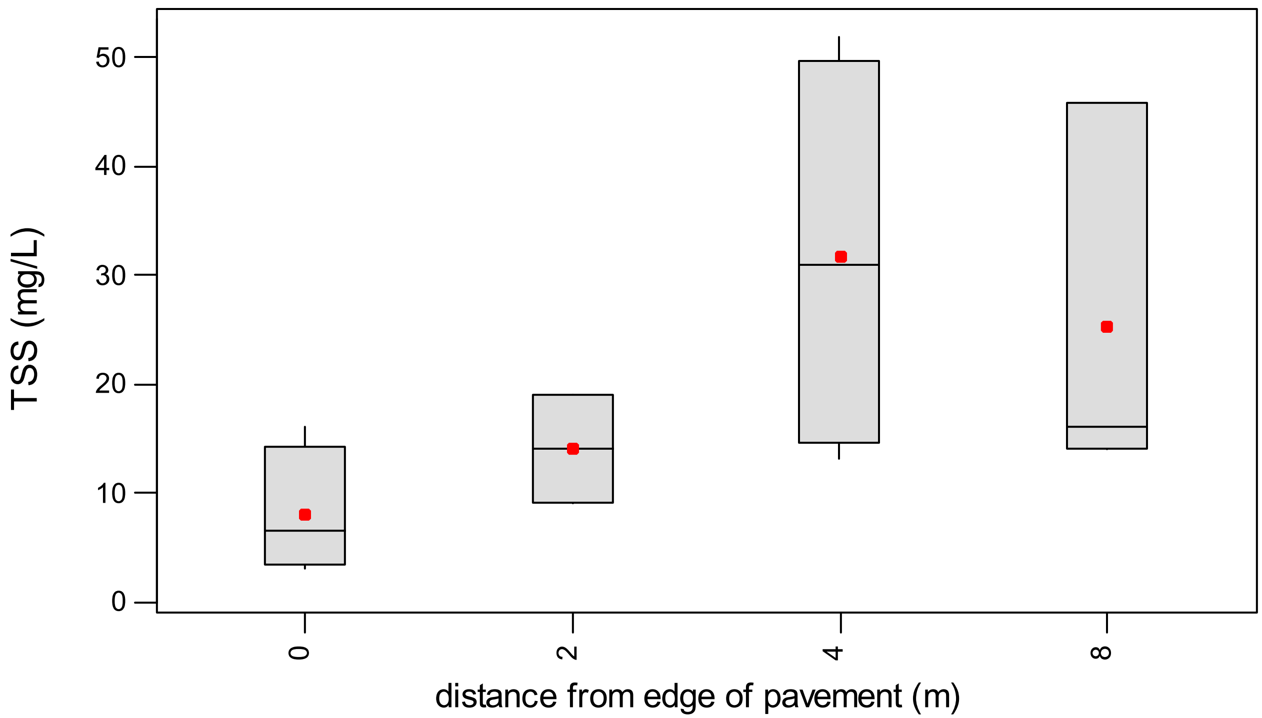

Figure B- 2 Boxplot of TSS at Site 1, PFC surface

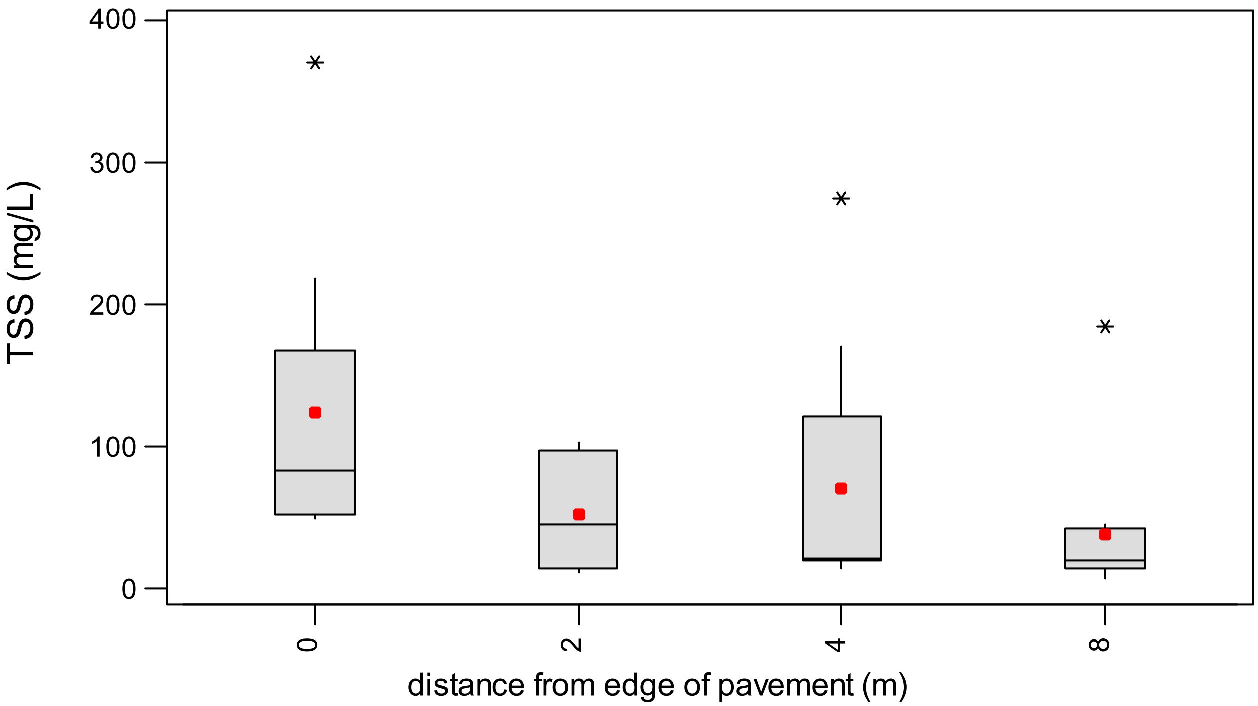

Figure B- 3 Boxplot of TSS at Site 2

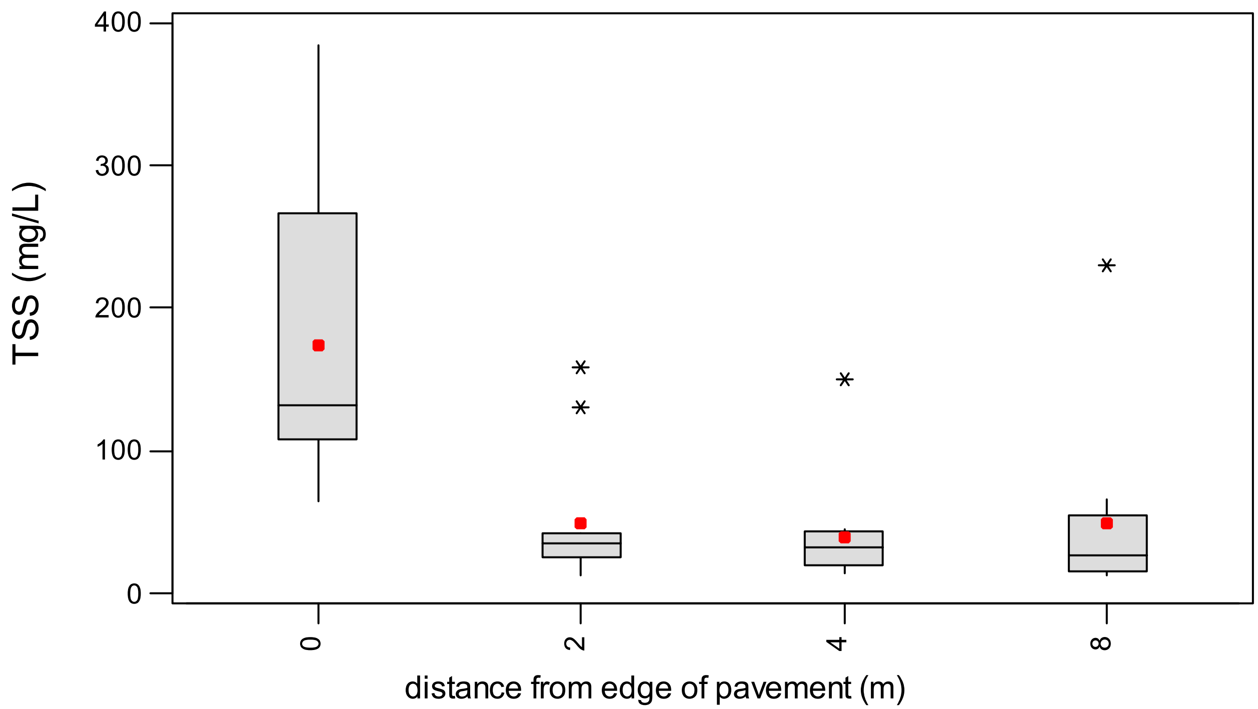

Figure B- 4 Boxplot of TSS at Site 3

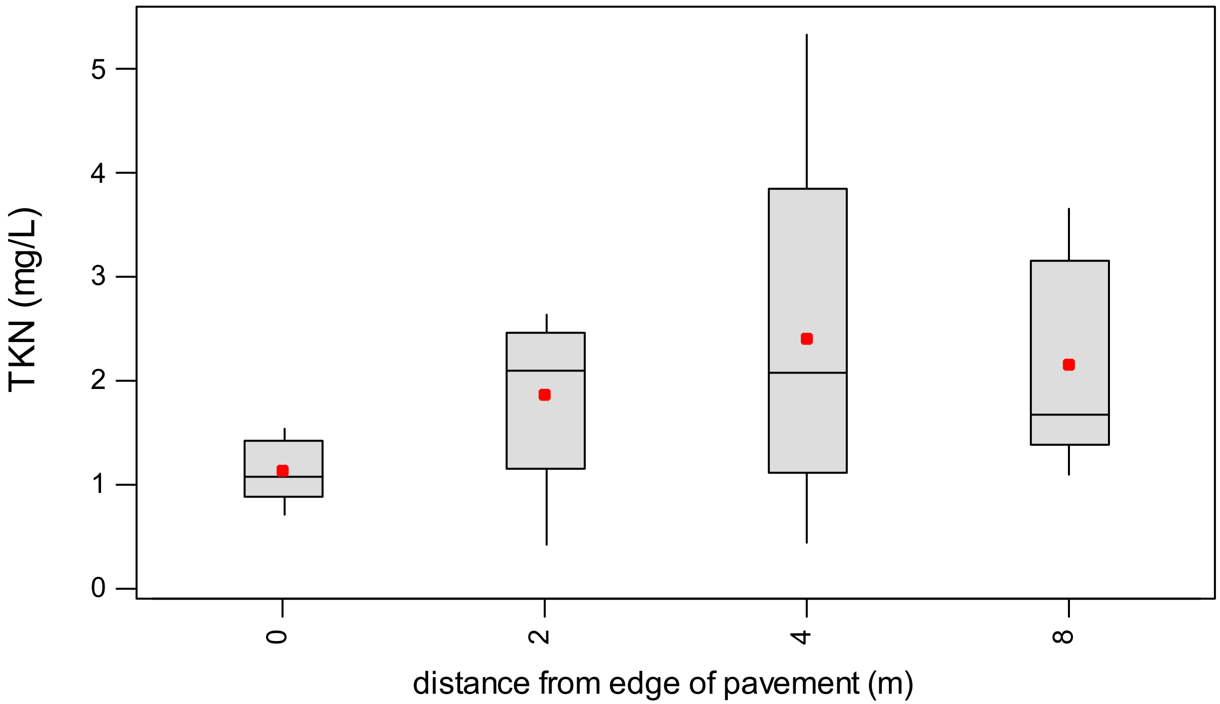

Figure B- 5 Boxplot of TKN at Site 1, conventional asphalt surface

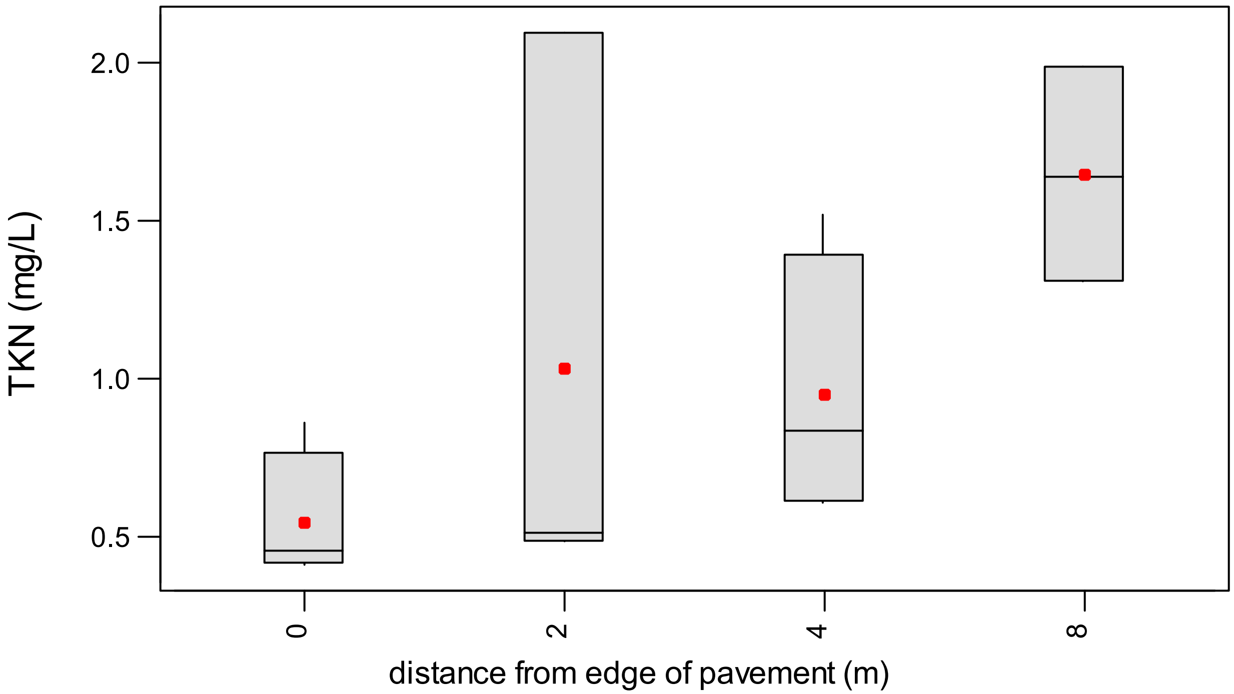

Figure B- 6 Boxplot of TKN at Site 1, PFC surface

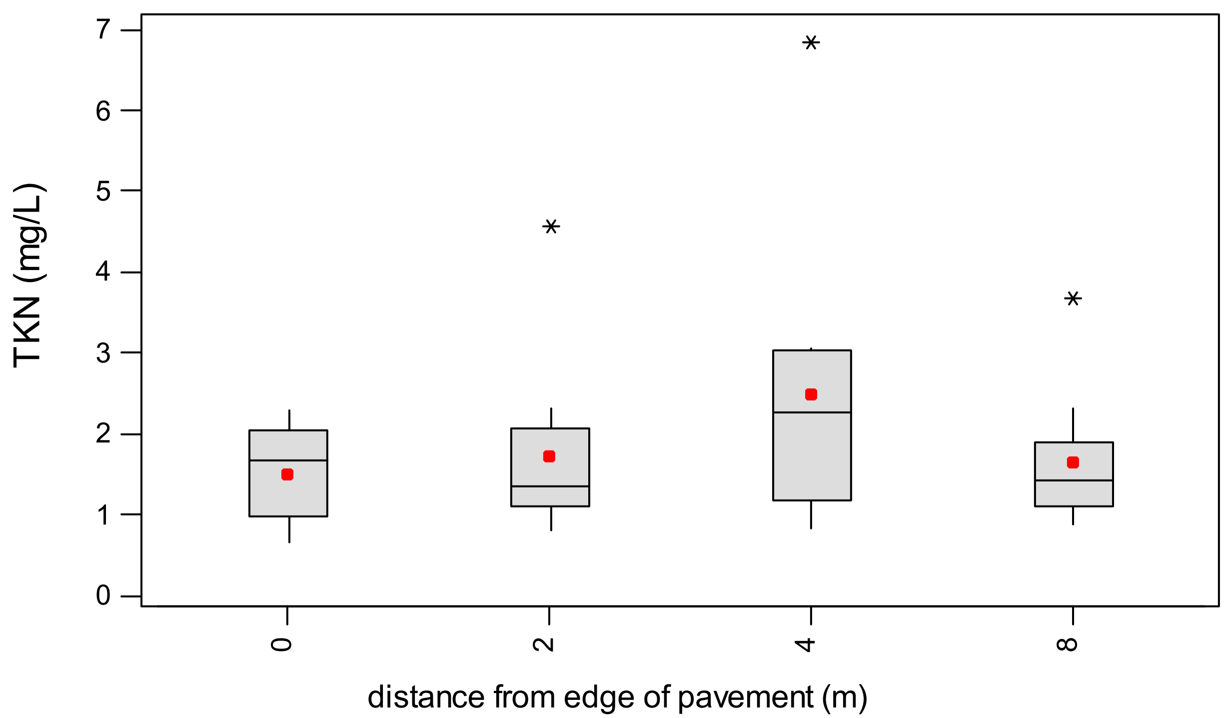

Figure B- 7 Boxplot of TKN at Site 2

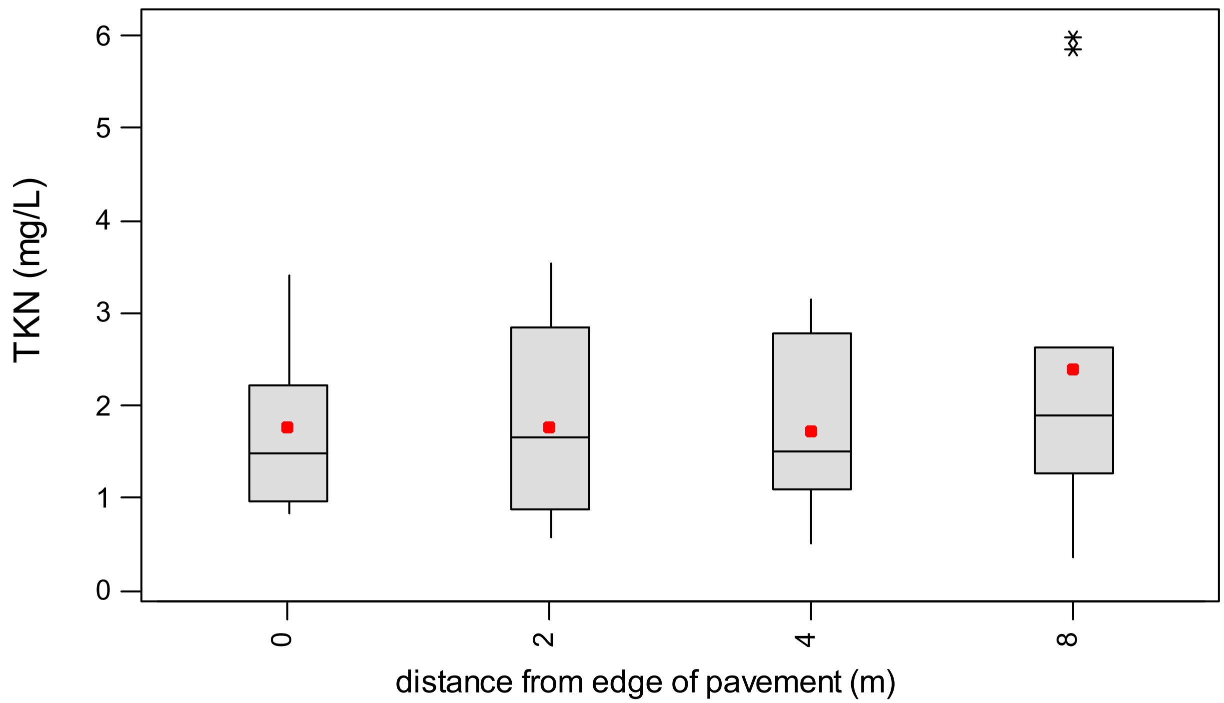

Figure B- 8 Boxplot of TKN at Site 3

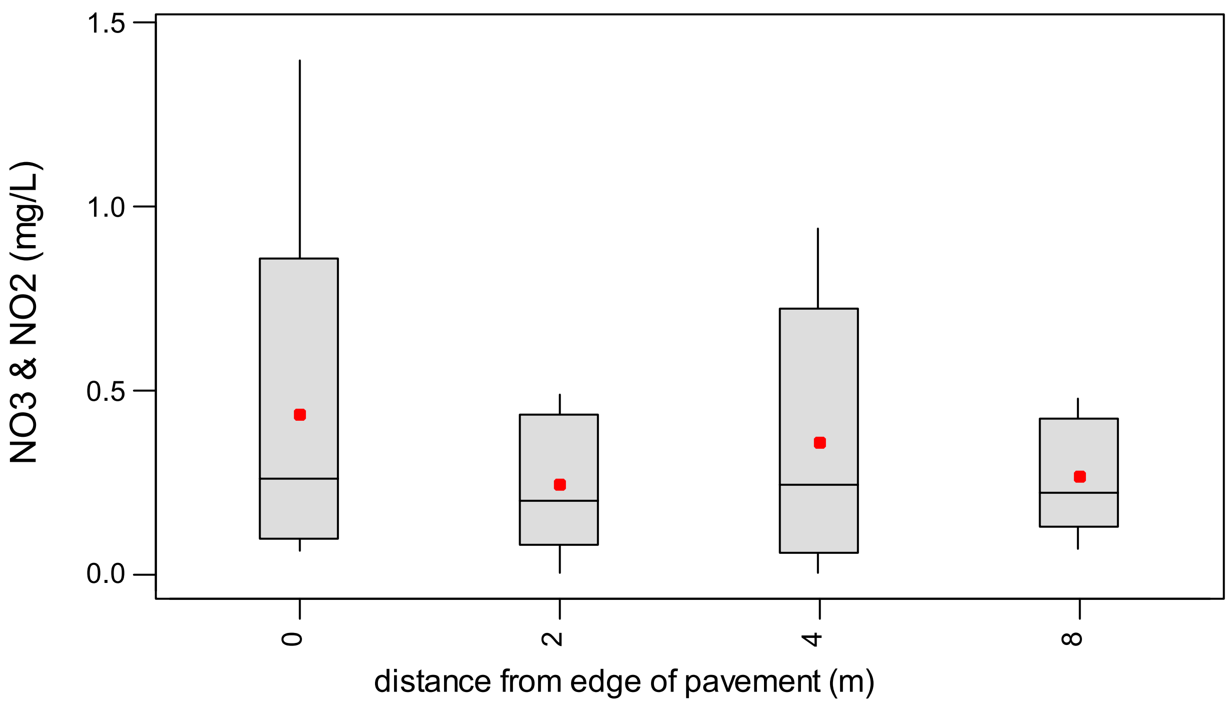

Figure B- 9 Boxplot of Nitrate & Nitrite at Site 1, conventional asphalt surface

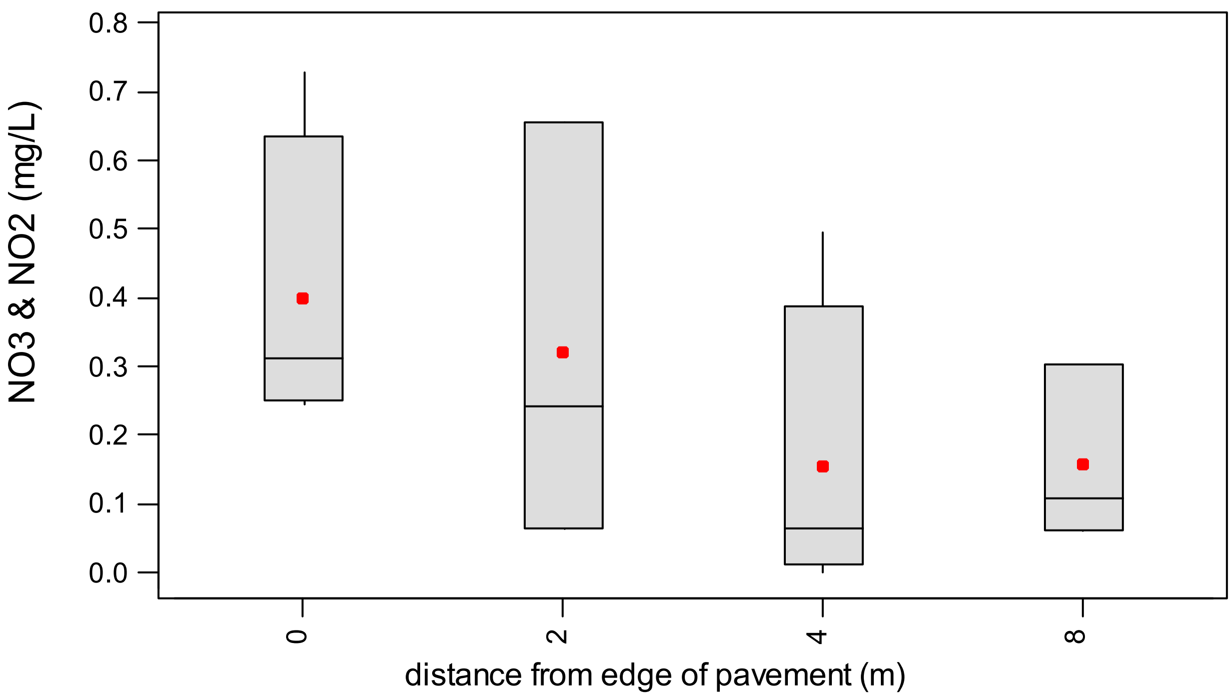

Figure B- 10 Boxplot of Nitrate & Nitrite at Site 1, PFC surface

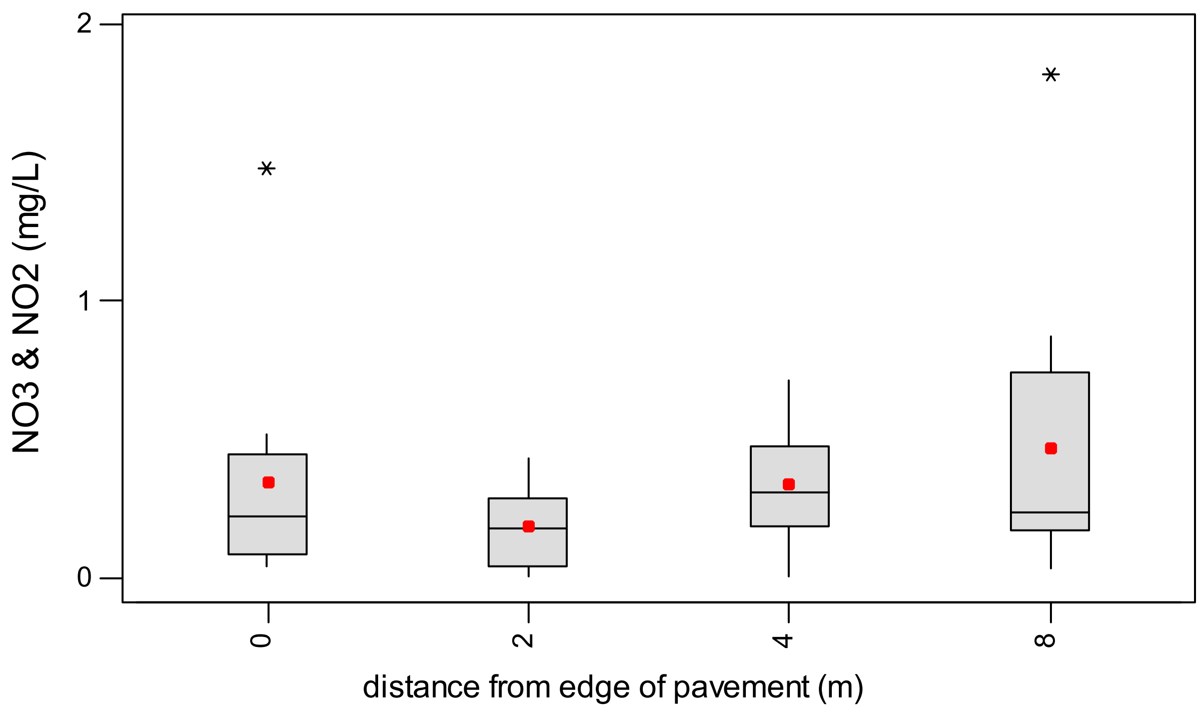

Figure B- 11 Boxplot of Nitrate & Nitrite at Site 2

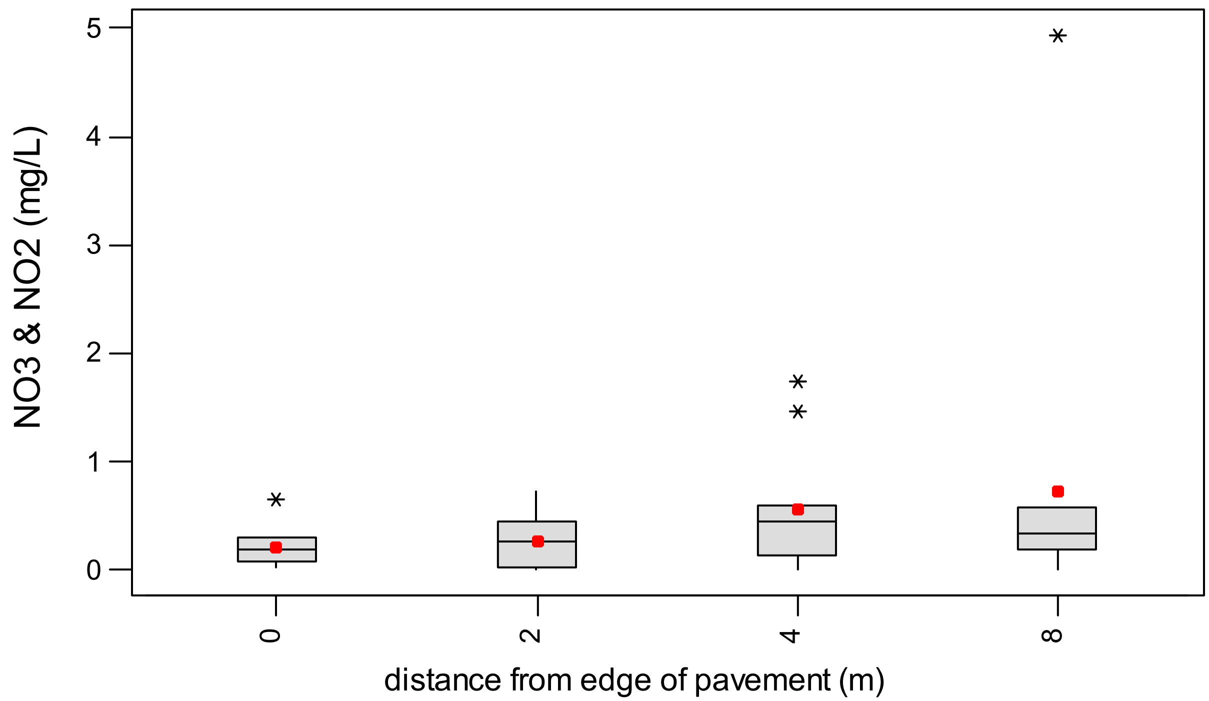

Figure B- 12 Boxplot of Nitrate & Nitrite at Site 3

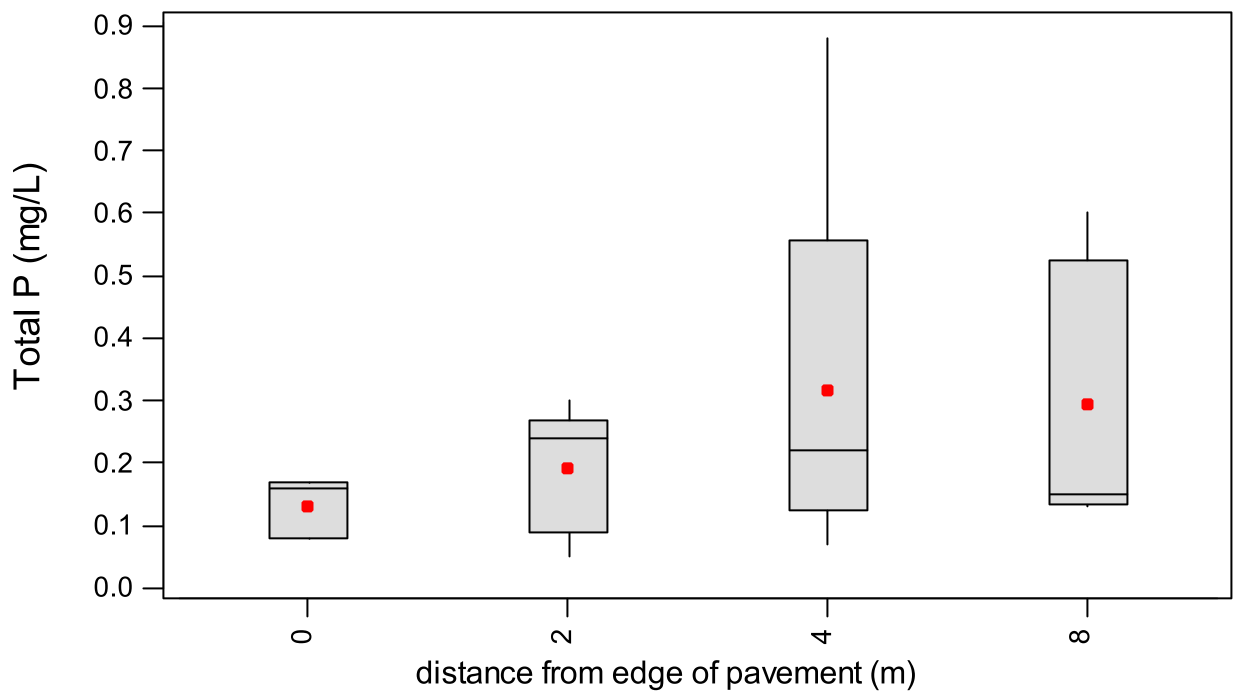

Figure B- 13 Boxplot of Total Phosphorus at Site 1, conventional asphalt surface

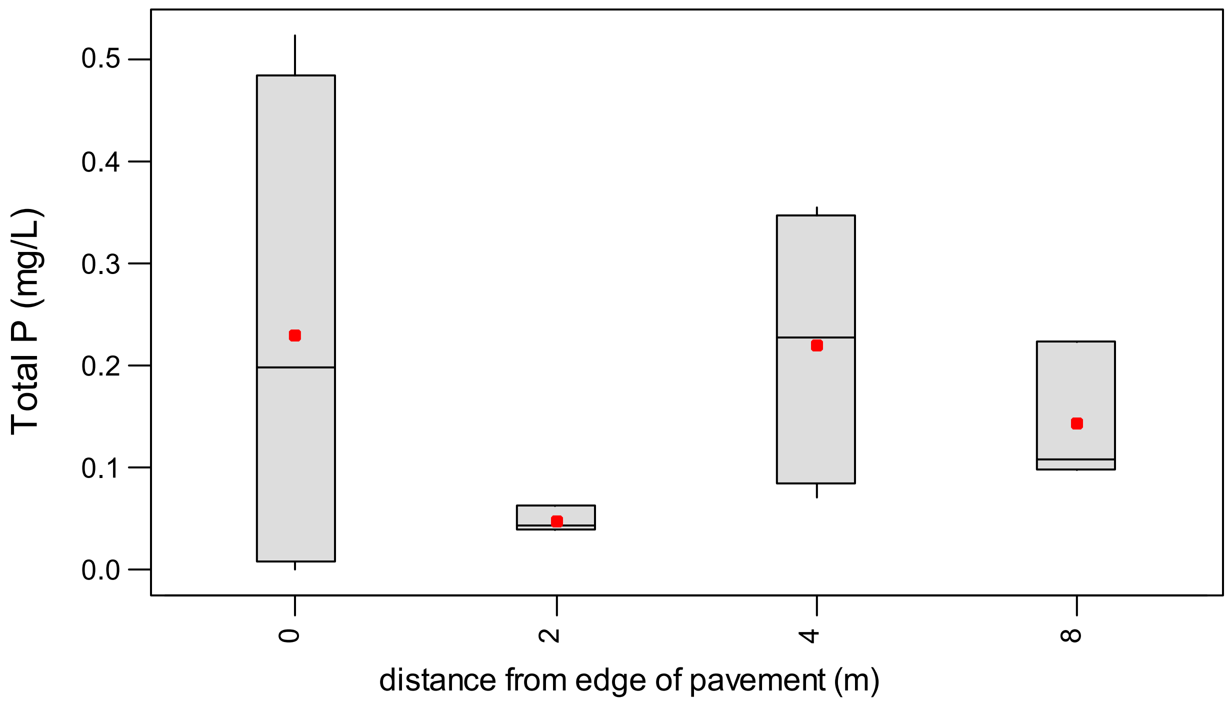

Figure B- 14 Boxplot of Total Phosphorus at Site 1, PFC surface

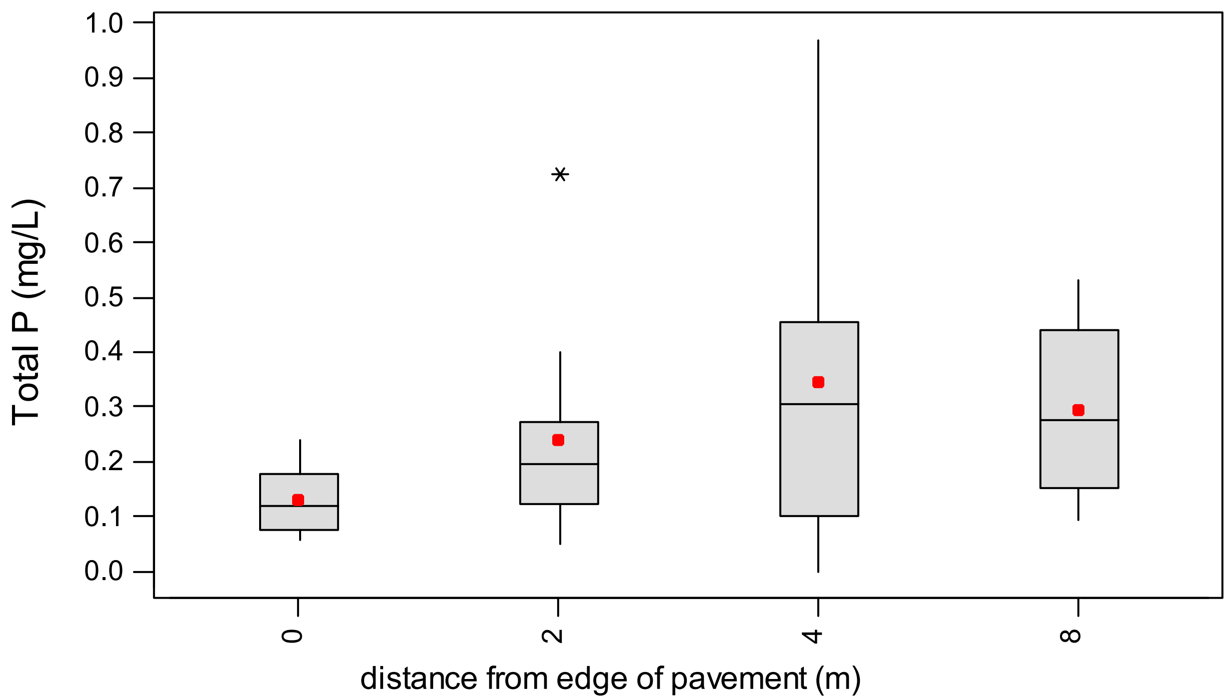

Figure B- 15 Boxplot of Total Phosphorus at Site 2

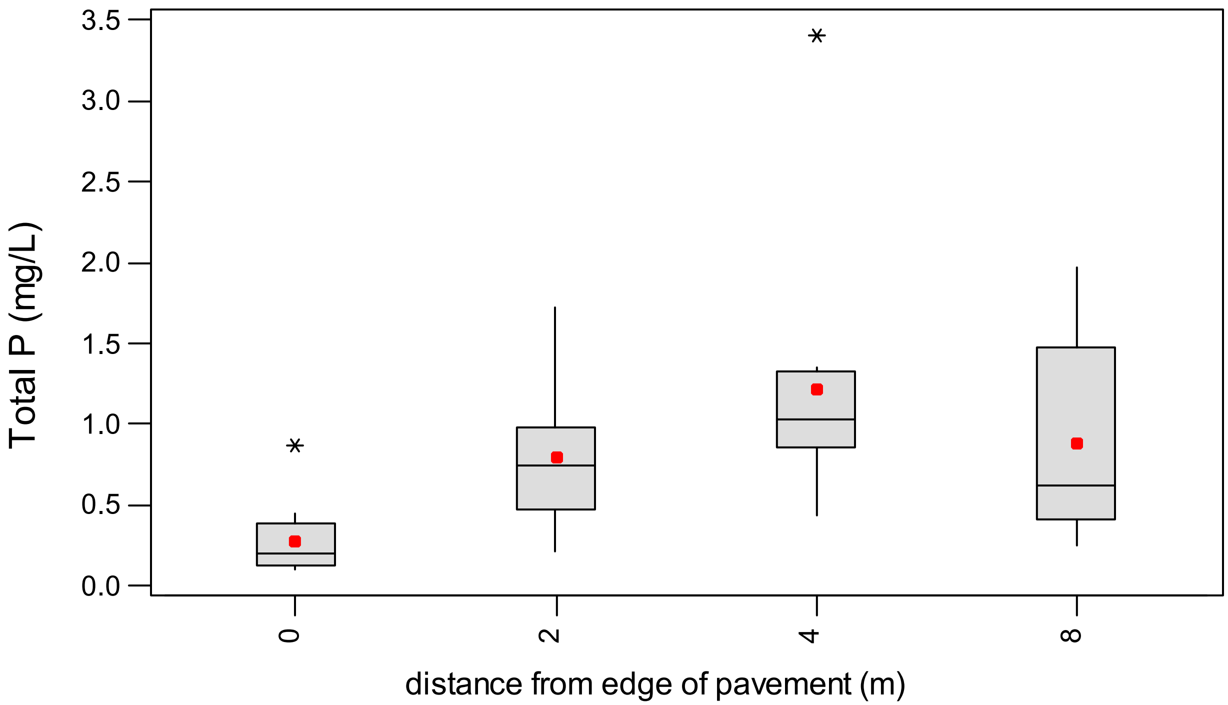

Figure B- 16 Boxplot of Total Phosphorus at Site 3

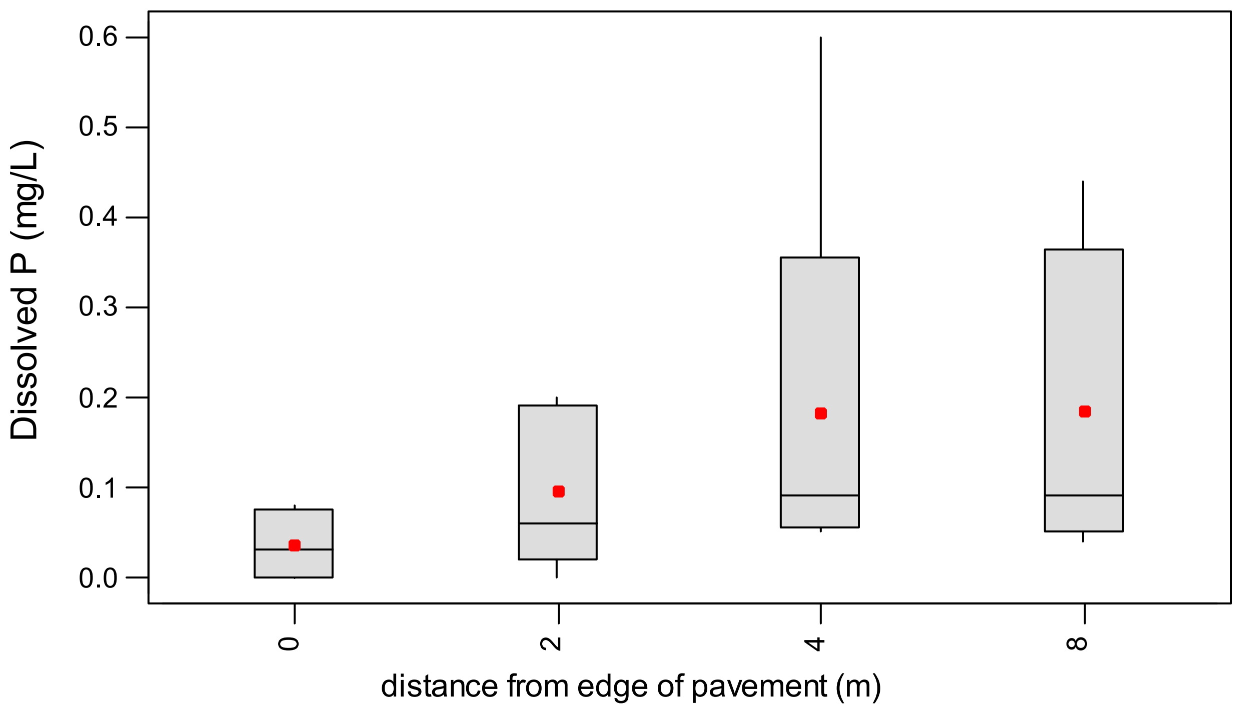

Figure B- 17 Boxplot of Dissolved Phosphorus at Site 1, conventional asphalt surface

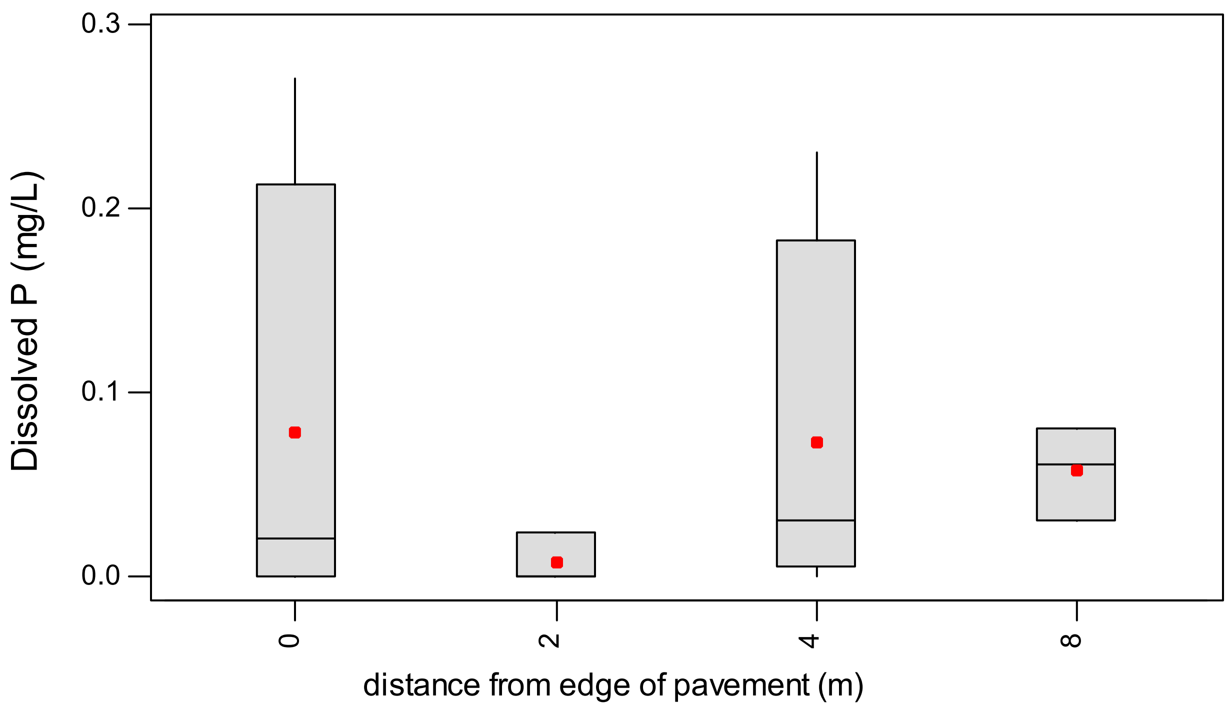

Figure B- 18 Boxplot of Dissolved Phosphorus at Site 1, PFC surface

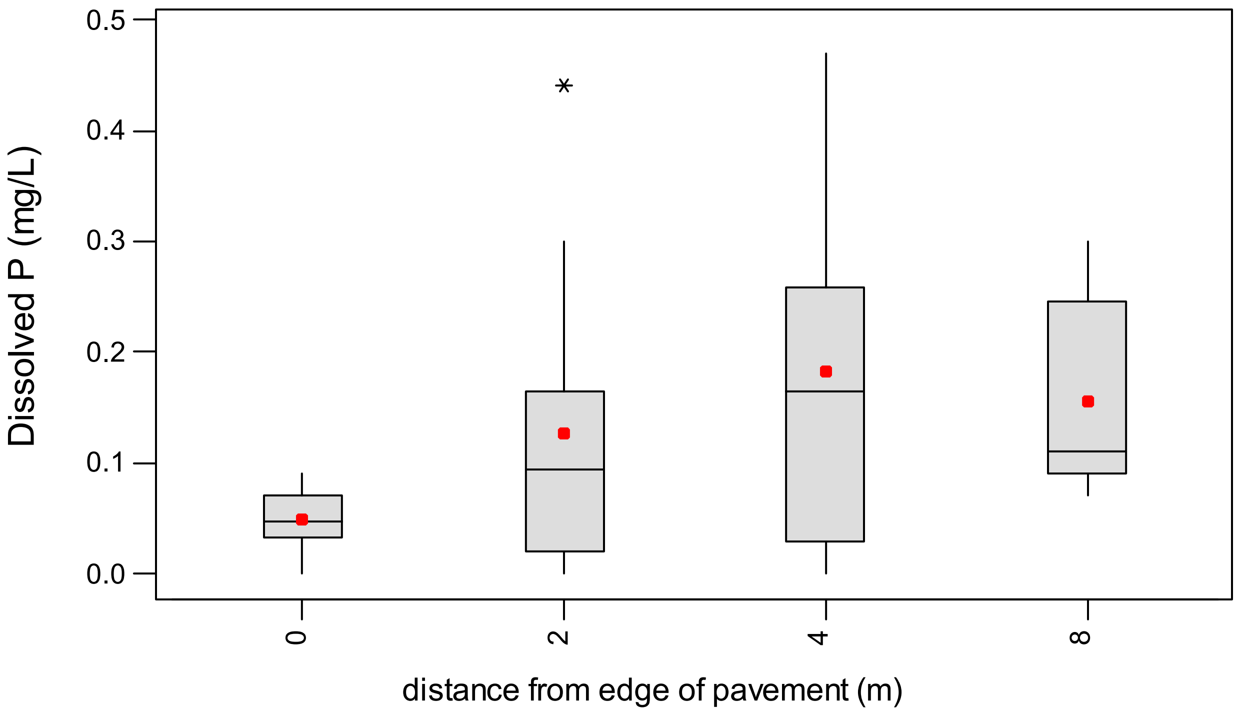

Figure B- 19 Boxplot of Dissolved Phosphorus at Site 2

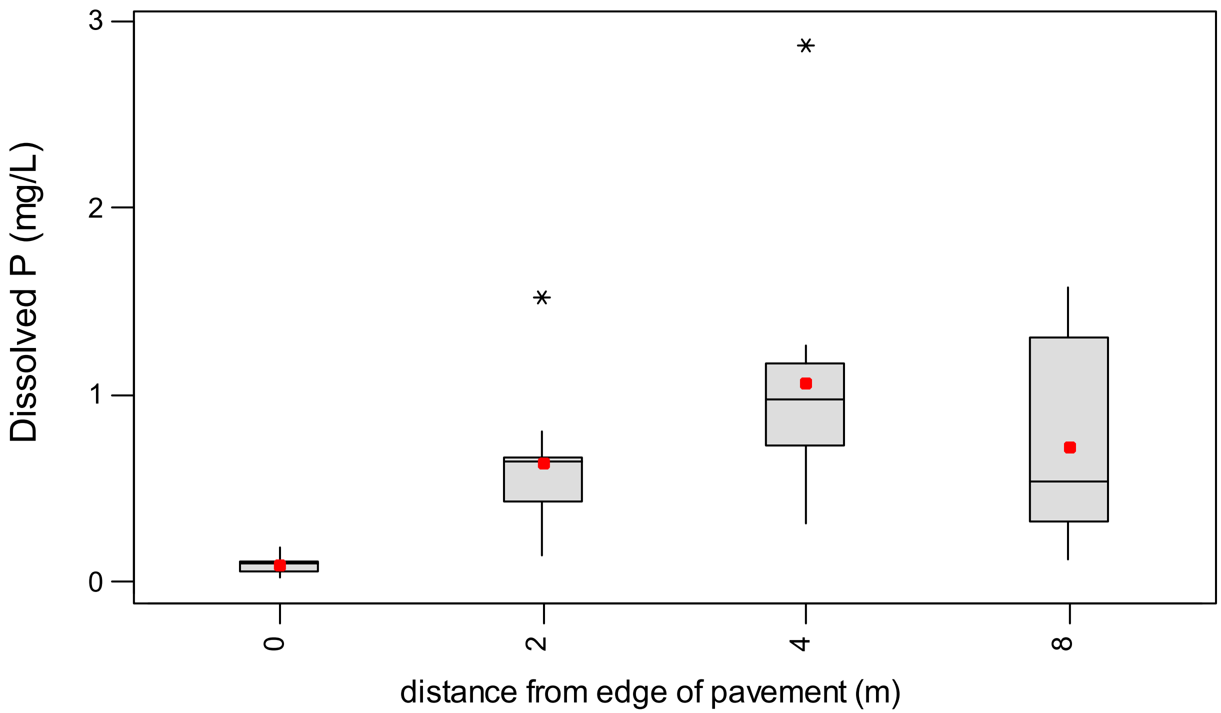

Figure B- 20 Boxplot of Dissolved Phosphorus at Site 3

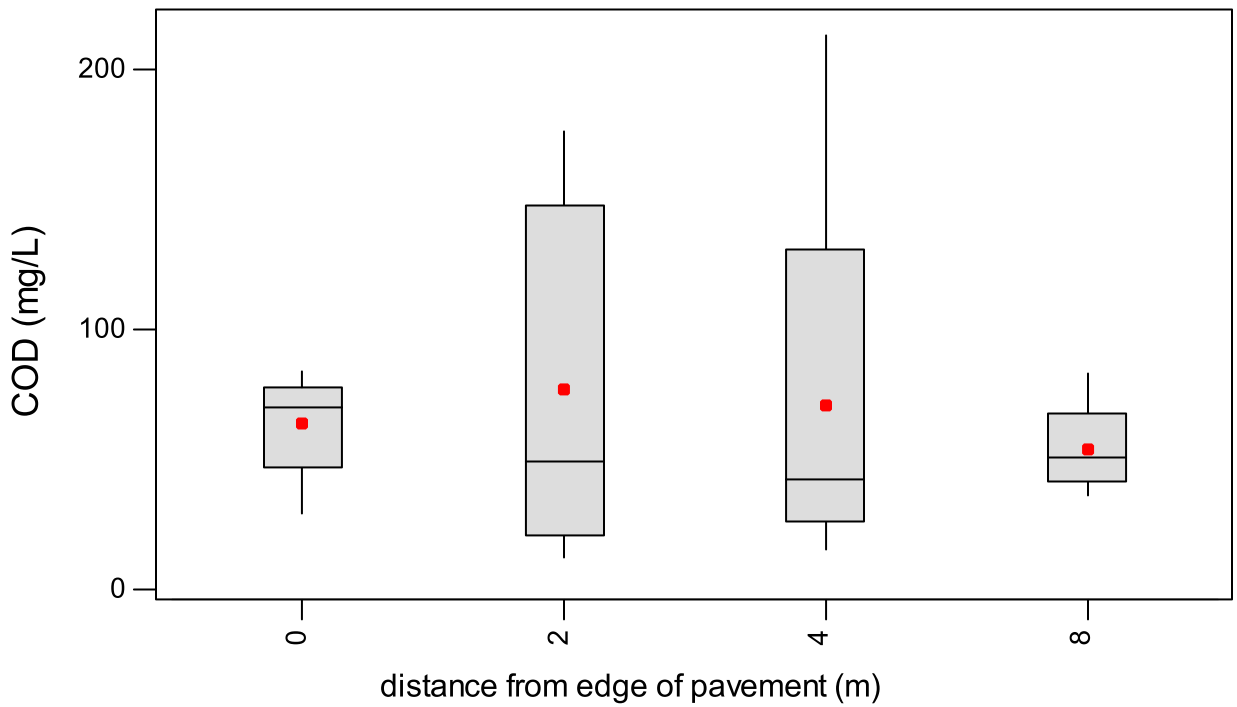

Figure B- 21 Boxplot of COD at Site 1, conventional asphalt surface

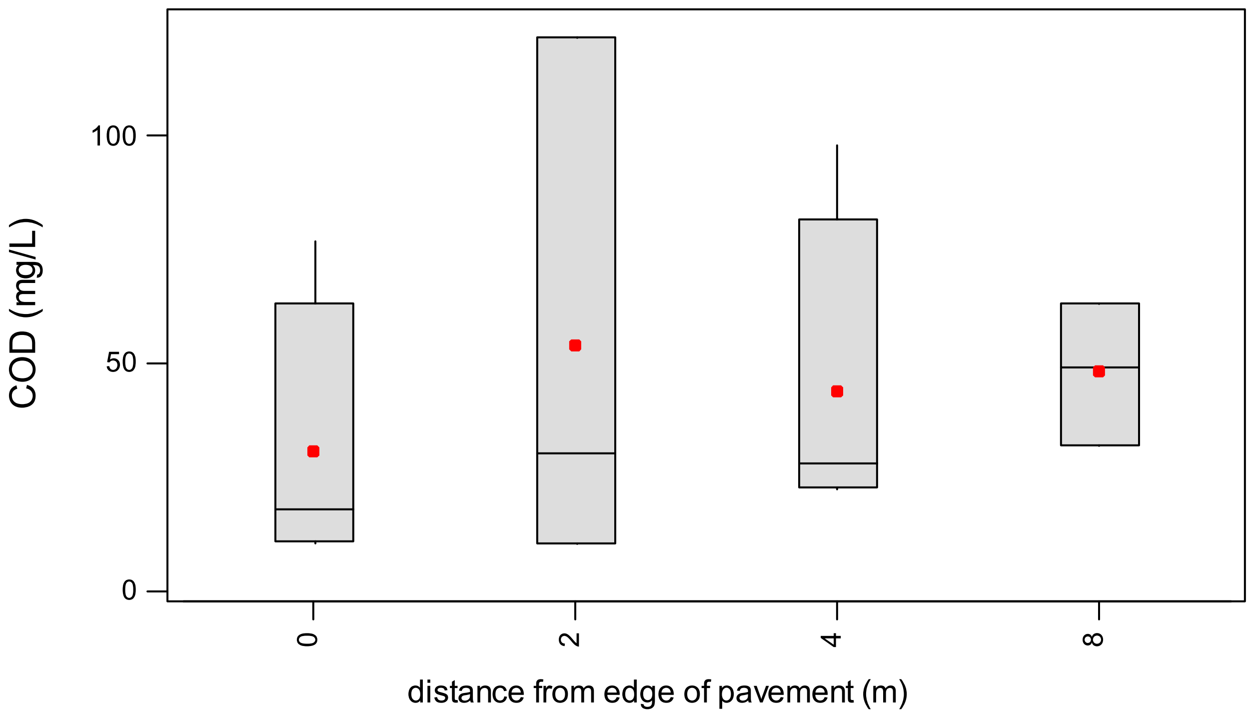

Figure B- 22 Boxplot of COD at Site 1, PFC surface

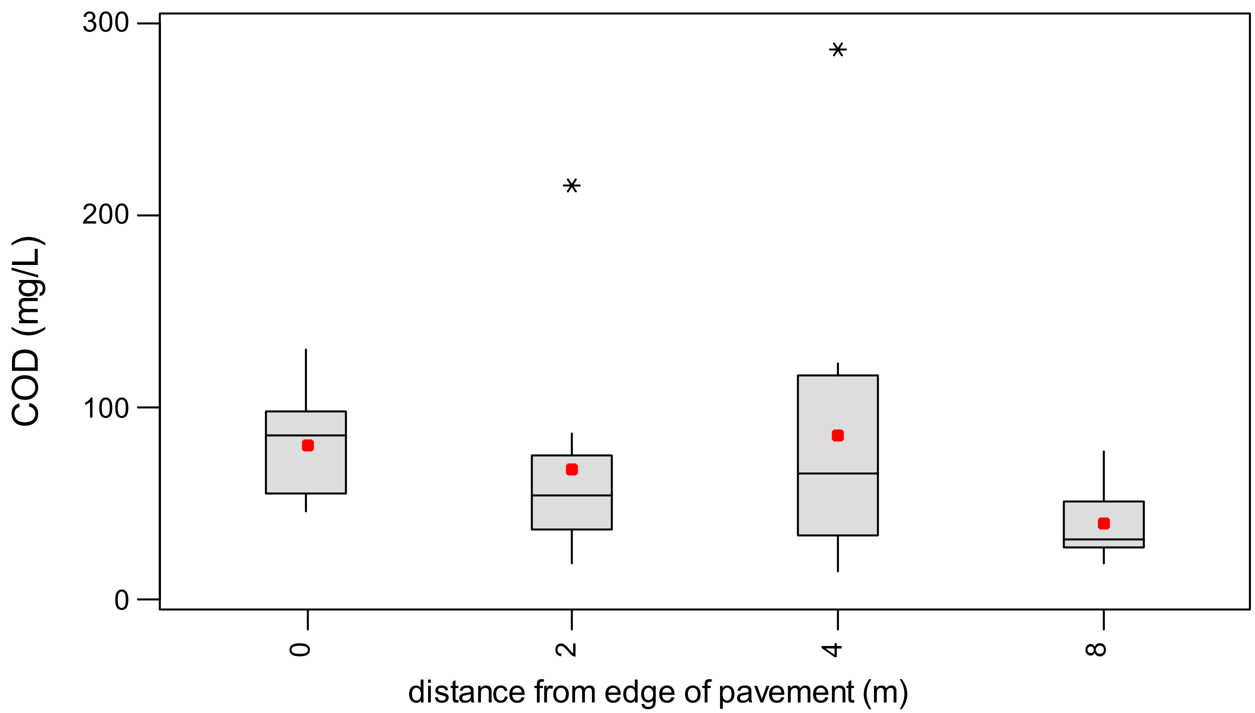

Figure B- 23 Boxplot of COD at Site 2

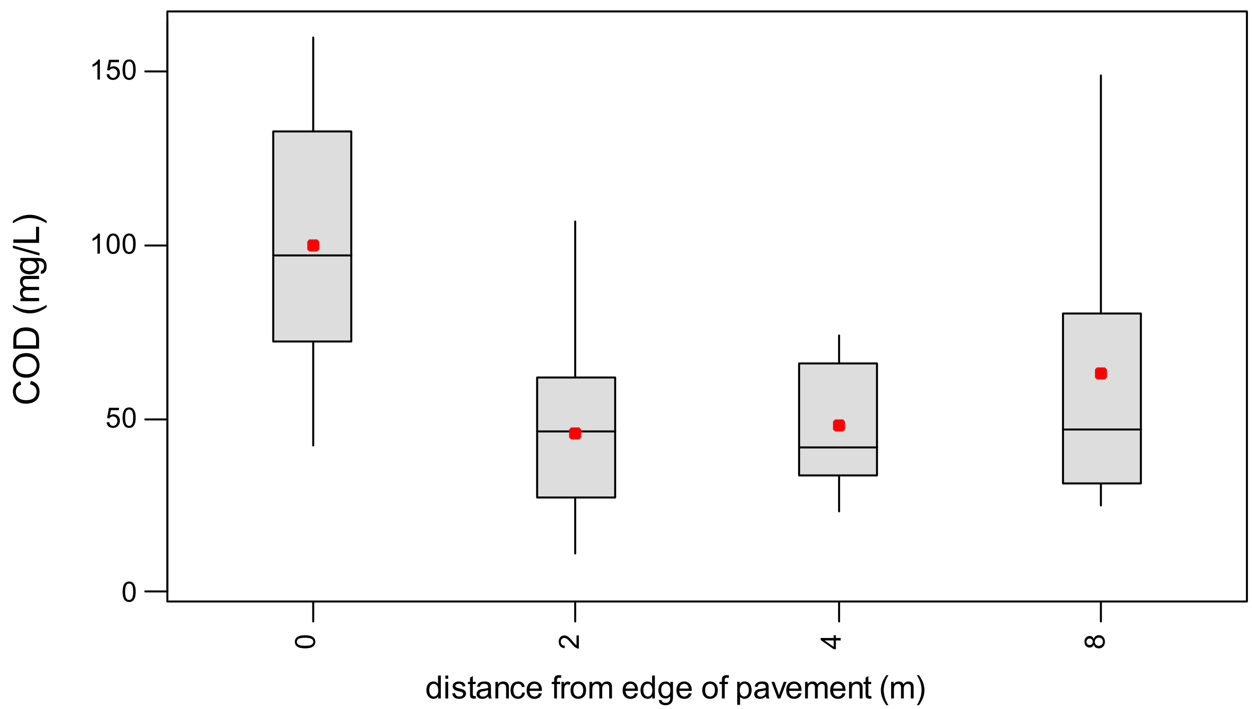

Figure B- 24 Boxplot of COD at Site 3

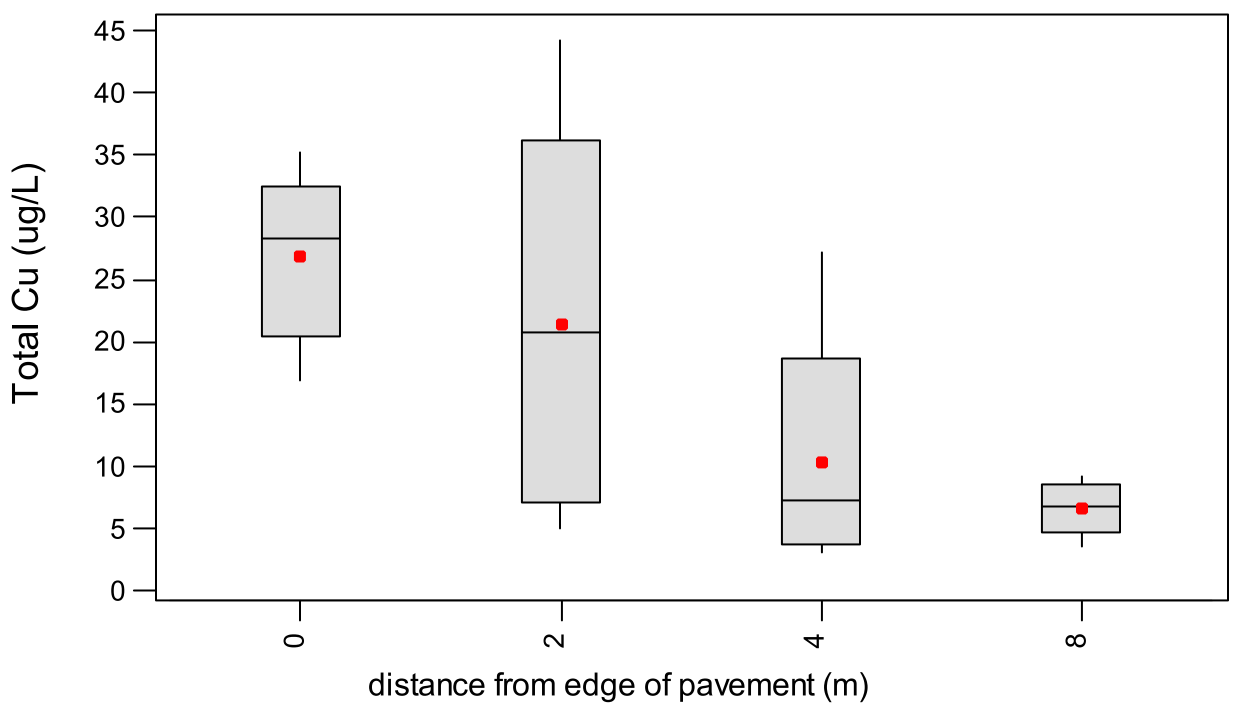

Figure B- 25 Boxplot of Total Cu at Site 1, conventional asphalt surface

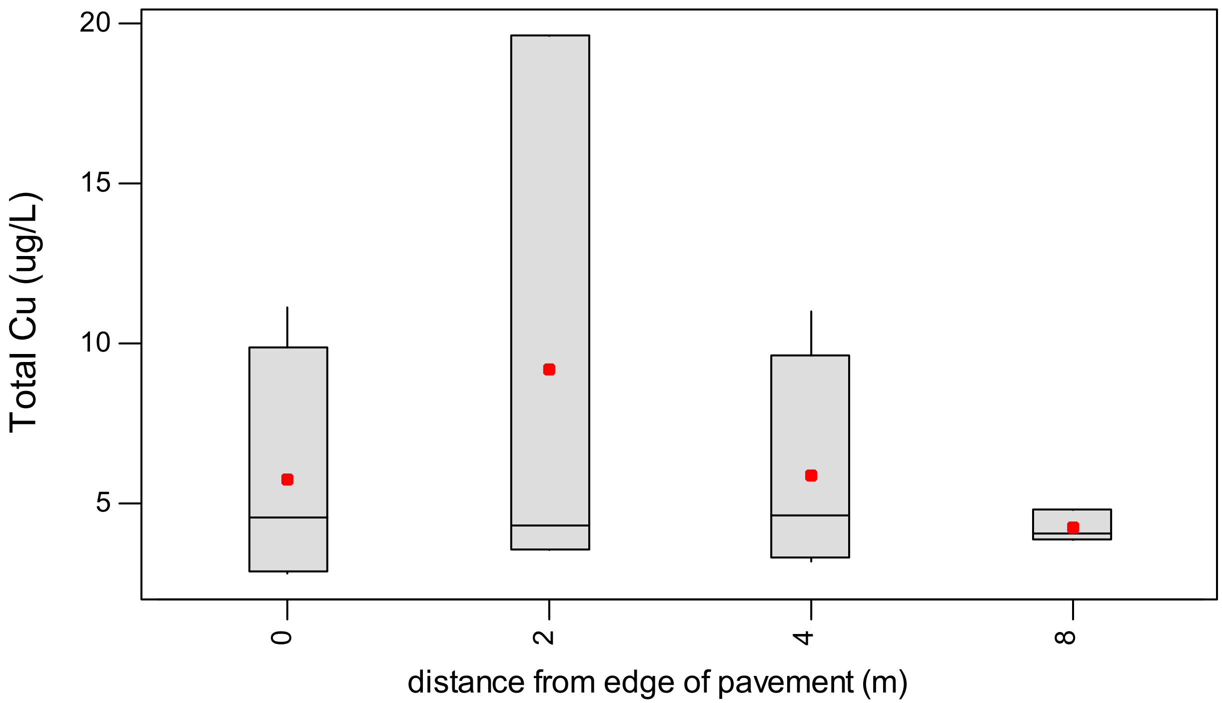

Figure B- 26 Boxplot of Total Cu at Site 1, PFC surface

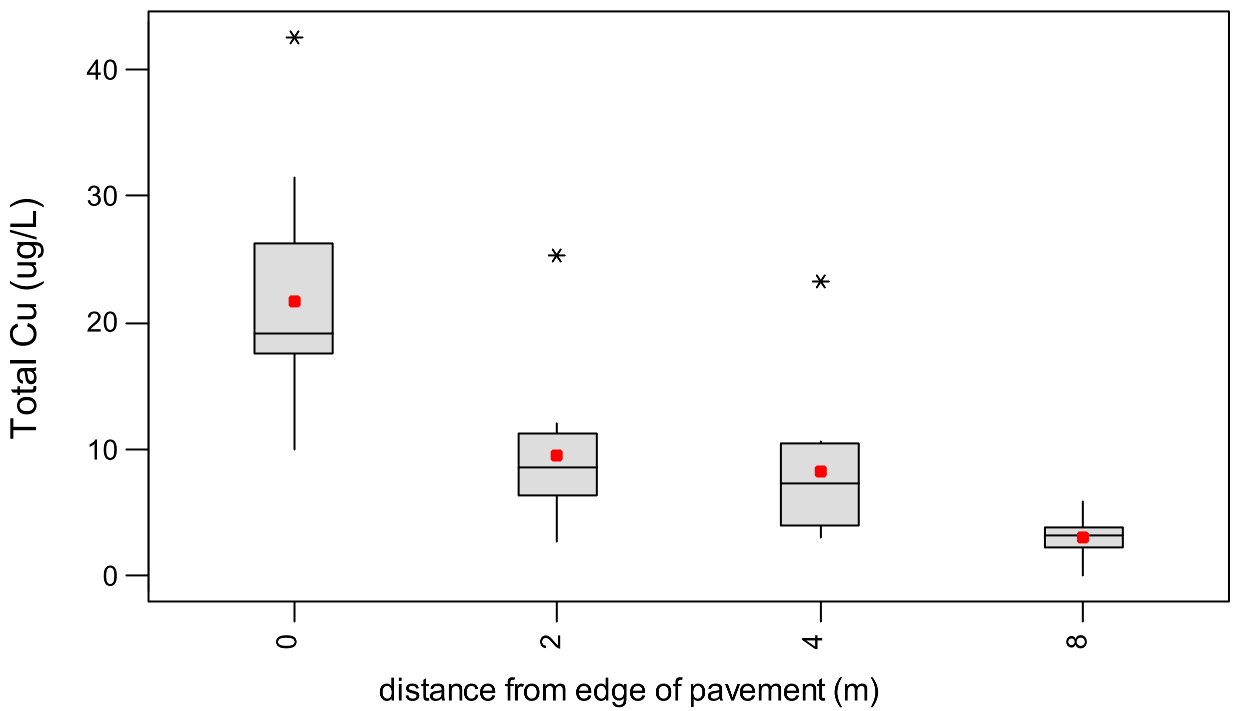

Figure B- 27 Boxplot of Total Cu at Site 2

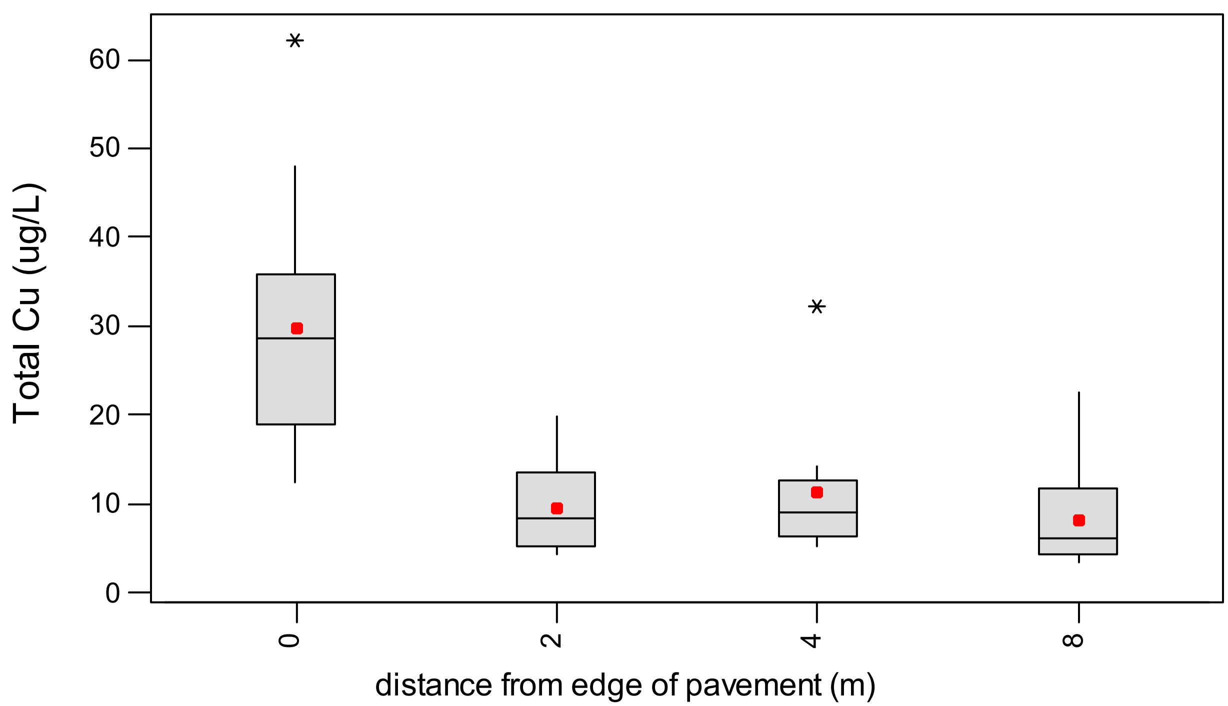

Figure B- 28 Boxplot of Total Cu at Site 3

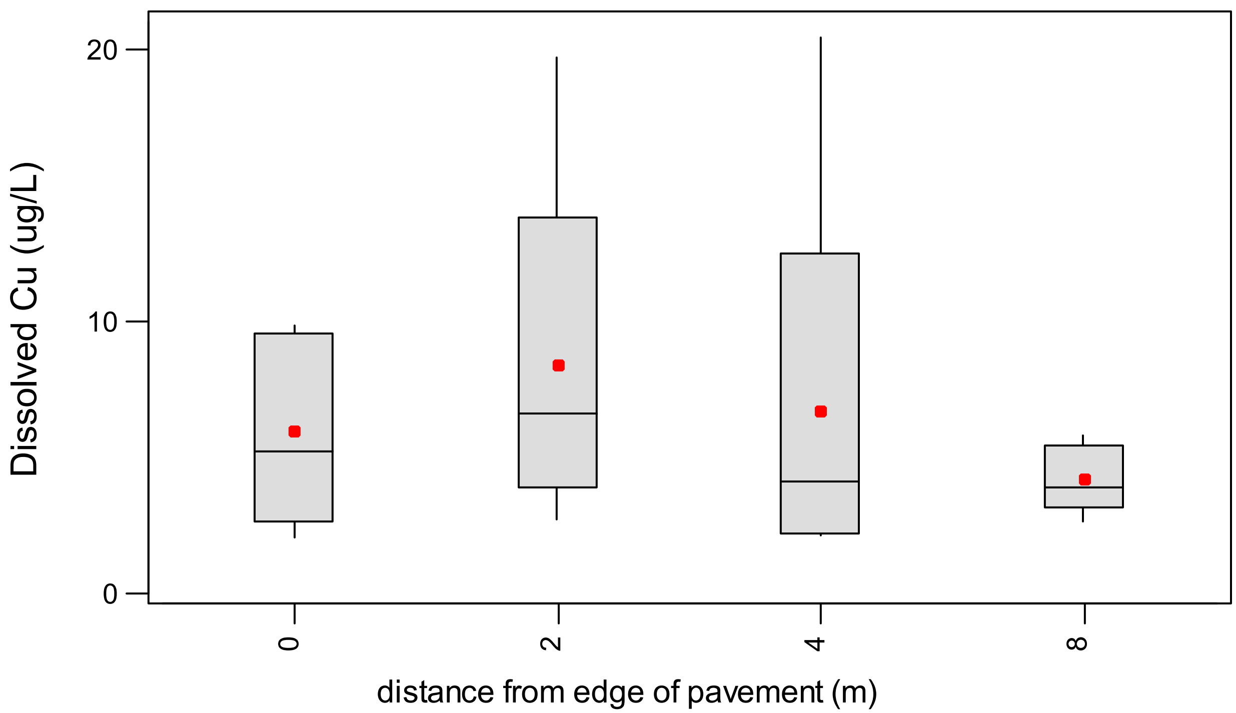

Figure B- 29 Boxplot of Dissolved Cu at Site 1, conventional asphalt surface

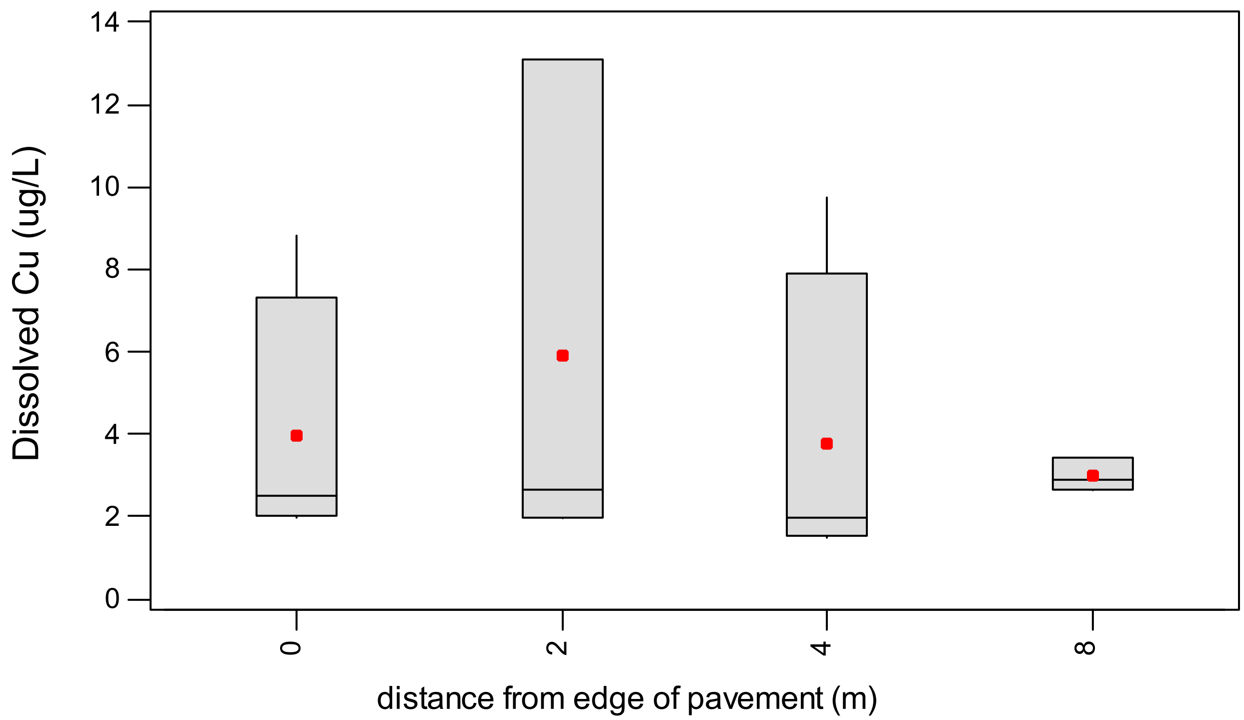

Figure B- 30 Boxplot of Dissolved Cu at Site 1, PFC surface

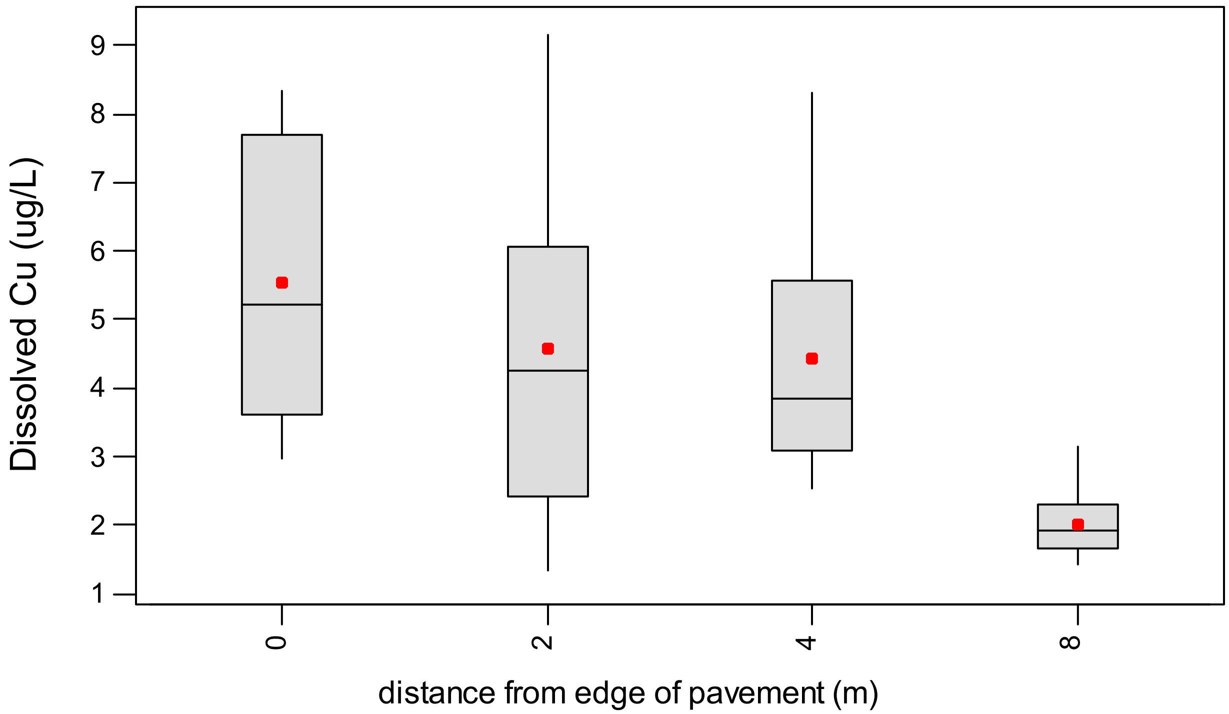

Figure B- 31 Boxplot of Dissolved Cu at Site 2

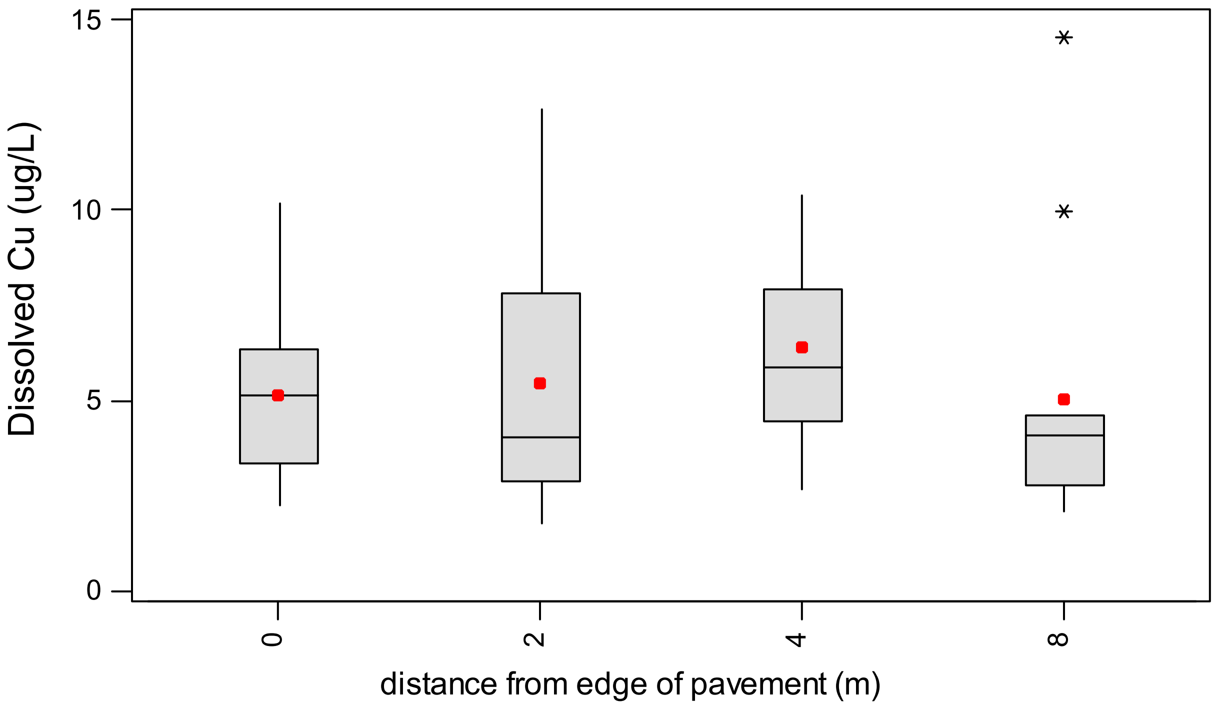

Figure B- 32 Boxplot of Dissolved Cu at Site 3

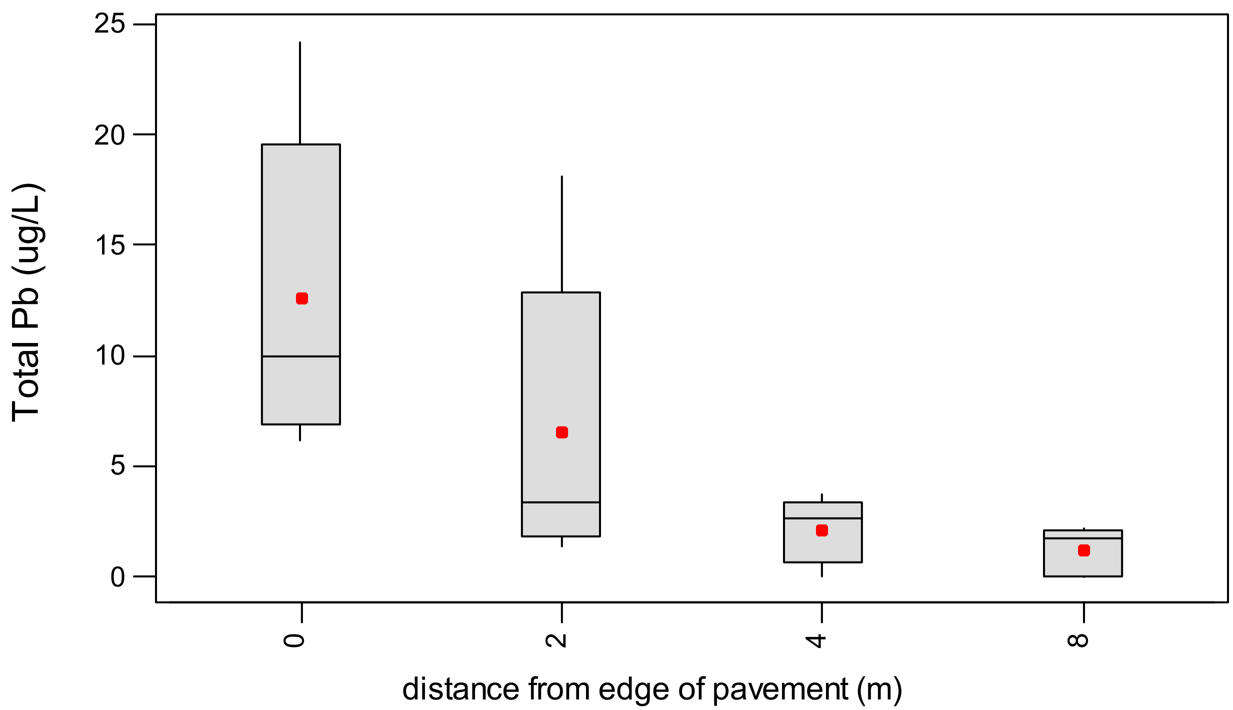

Figure B- 33 Boxplot of Total Pb at Site 1, conventional asphalt surface

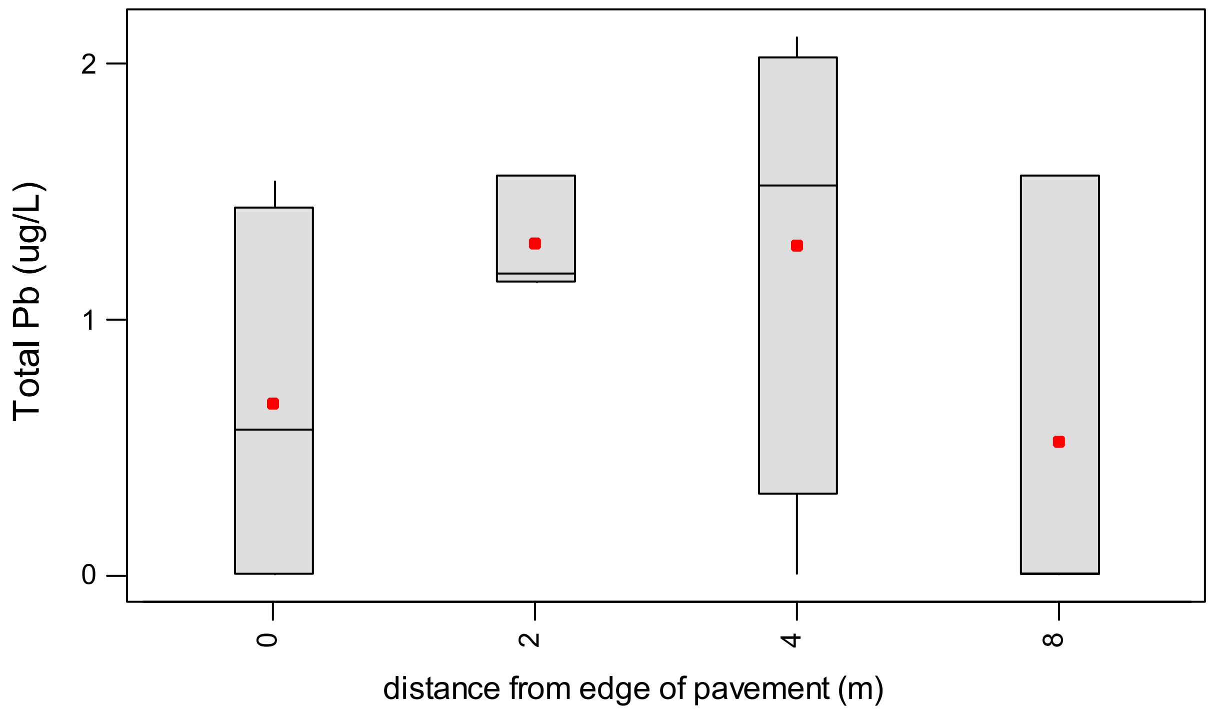

Figure B- 34 Boxplot of Total Pb at Site 1, PFC surface

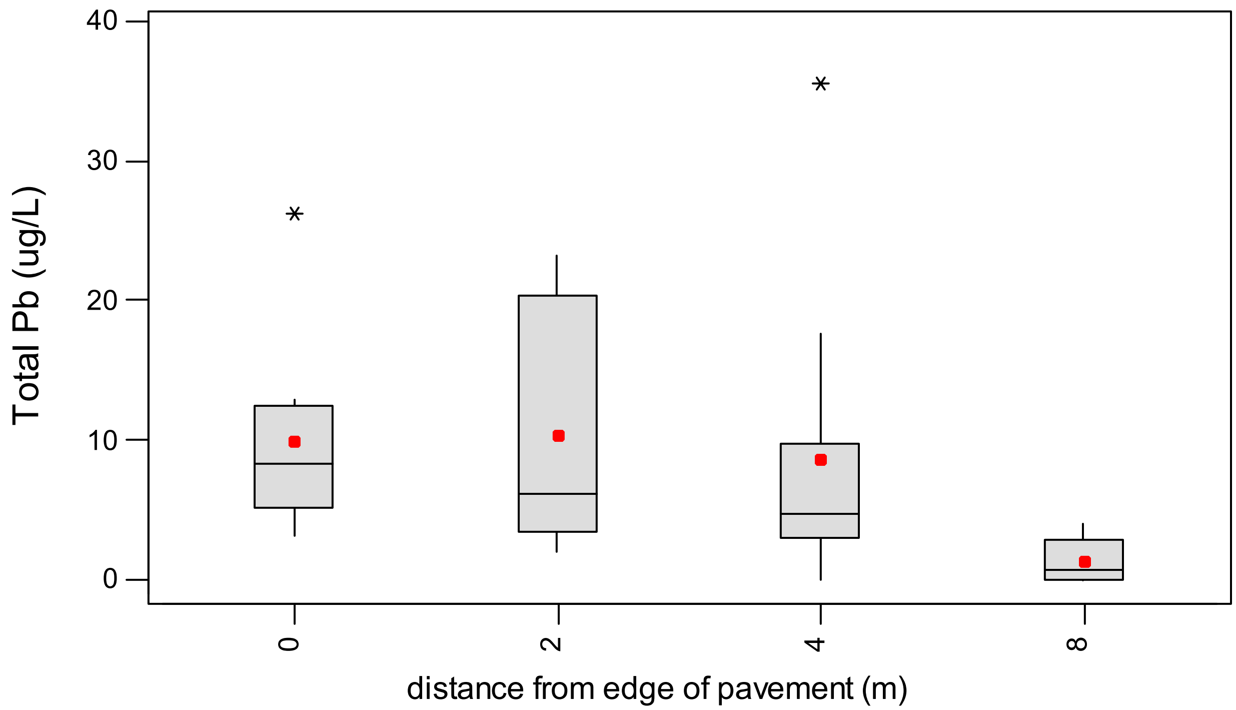

Figure B- 35 Boxplot of Total Pb at Site 2

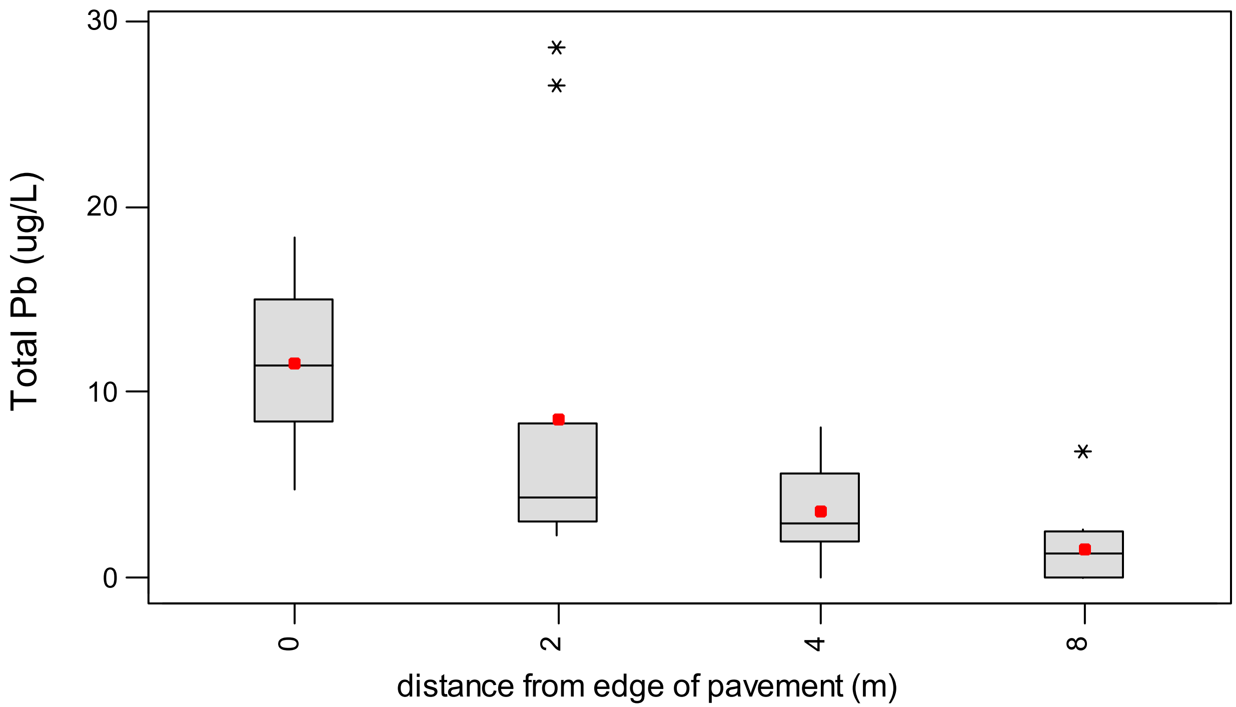

Figure B- 36 Boxplot of Total Pb at Site 3

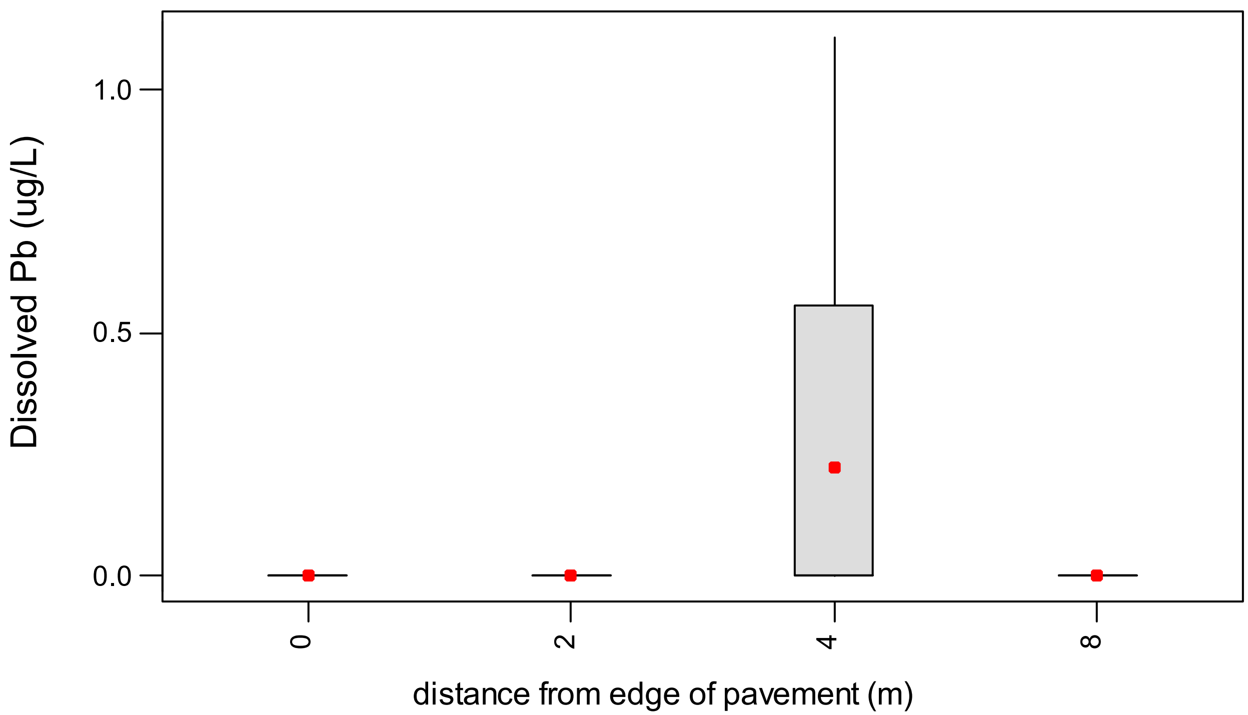

Figure B- 37 Boxplot of Dissolved Pb at Site 1, conventional asphalt surface

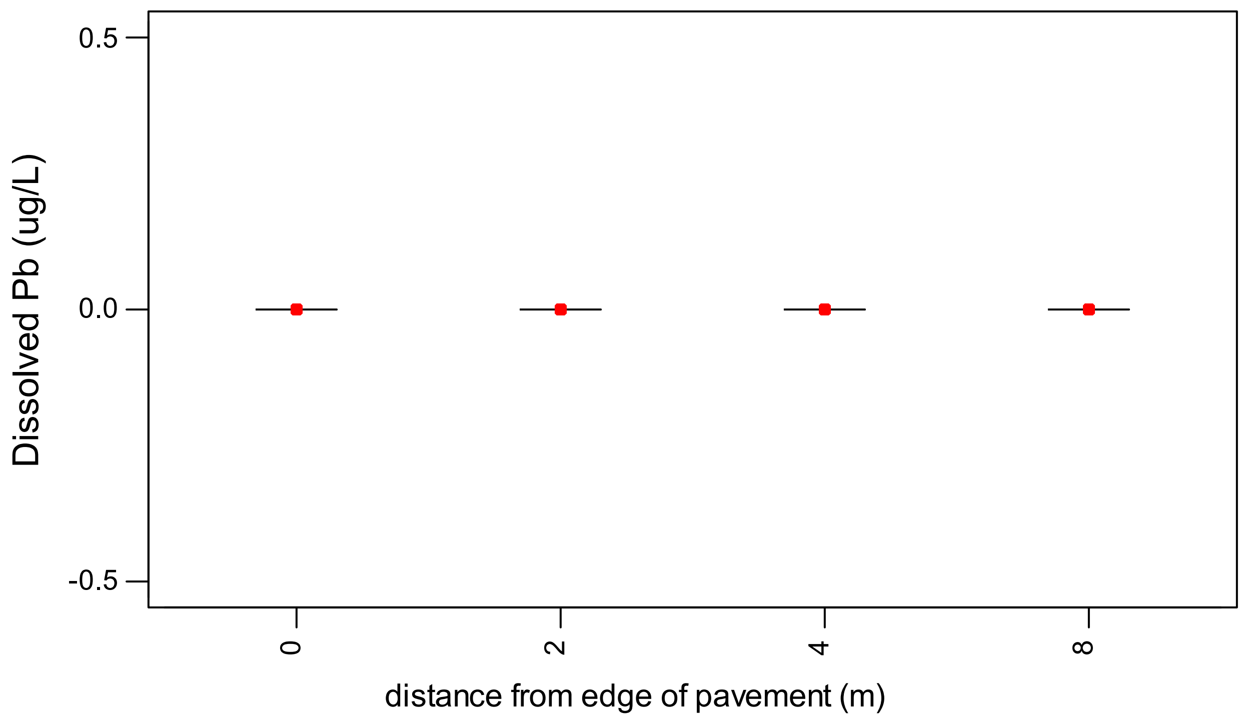

Figure B- 38 Boxplot of Dissolved Pb at Site 1, PFC surface

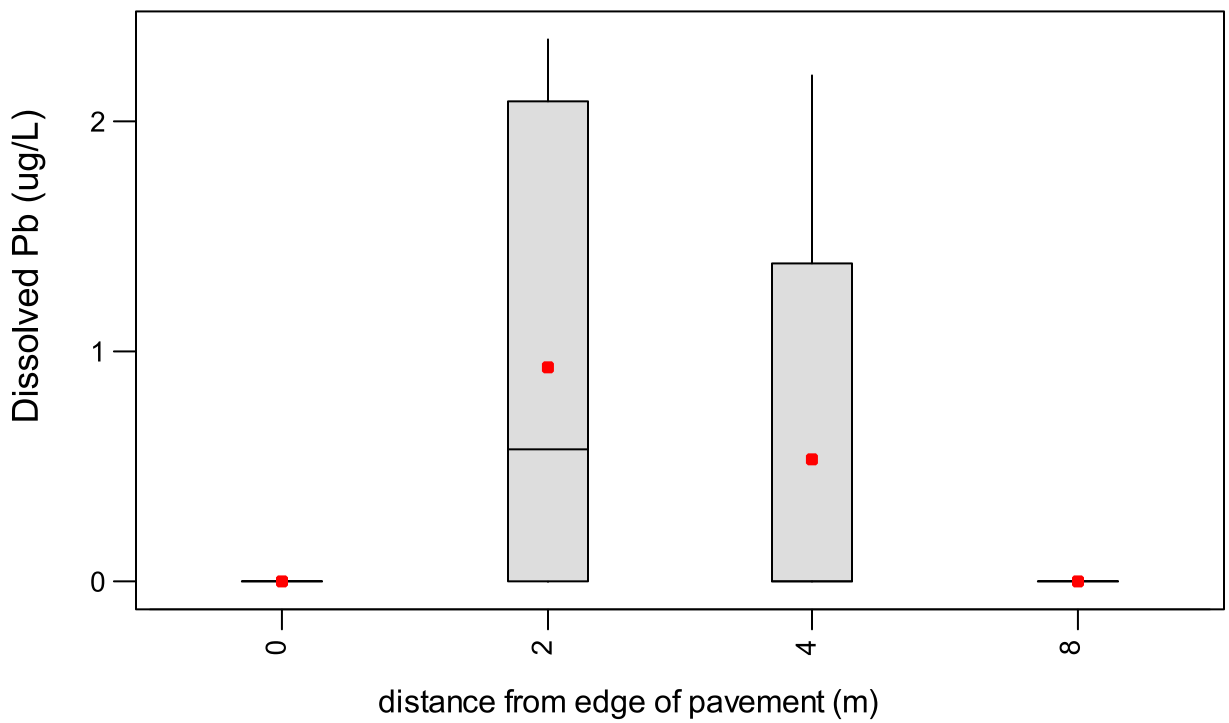

Figure B- 39 Boxplot of Dissolved Pb at Site 2

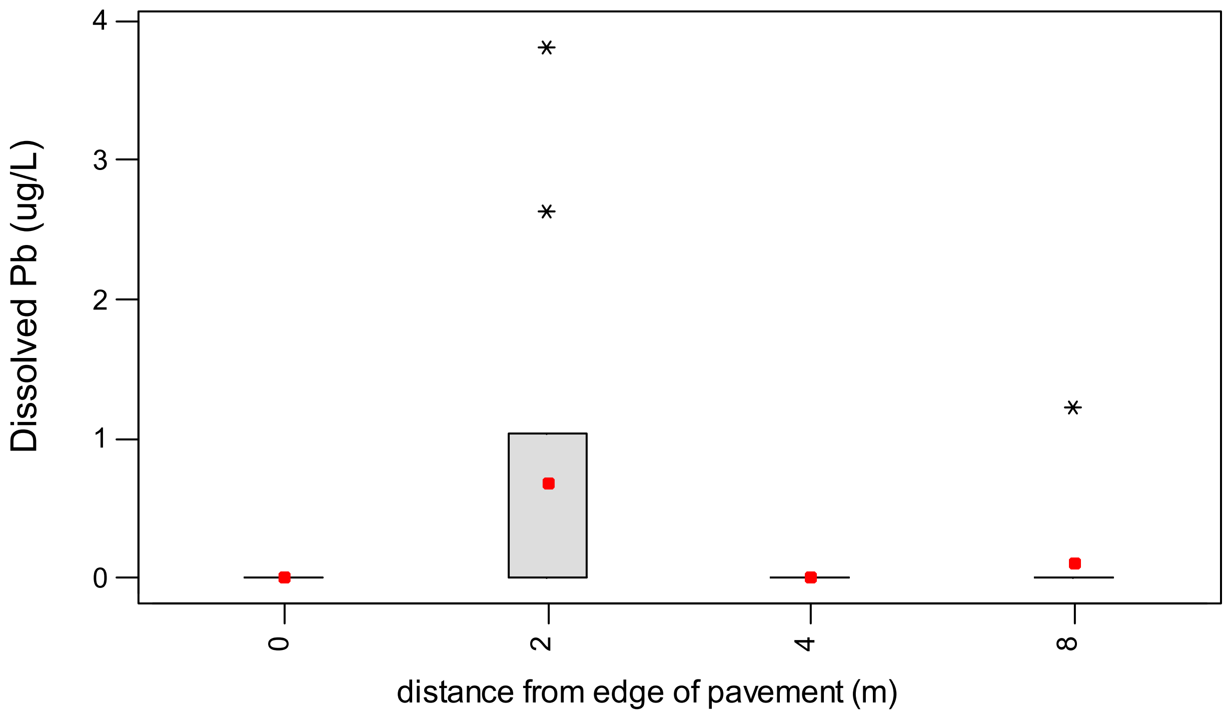

Figure B- 40 Boxplot of Dissolved Pb at Site 3

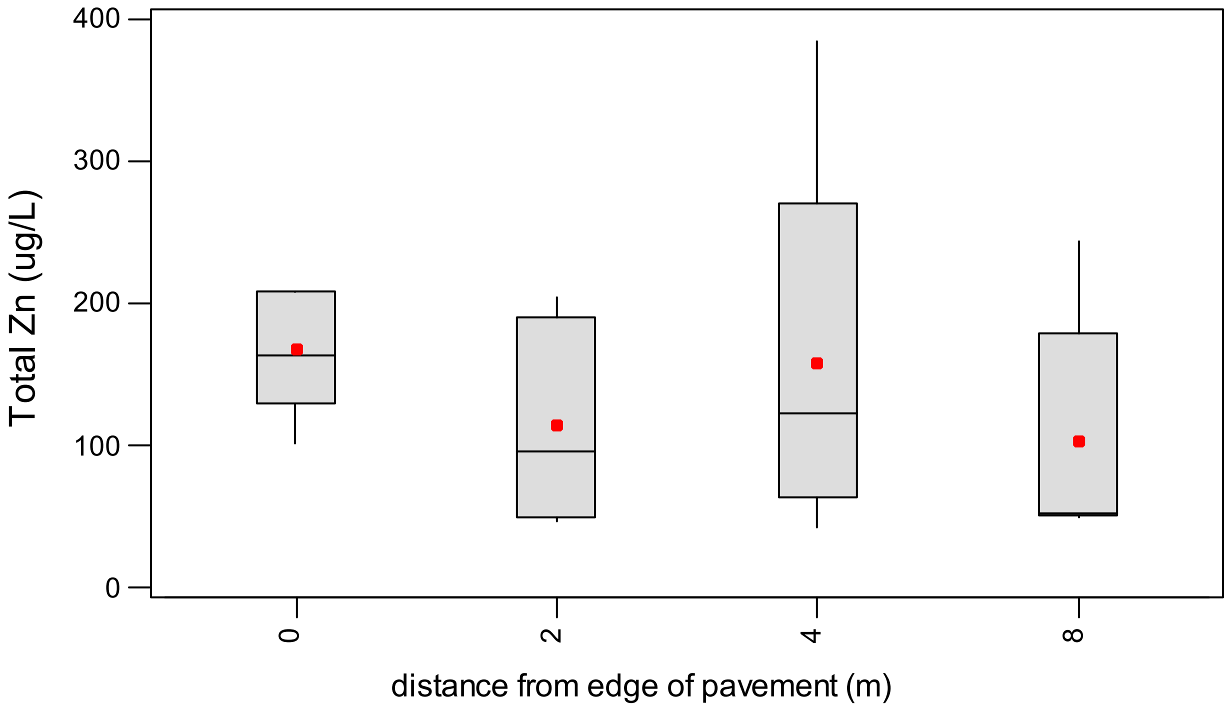

Figure B- 41 Boxplot of Total Zn at Site 1, conventional asphalt surface

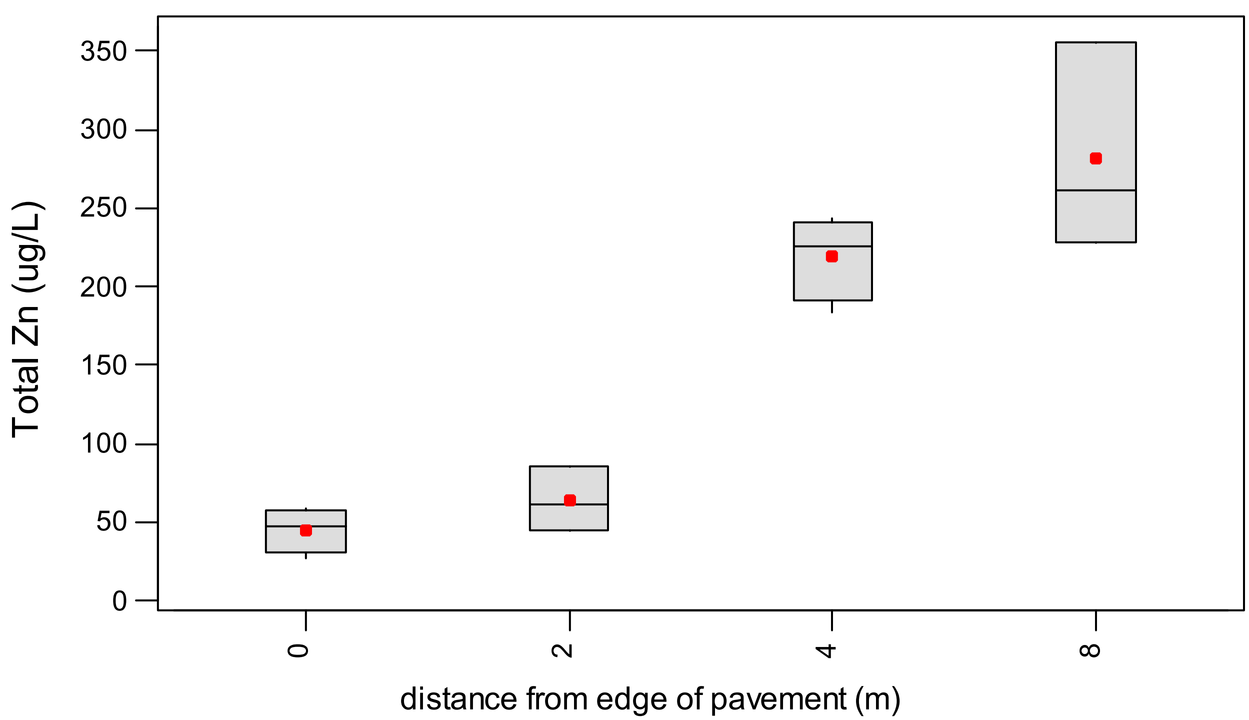

Figure B- 42 Boxplot of Total Zn at Site 1, PFC surface

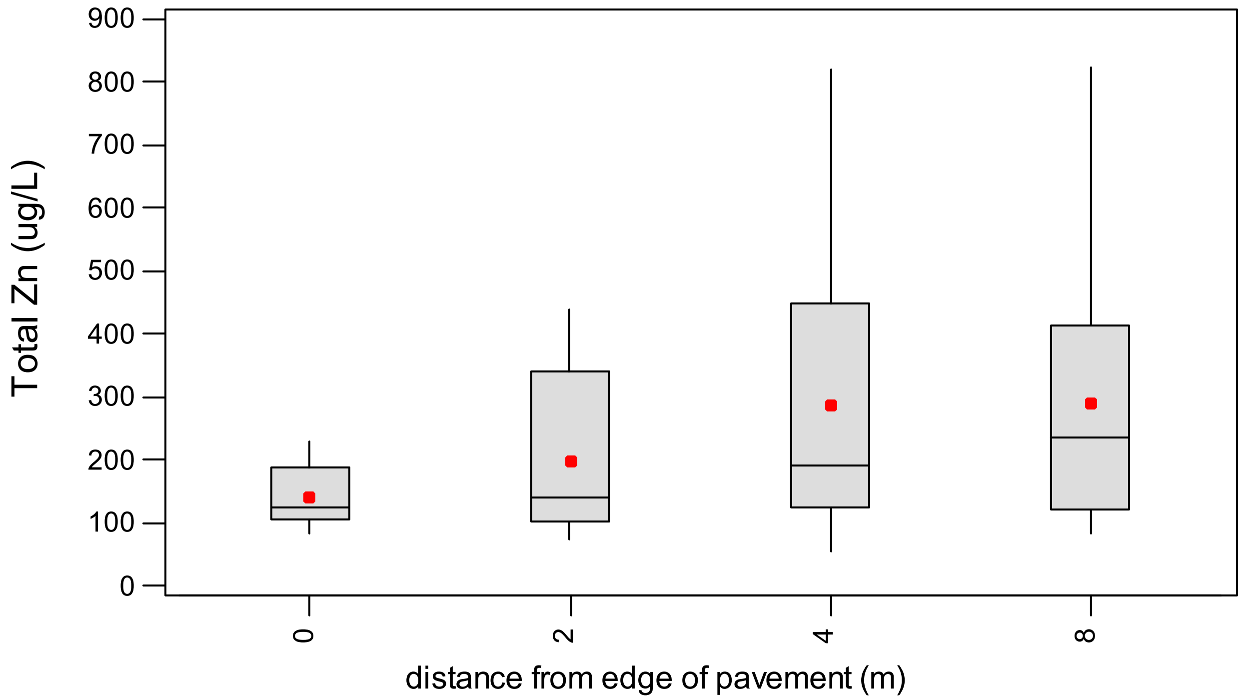

Figure B- 43 Boxplot of Total Zn at Site 2

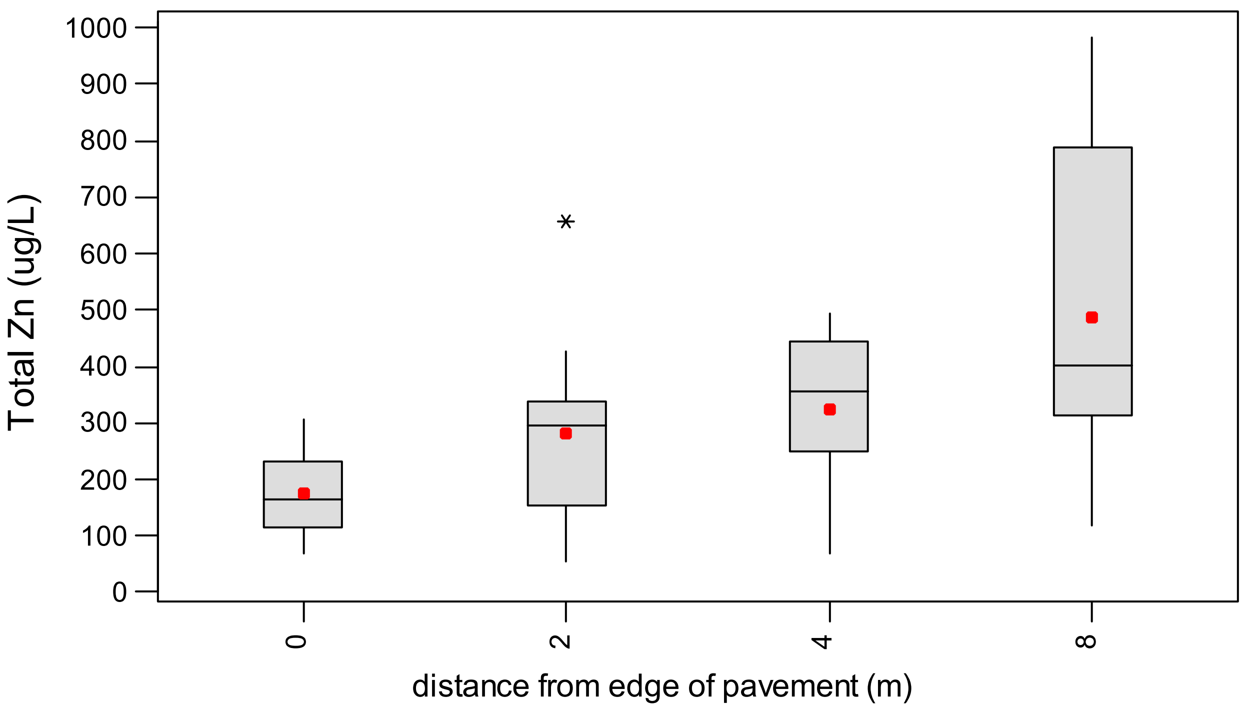

Figure B- 44 Boxplot of Total Zn at Site 3

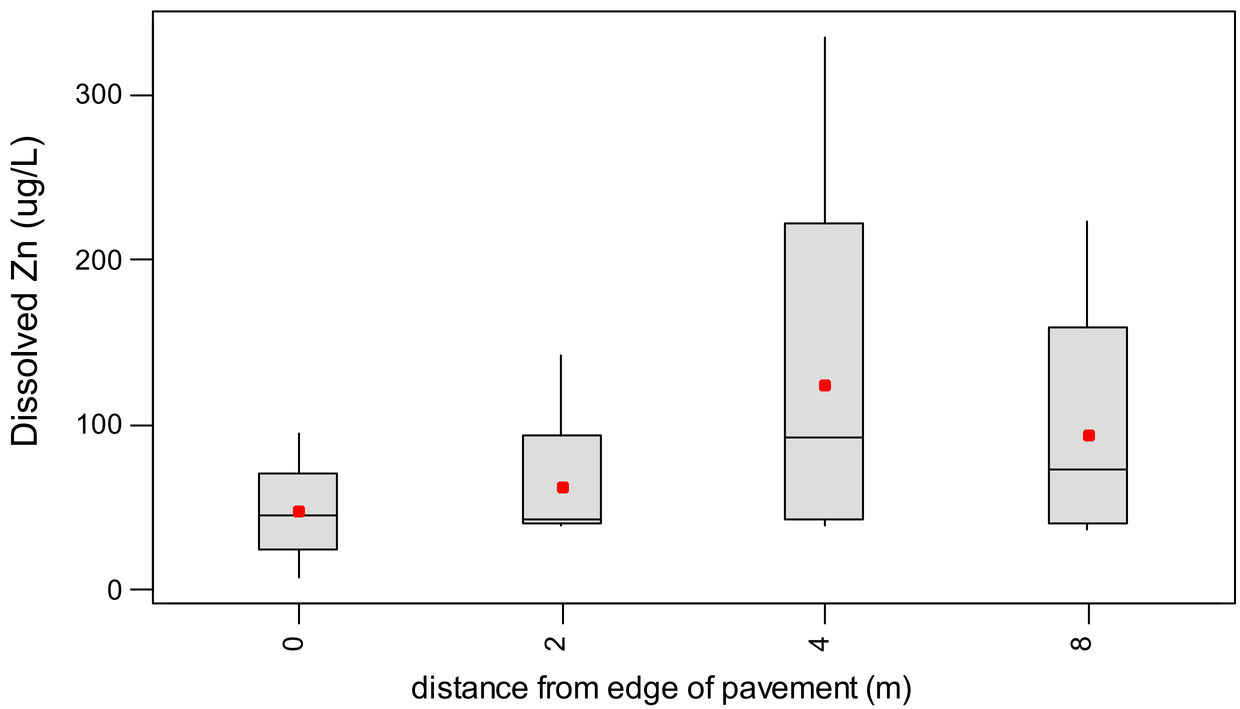

Figure B- 45 Boxplot of Dissolved Zn at Site 1, conventional asphalt surface

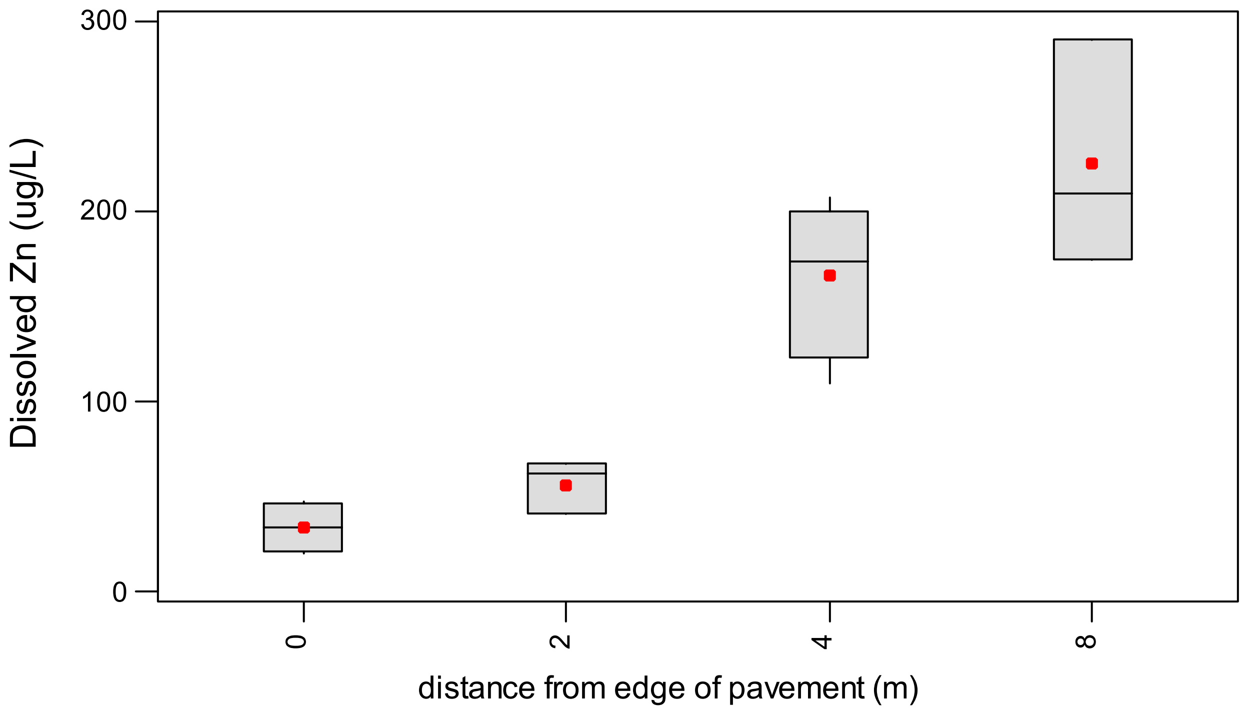

Figure B- 46 Boxplot of Dissolved Zn at Site 1, PFC surface

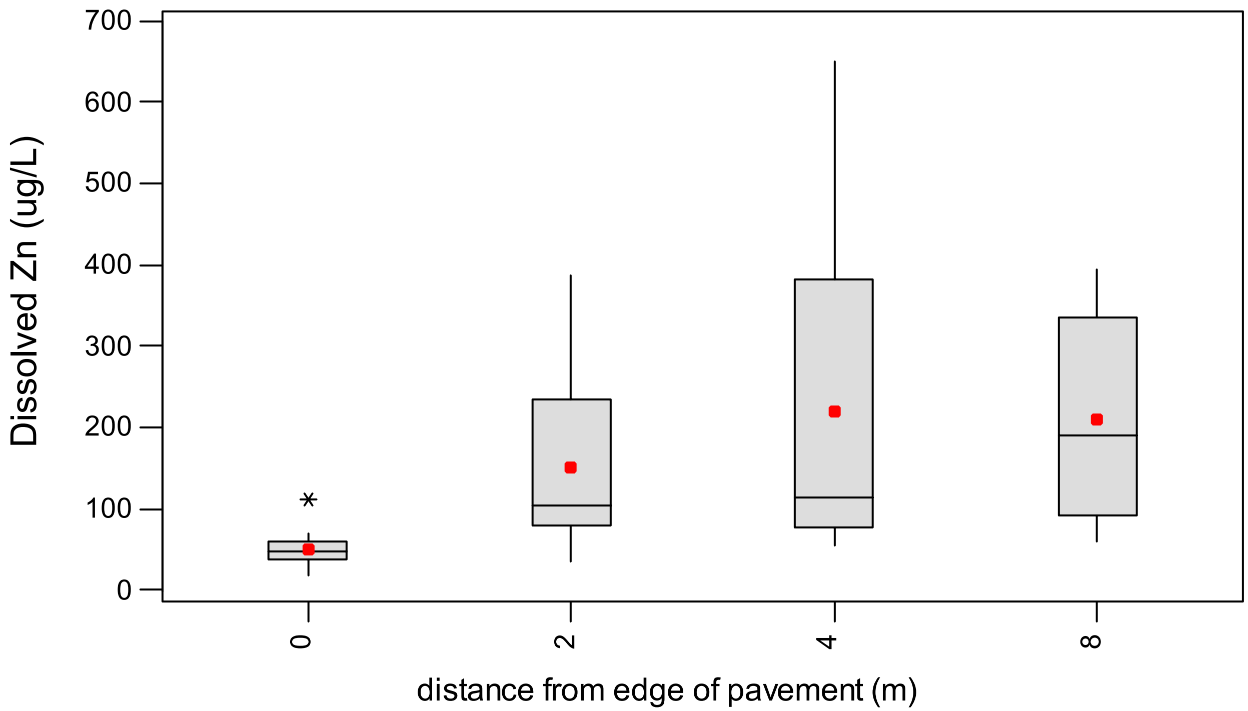

Figure B- 47 Boxplot of Dissolved Zn at Site 2

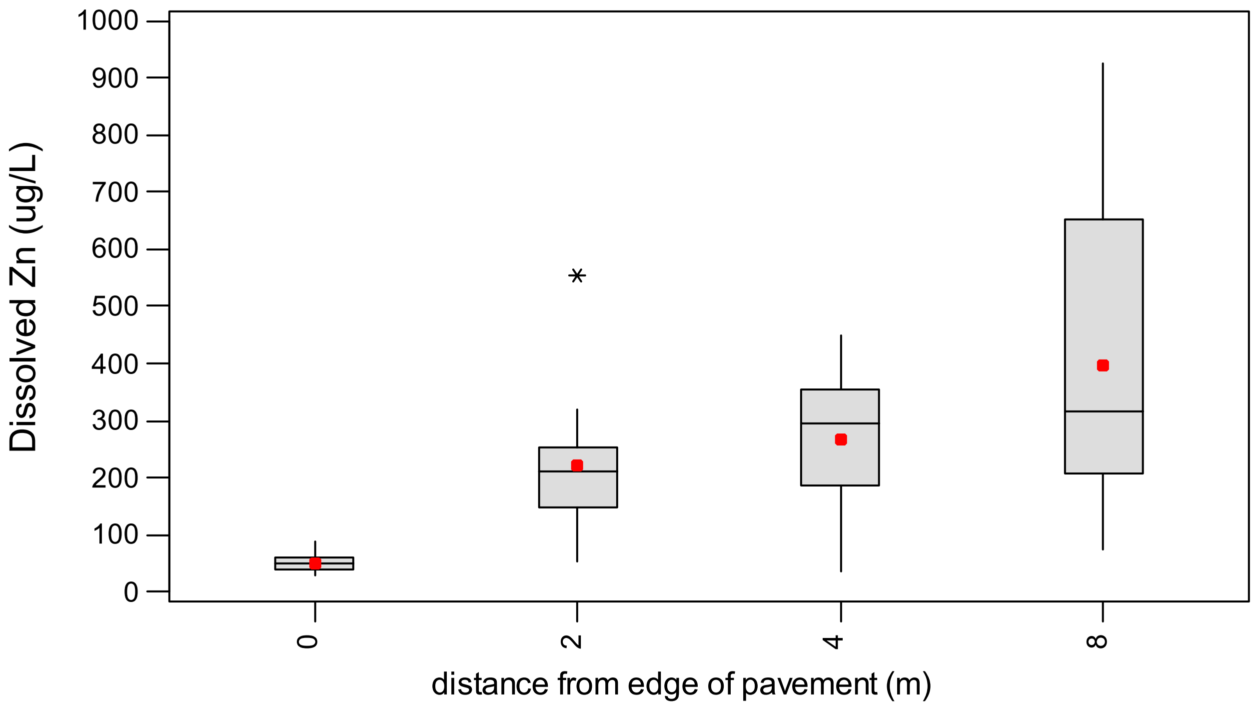

Figure B- 48 Boxplot of Dissolved Zn at Site 3

APPENDIX C POLLUTANT REMOVAL RATES

Table C- 1 Pollutant Removal at Site 1, conventional asphalt surface

removal between samplers	0-2m		2-4m		4-8m	
	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)
TSS (mg/L)	-3.1%	36.1%	50.2%	35.5%	30.5%	34.2%
TKN (mg/L)	-64.6%	-96.4%	-28.8%	-15.5%	10.2%	-12.1%
NO3/NO2-N (mg/L)	35.8%	32.6%	-5.3%	-34.5%	26.9%	-3.5%
Total P (mg/L)	-45.5%	-9.4%	8.9%	7.1%	-68.0%	-87.2%
Dissolved P (mg/L)	-166.7%	-138.7%	19.3%	13.9%	-137.4%	-143.6%
Total Cu (µg/L)	20.1%	37.8%	51.6%	42.8%	36.3%	31.1%
Total Pb (µg/L)	48.0%	70.0%	67.5%	62.8%	45.2%	53.9%
Total Zn (µg/L)	31.4%	48.6%	-37.7%	-37.4%	35.2%	25.8%
Dissolved Cu (µg/L)	-42.0%	-41.7%	20.2%	23.7%	37.2%	18.6%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-31.7%	-39.2%	-101.0%	-68.4%	24.3%	9.8%
COD (mg/L)	-20.6%	16.2%	54.0%	46.4%	-51.5%	-81.1%
net removal across site	**0-2m**		**0-4m**		**0-8m**	
TSS (mg/L)	-3.1%	36.1%	48.7%	58.8%	64.3%	72.9%
TKN (mg/L)	-64.6%	-96.4%	-112.1%	-126.8%	-90.5%	-154.4%
NO3/NO2-N (mg/L)	35.8%	32.6%	-5.3%	9.4%	26.9%	6.3%
Total P (mg/L)	-45.5%	-9.4%	-32.6%	-1.6%	-122.7%	-90.1%
Dissolved P (mg/L)	-166.7%	-138.7%	-115.3%	-105.4%	-411.1%	-400.4%
Total Cu (µg/L)	20.1%	37.8%	61.3%	64.4%	75.4%	75.5%
Total Pb (µg/L)	48.0%	70.0%	83.1%	88.8%	90.7%	94.9%
Total Zn (µg/L)	31.4%	48.6%	5.6%	29.3%	38.8%	47.6%
Dissolved Cu (µg/L)	-42.0%	-41.7%	-13.3%	-8.1%	28.8%	12.0%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-31.7%	-39.2%	-164.6%	-134.4%	-100.2%	-111.5%
COD (mg/L)	-20.6%	16.2%	44.5%	55.1%	15.9%	18.6%

Table C- 2 Pollutant Removal at Site 1, PFC surface

removal between samplers	0-2m		2-4m		4-8m	
	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)
TSS (mg/L)	-75.0%	-26.6%	-126.8%	-208.0%	20.2%	41.3%
TKN (mg/L)	-89.4%	-66.1%	8.0%	-3.4%	-73.2%	-42.4%
NO3/NO2-N (mg/L)	19.4%	27.7%	51.6%	50.6%	-1.7%	11.3%
Total P (mg/L)	79.0%	84.6%	-355.2%	-428.1%	34.7%	45.7%
Dissolved P (mg/L)	90.1%	92.5%	-842.4%	-1060.9%	21.1%	31.1%
Total Cu (µg/L)	-59.4%	-40.6%	36.2%	28.1%	27.8%	40.8%
Total Pb (µg/L)	-94.0%	-54.4%	0.6%	-28.4%	59.5%	71.0%
Total Zn (µg/L)	-41.5%	-14.2%	-243.7%	-319.3%	-28.5%	-4.8%
Dissolved Cu (µg/L)	-49.6%	-37.3%	35.9%	31.5%	21.3%	32.3%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-67.7%	-33.8%	-192.8%	-254.5%	-35.9%	-12.9%
COD (mg/L)	-77.0%	-63.8%	18.5%	11.1%	-9.1%	8.6%
net removal across site	0-2m		0-4m		0-8m	
	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)
TSS (mg/L)	-75.0%	-26.6%	-296.9%	-290.0%	-216.7%	-128.8%
TKN (mg/L)	-89.4%	-66.1%	-74.2%	-71.8%	-201.7%	-144.6%
NO3/NO2-N (mg/L)	19.4%	27.7%	61.0%	64.3%	60.3%	68.3%
Total P (mg/L)	79.0%	84.6%	4.5%	18.7%	37.6%	55.9%
Dissolved P (mg/L)	90.1%	92.5%	7.1%	13.0%	26.7%	40.1%
Total Cu (µg/L)	-59.4%	-40.6%	-1.7%	-1.0%	26.6%	40.2%
Total Pb (µg/L)	-94.0%	-54.4%	-92.9%	-98.2%	21.9%	42.5%
Total Zn (µg/L)	-41.5%	-14.2%	-386.4%	-378.9%	-524.9%	-401.7%
Dissolved Cu (µg/L)	-49.6%	-37.3%	4.2%	5.9%	24.6%	36.3%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-67.7%	-33.8%	-386.4%	-378.9%	-524.9%	-401.7%
COD (mg/L)	-77.0%	-63.8%	-391.1%	-374.3%	-567.7%	-435.3%

Table C- 3 Pollutant Removal at Site 2

removal between samplers	0-2m (mean EMC method)	0-2m (rainfall weighted average method)	2-4m (mean EMC method)	2-4m (rainfall weighted average method)	4-8m (mean EMC method)	4-8m (rainfall weighted average method)
TSS (mg/L)	57.8%	73.4%	-34.7%	18.6%	44.8%	48.5%
TKN (mg/L)	-15.0%	7.5%	-43.2%	-37.4%	33.8%	36.3%
NO3/NO2-N (mg/L)	46.7%	60.2%	-81.8%	-180.2%	-39.6%	-46.9%
Total P (mg/L)	-82.3%	33.9%	-43.9%	-160.4%	15.4%	15.2%
Dissolved P (mg/L)	-162.5%	34.5%	-44.4%	-255.1%	14.2%	3.4%
Total Cu (µg/L)	56.0%	67.8%	13.6%	21.2%	62.7%	63.6%
Total Pb (µg/L)	-4.1%	27.8%	16.5%	59.7%	84.5%	75.0%
Total Zn (µg/L)	-41.5%	7.8%	-44.4%	-55.3%	-1.3%	15.7%
Dissolved Cu (µg/L)	17.5%	28.5%	3.1%	-15.6%	54.7%	52.9%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-207.4%	-148.0%	-45.1%	-72.9%	4.2%	15.4%
COD (mg/L)	15.5%	69.4%	-25.0%	-14.5%	53.3%	3.2%

net removal across site	0-2m (mean EMC method)	0-2m (rainfall weighted average method)	0-4m (mean EMC method)	0-4m (rainfall weighted average method)	0-8m (mean EMC method)	0-8m (rainfall weighted average method)
TSS (mg/L)	57.8%	73.4%	43.1%	78.4%	68.6%	88.9%
TKN (mg/L)	-15.0%	7.5%	-64.6%	-27.1%	-8.9%	19.0%
NO3/NO2-N (mg/L)	46.7%	60.2%	3.2%	-11.5%	-35.2%	-63.9%
Total P (mg/L)	-82.3%	33.9%	-162.4%	-72.0%	-122.1%	-45.9%
Dissolved P (mg/L)	-162.5%	34.5%	-279.2%	-132.6%	-225.2%	-124.7%
Total Cu (µg/L)	56.0%	67.8%	62.0%	74.6%	85.9%	90.8%
Total Pb (µg/L)	-4.1%	27.8%	13.1%	70.9%	86.6%	92.7%
Total Zn (µg/L)	-41.5%	7.8%	-104.3%	-43.2%	-107.1%	-20.7%
Dissolved Cu (µg/L)	17.5%	28.5%	20.0%	17.3%	63.8%	61.1%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-207.4%	-148.0%	-328.7%	-328.7%	-327.1%	-262.7%
COD (mg/L)	15.5%	69.4%	-5.7%	64.9%	50.7%	66.0%

Table C- 4 Pollutant Removal at Site 3

removal between samplers	0-2m		2-4m		4-8m	
	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)
TSS (mg/L)	71.0%	82.1%	21.3%	14.7%	-25.5%	0.2%
TKN (mg/L)	-0.3%	29.3%	2.4%	8.9%	-39.3%	-88.4%
NO3/NO2-N (mg/L)	-24.9%	10.3%	-108.0%	-137.6%	-28.3%	-9.2%
Total P (mg/L)	-181.0%	-109.1%	-53.5%	-107.3%	27.6%	19.1%
Dissolved P (mg/L)	-610.5%	-400.8%	-68.1%	-131.9%	32.1%	22.4%
Total Cu (µg/L)	68.2%	80.2%	-18.0%	-47.9%	26.3%	30.9%
Total Pb (µg/L)	26.4%	22.5%	58.3%	37.5%	56.4%	67.4%
Total Zn (µg/L)	-60.7%	-5.0%	-15.3%	-16.8%	-50.3%	-49.7%
Dissolved Cu (µg/L)	-6.7%	12.6%	-16.9%	-40.7%	21.1%	13.2%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-339.7%	-247.7%	-20.6%	-21.1%	-49.6%	-52.9%
COD (mg/L)	54.0%	70.6%	-5.0%	-6.3%	-30.8%	-67.9%

net removal across site	0-2m		0-4m		0-8m	
	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)	(mean EMC method)	(rainfall weighted average method)
TSS (mg/L)	71.0%	82.1%	77.2%	84.7%	71.4%	84.8%
TKN (mg/L)	-0.3%	29.3%	2.1%	35.5%	-36.4%	-21.4%
NO3/NO2-N (mg/L)	-24.9%	10.3%	-159.7%	-113.0%	-233.4%	-132.6%
Total P (mg/L)	-181.0%	-109.1%	-331.4%	-333.5%	-212.2%	-250.9%
Dissolved P (mg/L)	-610.5%	-400.8%	-1094.2%	-1061.2%	-711.3%	-801.6%
Total Cu (µg/L)	68.2%	80.2%	62.5%	70.7%	72.3%	79.8%
Total Pb (µg/L)	26.4%	22.5%	69.3%	51.6%	86.6%	84.2%
Total Zn (µg/L)	-60.7%	-5.0%	-85.2%	-22.6%	-178.2%	-83.6%
Dissolved Cu (µg/L)	-6.7%	12.6%	-24.7%	-22.9%	1.6%	-6.7%
Dissolved Pb (µg/L)	*	*	*	*	*	*
Dissolved Zn (µg/L)	-339.7%	-247.7%	-430.2%	-321.1%	-693.3%	-543.9%
COD (mg/L)	54.0%	70.6%	51.7%	68.8%	36.8%	47.6%

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